BIOBASED BEE HOTEL FROM FLOWER WASTE

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“Anyone who thinks they’re too small to make a difference has never met the honey bee.”

~unknown

ABSTRACT

In this report, flower waste was used for the first time as a circular material to produce a completely bio-based and environmentally friendly particle board, henceforth called flowerboard. Flowerboard is completely biodegradable, regenerative and waste-free. Condensed tannins from mimosa extract were used as a natural adhesive for the flower waste. The tannin increased the strength and presumably the pathogen resistance of the flowerboard. Some properties of the flowerboard were a flexural strength of 8 MPa and exterior grade resistance against the common white-rot fungi *T. versicolor*. It could therefore compete with artificial wood based panels, but without deforestation, the use of toxic adhesives and CO_2 emissions. When coated with a layer of tung oil and Danish oil, the flowerboard could withstand 24 hours of constant water exposure with a thickness increase below 20%. This might make Flowerboard the first completely biodegradable organic particle board suitable for prolonged exterior use. Furthermore, the flowerboard proved to be processable and could be drilled, sawed and laser-cut in any desired shape. To test the feasibility of using the flowerboard as exterior construction material, a completely bio-based and bio-inspired bee hotel prototype was designed from flowerboard. The bee-hotel was commercially feasible to produce, had an attractive look and was designed to function. The prototype will be produced and tested outside to determine its lifespan. This project shows that with the right tools and knowledge, a regenerative future is just around the corner.

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INTRODUCTION

This research project was brought by *Groot Packaging*. *Groot* is a start-up company founded by Patrick Kapteijn. The mission of *Groot* started during the pandemic, when millions of bouquets meant for export had to be thrown away, creating a massive amount of organic and plastic waste. To prevent this from happening again, *Groot* wants to help create a ***waste-free floral industry***.

As big exporter of flowers, the Netherlands produces a lot of yearly flower waste (approximately 300.000 m^3). This waste mainly consists of cut of stems and flowers that did not reach the quality standard. From this waste material *Groot* created *flower paper*[1]. This biodegradable paper is currently circularly used in the floral industry as bouquet covers (Figure 1). Groot continues to seek new ways to give value to the produced flower waste.

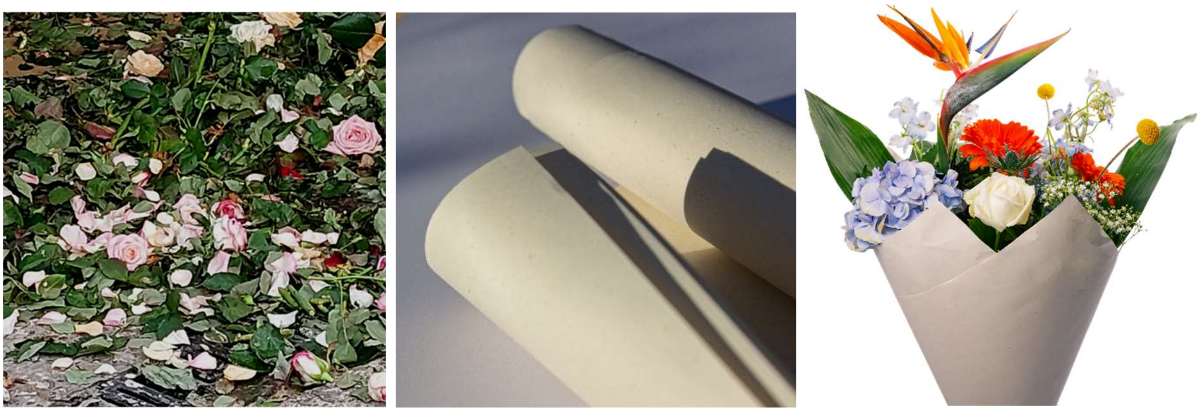

Figure 1: Flower waste used by *Groot* as circular material to create flowerpaper and bouquet covers.

The aim of this project was to create a biodegradable bee-hotel from flower waste. This concept was developed for *Groot* by Naomi Aanhane as part of her bachelor end project[2]. The combination of using the flower waste in a regenerative way to repopulate the bees in urban areas and the common association of flowers with bees, made this concept such a success with the clients of *Groot*. In this report, we realised this concept and created a new kind of material from flower waste.

The project was divided into a few distinct parts, it started with the development of a biobased, environmentally friendly and biodegradable particle board from flower waste. The board would then be used as construction material for a bee-hotel. This meant that the particle board had to be suitable for exterior use, something that was not yet achieved without the use of harmful chemicals.[3,4]

After the material development, we therefore performed some tests with the flowerboard to determine if it would potentially survive outside. Then, a bee-hotel and prototype had to be designed and developed. Meanwhile, we needed to consider a business case that would make the hotel commercially feasible to produce and sell. All these steps were performed according to the ideals of *Groot,* so without the use of plastic, toxic chemicals or green-washing of the end-product.

THEORETICAL BACKGROUND

In this chapter some essential theoretical background is provided to clarify the project. The information will provide a deeper understanding of the development of the flowerboard and explain some of the decisions and reasoning throughout this project.

1 Biobased binders

Health and sustainability have become increasingly important across the globe. Society demands more circularity, reduced plastic use and environmentally friendly production. Ever since it was discovered that certain materials inside our houses pose real health risks, new regulations to reach living standards have been set in place.[5] One of those industries that had to adapt is the massive artificial wood panel industry. For decennia formaldehyde-based adhesives and resins have been used to produce wood-based panels, but studies showed that the petrochemical is volatile and carcinogenic.[3] Together with the desire to reduce dependency on oil, there has been an increasing industrial and societal demand for new formaldehyde-free and sustainable adhesives or binders.[3]

Solutions have been found with the addition of natural components. Some of these, like soy, lignin and tannins, have the advantage that they are the by-product of other large industries and therefore entail lower costs, less volatile carcinogenic emissions and possible sustainability.[6] A full bio-based binder has the potential to be completely sustainable, healthy and eco-friendly.

Bio-based adhesives have historically been used in a variety of wood based panels but were soon outclassed in their flexibility of use, mechanical and physical properties by the petrochemically-based adhesives.[7] Currently, not a single completely bio-based adhesive has the quality, quantity, ease of use and cost-effectiveness to replace the formaldehyde-based adhesive systems. However, niche producers have developed interior grade particle-board for a slightly higher price with adapted bio-based adhesives.[8]

In this project we were trying to develop a completely bio-based exterior grade particle board made from flower-waste which was economically viable and environmentally friendly. Since the particle board industry is the biggest stimulator behind biobased binders the solution to our problem was also sought in this market. Unfortunately, not a single completely bio-based and natural adhesive that reached exterior grade particle board is currently on the market. Many popular bio-based adhesives were actually ineffective outside and were therefore rejected for use in this project (Table 1[3,9,10]).

Table 1: Some natural based adhesives on the market and the reason for their rejection in this project.

Type of bio-adhesives	Reasons for rejecting
Proteins (casein, soy)	Poor water-resistance and susceptibility to pathogens
Enzymes	low durability, incubation time, high cost, slow cure time
Modified vegetable oils	In development, susceptible to pathogens, melts in the sun
Cellulose	Poor water-resistance, too flexible
Starch	Poor water-resistance, slow drying, poor storage, poor bonding strength
Lignin	Not eco-friendly production, high costs

In the end, the most promising adhesives that were consistently mentioned in literature were the tannin-based adhesives.[3,7,11] Tannin adhesives were completely natural, environmentally friendly, did not need chemical modification and were cost-effective.[12] Together with their inherent properties of pathogen resistance[13], hydrophobicity[14] and their ease of use[15] it appeared to be the best type of adhesive to use for this project. To not completely rule out the other type of binders, we tested two different binders as well.[16,17]

2 Tannin as adhesive

Tannin is a conjunction of complex organic compounds with a phenolic structure and occurs in natural abundance.[7] They are used by plants in their vascular tissue to protect themselves against pathogens.[13] Historically, they have been used for tanning, the preservation of hides to leather, but they are also used in food, ink, beverages, medicines, pigments, water purification, plastic resins and surface coatings.[7] Tannins are therefore already available at commercial-scale. They can be categorized as hydrolysable or condensed tannins. As a wood adhesive, the condensed tannins are preferred over the hydrolysable ones. They have been primarily interesting because of their similar reactivity and cross linking chemistry with formaldehyde as current phenol-formaldehyde systems.[10] The condensed tannins, unlike the hydrolysable tannins, are also hydrophobic and have a higher polymerisation reactivity.[18]

Condensed tannins are present in decent concentrations in the bark and wood of various trees. One of the largest commercially available tannin extract is the Mimosa tannin from Acacia species in South Africa and South America. Tannin can be very easily and environmentally friendly extracted from the bark using water and heat.[7]

Mimosa tannin extract has already been successfully used in multiple wood adhesive applications[14,19] and consists of 65-80% condensed tannins (Figure 2).[7] Which is one of the highest natural occurring concentration of condensed tannins. The remaining percentage consists of non-tannin compounds that potentially weaken the wood products and may also decrease moisture-resistance.[7] However, separation of the tannins from the non-tannins requires a lot more chemicals and special equipment. For this project, pure grade tannin was not in line with the desire of environmentally friendly production and we therefore used only natural extracts.

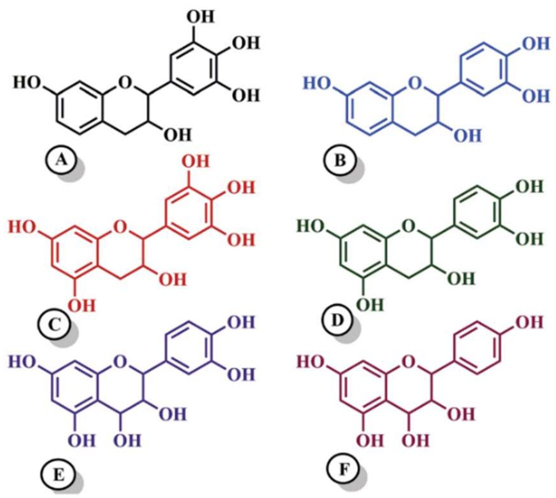

Figure 2: Chemical structure of condensed tannins (A-D) and non-tannins (E-D) occurring in mimosa extract. Figure adapted from P. V. Dhawale, *et al.* (2022)

3 Tannin adhesive in combination with flower waste

The flower waste that we use is a lignocellulosic material which means that it consists almost entirely of hemicellulose, cellulose and lignin.[20] Lignin provides strength to the plant material and can be bound to the cellulose in multiple ways to form polymer networks (Figure 3[21]). For high lignin containing plant material a binder is not even needed to reach interior grade particle boards since under certain heat and pressure the lignin is able to form new bonds between the particles.[22]

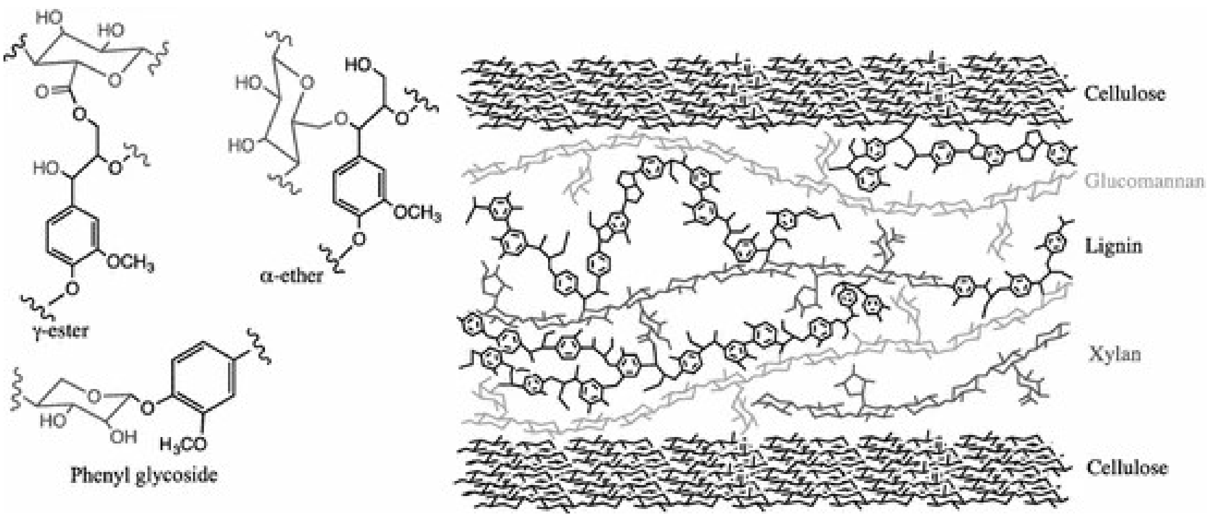

Figure 3: Lignin carbohydrate complexes. The most common covalent bonds between lignin and polysaccharides (left) and a schematically lignin polysaccharide network in wood (right). Adapted from Aminzadeh *et al.* (2017)

Our flower waste will most likely not contain enough lignin to reach the minimal strength required. We can therefore reinforce the crosslinked structure by adding the tannin adhesive. The hardening of the tannin adhesive is the result of auto-condensation that tannins undergo when catalysed by a lignocellulosic substrate (Figure 4[11]).[23] The combination of the tannin and lignin polymer networks will provide increased internal bonding strength of the material.

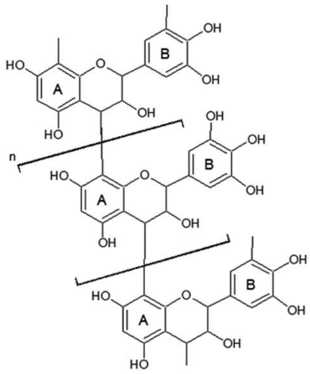

Figure 4: Auto-condensation of condensed tannins. Figure adapted from Hemmilä *et al.* (2017)

The exact amount of crosslinking and manner of polymerisation of the flower waste in combination with the tannin is unclear, since it has not been tried before. Only further research on the subject will provide this missing information.

4 Bio-based exterior protection

The expectations was that the tannin would not make the flower-board water resistant enough to reach exterior grade particle board. A few different bio-based coatings to protect exterior wood and mycelium are currently commercially available and were considered and tested in this report.

Most of them were oil based and therefore have a natural water repellence due to the hydrophobic nature of oil (Figure 5A[24]). The oil coating will be absorbed by the upper layers of the wood which will protect the wood even after erosion or tearing of the material. This is an advantage compared to more rigid coatings were tearing would create vulnerable spots in the material.

A different approach to wood protection is the Yakisugi method (Figure 5B[25]). This is a traditional Japanese method to preserve exterior wood and still meets the requirements of wood preservatives for timber in the 21st century[26]. The wood is burned on the outside and the charcoal layer protects against moisture and pathogens. An oil layer is also often applied for extra protection and reducing the deposit of soot.

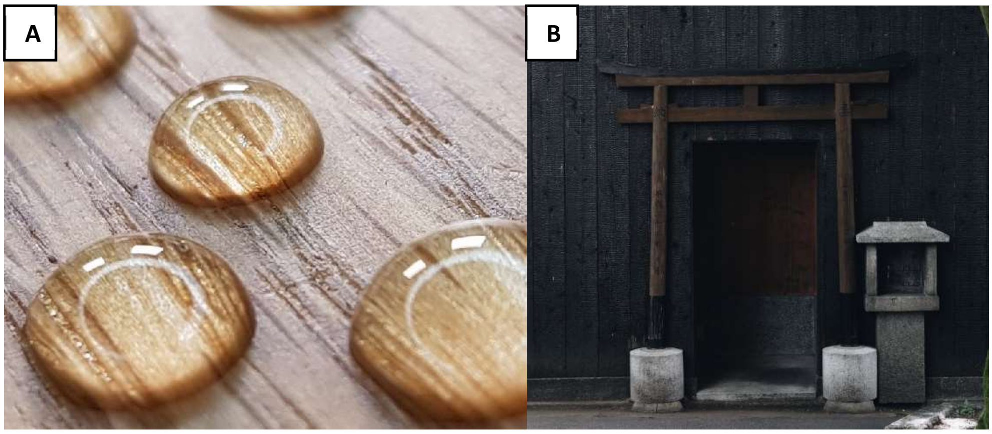

Figure 5: Biobased exterior protection methods. (A) Oil-based coatings. (B) Sugi timber.

PART A: MATERIAL DEVELOPMENT

In *Part A* we show the experimental process that lead us to the flower board prototype. The goal was to develop a bio-based material from flower waste that could function as the building material of a bee hotel. Experiments in this part were mainly judged by eye and feel, with some assistance from the bending tests in *B.2.1 Flexural strength tests*. The experiments are mainly written in chronological order and results from the first parts are incorporated in the later stages of the material development.

A.1 Material and methods

A.1.1 Materials

All materials were commercially bought and not altered in any way. The used materials were: Dried rose waste (MC ~10%, Van den Berg roses, processed to pellets by Herrejan Veenema), Sucrose (fine powder), Cutch of cachou (Verfmolen de Kat), Mimosa tannin (UCL Zuid-Afrika).

All pictures in this part were made with a Xiaomi Redmi Note 8 Pro mobile phone.

A.1.2 Methods

A 20 ton heated mould press built by studio MBB with variable upper and lower heat was used during the experiments. The press is owned by The Living Lab in Bleiswijk and was freely available for our experiments. The boards were pressed inside a mould with a dimension of 150X200x6 mm (Figure 6). Standard upper and lower heat was set to 180 degrees. The mould was always preheated for a minimum of 15 min before pressing. Standard baking paper was used inside the mould for easy and clean removal of the pressed boards.

Figure 6: Mould used for pressing experiments.

In the following section detailed explanations of the methods and raw materials that were used per board are written in conjunction with their corresponding figures in the results chapter. The grain mill used was a NOVITAL grain mill GOLIA 4V.

Particle size experiments

Figure 9A: Dried rose waste was shredded into particles with an approximate size of 2 cm. The particles had a very low density/volume ratio due to the airiness of the material which meant that the board first needed to be cold pressed in multiple steps before it fitted the mould. The steps were 50 grams, 25 grams, 25 grams, making a total of 100 grams of dried rose particles. The board was then heat pressed at 180 degrees for 5 min at 8 tonnes.

Figure 9B: A total of 200 grams of pre-processed flower waste pellets with a particle size of 4 mm were used for this board. The pellets were then pressed for 5 min at 180 degrees and 8 tonnes. The pressing step was repeated with 10 tonnes of pressure.

Figure 9C: 200 Grams of pre-processed flower waste pellets with a particle size of 4 mm were first crushed and sieved using a grain mill with a 8 mm sieve before pressing for 5 min at 180 degrees and 8 tonnes. The plate was turned around and the pressing step was repeated.

Figure 10B: 200 Grams of pre-processed flower waste pellets with a particle size of 0.5 mm were first crushed and sieved using a grain mill with a 2.5 mm sieve before pressing for 10 min at 180 degrees and 10 tonnes.

Binder experiments

Figure 11A: 200 Grams of pre-processed flower waste pellets with a particle size of 4 mm were first crushed and sieved using a grain mill with a 8 mm sieve, then 12 wt% of tap water was sprayed and hand stirred into the rose particles. The mixture was pressed for 10 min at 180 degrees and 10 tonnes.

Figure 11B: 200 Grams of pre-processed flower waste pellets with a particle size of 4 mm were first crushed and sieved using a grain mill with a 8 mm sieve. Then, 8 wt% cutch of cachou was dissolved in 12 wt% tap water and gradually stirred into the rose particles. The mixture was pressed for 10 min at 180 degrees and 10 tonnes.

Figure 11C: 200 Grams of pre-processed flower waste pellets with a particle size of 4 mm were first crushed and sieved using a grain mill with a 8 mm sieve, then 2 wt% cutch of cachou and 6 wt% sugar was dissolved in 12 wt% tap water and gradually stirred into the rose particles. The mixture was pressed for 10 min at 180 degrees and 10 tonnes.

Optimizing parameter experiments

Figure 12A: 200 Grams of pre-processed flower waste pellets with a particle size of 0.5 mm were first crushed and sieved using a grain mill with a 2.5 mm sieve. Then, 8 wt% cutch of cachou was gradually stirred into the rose particles. The mixture was pressed for 10 min at 180 degrees and 10 tonnes.

Figure 12B: 200 Grams of pre-processed flower waste pellets with a particle size of 0.5 mm were first crushed and sieved using a grain mill with a 2.5 mm sieve. Then, 8 wt% cutch of cachou was gradually stirred into the rose particles. The mixture was pressed for 2 min at 180 degrees and 15 tonnes afore the heating system was shut down. Cooling down starts fast and then slows down, after approximately 4 min the temperature reached 140 degrees and after 15 minutes the temperature was below 100 degrees. The plate was removed at 50 degrees after a total of 1.5 hours at 15 tonnes.

Aesthetics experiments

Figure 13A: 200 Grams of pre-processed flower waste pellets with a particle size of 0.5 mm were first crushed and sieved using a grain mill with a 2.5 mm sieve. Then, 8 wt% cutch of cachou and later 12 wt% water was gradually stirred into the rose particles. Shredded dried roses with a particle size of approximately 2 cm were added to the bottom of the mould. The flower waste mixture was then poured over these shredded roses and another layer of shredded roses wat put on top. The raw materials were pressed for 2 min at 180 degrees and 13 tonnes afore the heating system was shut down. The plate was removed from the mould at 60 degrees after 1.5 hours.

Figure 13B: The exact procedure as Figure 13A only with dried intact rose leaves with their stems added to the top and bottom of the mould.

Figure 14A: The exact procedure as Figure 13A only with dried intact rose leaves with their stems added to only the top of the mould.

Figure 14B: The exact procedure as Figure 13A only with partially dried intact roses and dried leaves with their stems added to only the top of the mould.

Figure 15A: 200 Grams of pre-processed flower waste pellets with a particle size of 0.5 mm were first crushed and sieved using a grain mill with a 2.5 mm sieve. Then, 8 wt% Mimosa tannin was gradually stirred into the rose particles. Dried rose leaves were used to decorate the top of the board. The raw materials were pressed for 1 min at 180 degrees and 13 tonnes afore the heating system was shut down. The plate was removed from the mould at 90 degrees after 1 hours.

Figure 15B: The exact procedure as Figure 15A only with dried rose petals as well as intact rose leaves with their stems used do decorate the top of the board.

Scaling up experiments

Figure 16: Flower board made in collaboration with Bluecity and their available Fontijne Holland LabPro heat press (Figure 7A). The board is made out of approximately 300 grams of pre-processed flower waste pellets with a particle size of 0.5 mm that were first crushed and sieved using a grain mill with a 2.5 mm sieve. A total of 8 wt% cutch of cachou was gradually stirred into the rose particles. Dried rose leaves were used to decorate the top of the board. The press did not possess a mould so a handmade 180x280x6 mm frame was made out of wood (Figure 7C). There was no baking paper present so instead aluminium foil was used. The raw material was pressed between two aluminium plates for 4 minutes at 180 degrees and 15 tonnes. Afterwards the board was placed in a cold press to cool down for 25 minutes (Figure 7B).

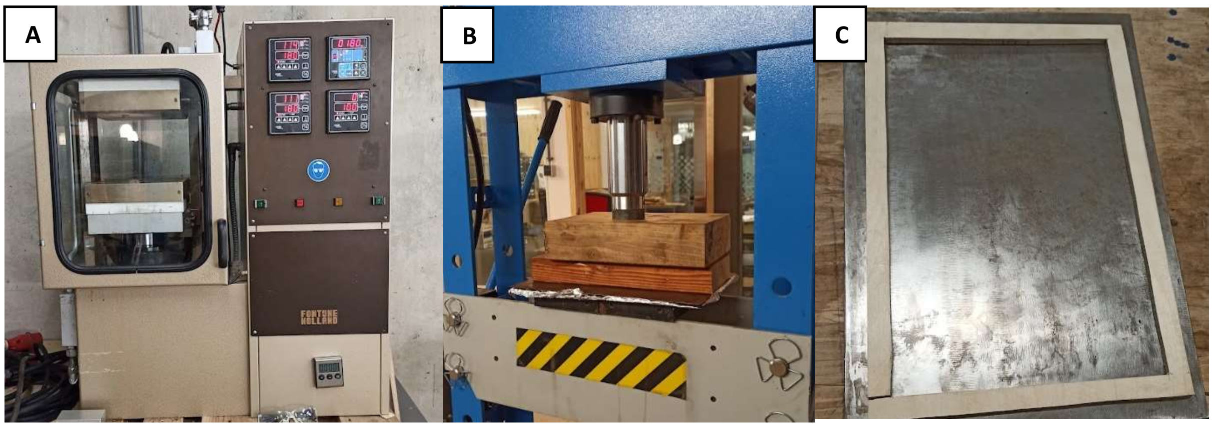

Figure 7: Equiment used in Bluecity (A) Fontijne Holland Labpro heat press. (B) Cold press. (C) Wooden frame.

Figure 17: Flower board made in collaboration with Circlefied and their available OTT Stabil 2511 veneer press (Figure 8A). The board is made out of 4500 grams of pre-processed flower waste pellets with a particle size of 0.5 mm that were first crushed and sieved using a grain mill with a 2.5 mm sieve. A total of 8 wt% cutch of cachou was gradually stirred into the rose particles. Dried rose leaves were used to decorate the top of the board. The material was distributed in a wooden frame but the frame was removed before pressing between baking paper and two aluminium plates (Figure 8B). The board was pressed for 4 min at 180 degrees and 5 kg/cm^2 before the heat was turned off and the board was cooled down under pressure. After approximately 5 hours the board was removed from the press.

Figure 8: (A) Circlefieds OTT Stabil 2511 veneer press. (B) The flower board just before pressing, the aluminium slats determined the thickness of the board.

A.2 Results and discussion

A.2.1 Particle size

In a first set of experiments the ideal particle size of the dried flower waste was determined. According to literature[22], using a small particle size (<2 mm) increases the surface of bonding, resulting in a more sturdy board after heat and pressure treatment. However, for aesthetic purposes a big particle size (>1 cm) is preferred.

Quality of the boards was determined by feel and eye. Important factors that were looked at were homogeneity of the board, smoothness and relative strength/processability. Homogeneity is important in a later stage when the board is processed to ensure every part of the board has the same material properties. Smoothness helps with water resistance, which is important for an exterior material. Water will then be less likely to collect in grooves and damage the material. The relative strength/processability of the boards was important for its final purpose as a bee hotel.

The first board (Figure 9A) was made using flower particles with a size of approximately 2 cm. The result was an aesthetically pleasing board with not much strength or processability due to its brittle nature.

The second board (Figure 9B) was pressed using pre-processed dried flower pellets with a particle size of 4 mm. However, due to not enough pressure and cohesiveness of the pellets a homogeneous board was not achieved. Repeating the pressing step yielded no better results. The large gaps and grooves made the board brittle on the edges but in the high density places the board was smooth and strong.

The third board (Figure 9C) was pressed with the same 4 mm flower pellets. In this case, the pellets were crushed and sieved beforehand. The resulting board was smooth, homogeneous and strong, if still a bit brittle on the edges. The procedure of first crushing and sieving the pellets was repeated in the following experiments to create a homogeneous board.

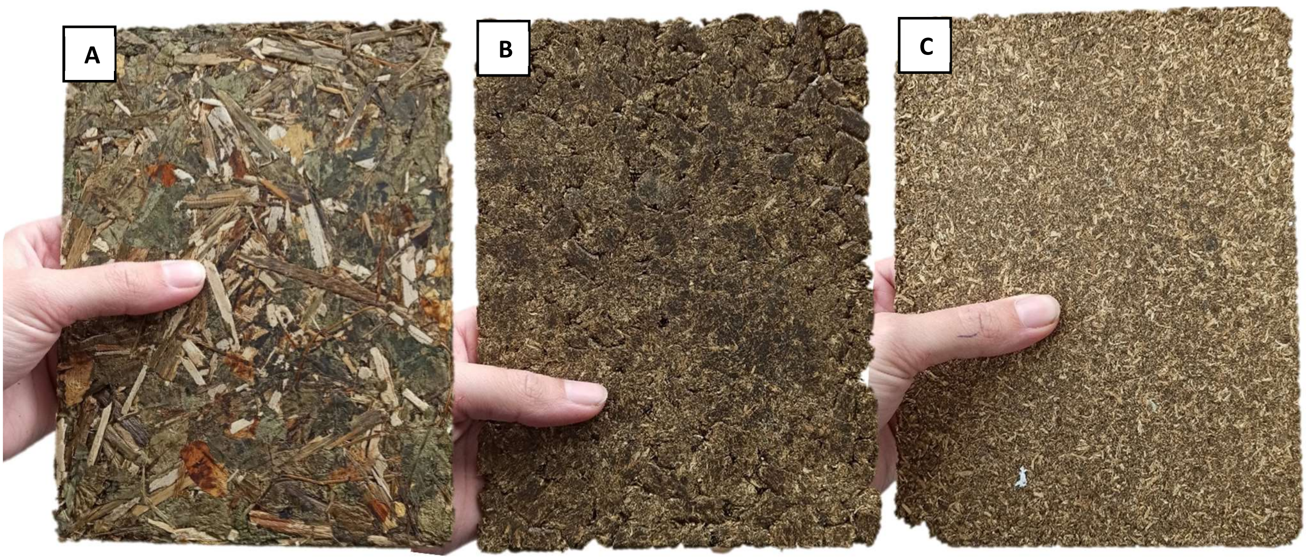

Figure 9: Board pressed from dried flowerwaste with different particle sizes. (A) 2 cm particles. (B) 4 mm pellets (C) milled 4 mm pellets

Following this trend of improved strength and smoothness with smaller particles we ultimately decided to use flower pellets with a particle size of 0.5 mm (Figure 10A). These pellets only became available after some binder experiments with the 4 mm particles were already performed (Figure 11). The smaller particles resulted in the highest quality board of them all (Figure 10B). The board felt relatively smooth, strong and homogeneous. It was also the least brittle compared to the other particle sizes. We also expected this board to be highly processable, due to the fine grain. All these qualities were important for its final purpose as a bee hotel.

Figure 10: (A) 0.5 mm rose pellets, the raw material used for the boards. (B) close up of 200 g of 0.5 mm rose particles pressed into a board.

A.2.2 Binder

A binder was needed to improve the strength of the board. We tested three different binders, as well as the moisture content, to investigate which settings had the most potential.

One of the binders was a 100% biobased epoxy resin from *Orineo* called *OriBond*. The resin would have the added benefit of instantly making the board water resistant as well as binding the particles together. However, the rain tests (B.2.2 Rain test) showed that the boards water repellence was actually not enough to keep the board intact. Put together with the relatively high costs of the *Oribond* and better alternatives, we decided not to use this binder.

The work of Zhao and Emumara[16] provided the foundation for the following experiments. Herein, particle board is bound with sugar and tannin as natural binders.

Three boards were pressed with different binders. For the first (control) board only 12 wt% water was added to the flower waste. The moisture formed into a (explosive) steam cloud when pressure was released. The result was an inhomogeneous board with some very smooth dark spots (Figure 11A). These dark spots were the water had probably congregated felt very strong and smooth. Probably due to the promoted transport and consequent binding of the lignin from the rose particles in these places. Moisture therefore seems to play a crucial role in the amount of binding of the board.

The next board was pressed with 8 wt% Cutch of Cachou dissolved in 12 wt% water (Figure 11B). The added moisture again resulted in a quick release of steam when opening the mould. The board showed the same dark inhomogeneous spots as the control. However they looked a bit more distributed over the whole surface of the board. The added tannin felt to have made the board stronger. Just like the lignin, the binding of the tannin was probably promoted with the added moisture present. The tannin seemed to work as an excellent additional binder, creating a very smooth strong board that felt to have met all the necessary requirements.

The third board was pressed with 8 wt% of sucrose and tannin in a 3:1 ratio dissolved in 12 wt% water according to Zhao and Emumara[16] (Figure 11C). However, it soon became clear that this mixture was unsuccessful (Figure 11D). Because of the high moisture content the sugar crystalized and exploded the board when pressure was released. The paper did suggest to dry the material before pressing, and this did work (data not shown) but added an unwanted extra step in the production chain, which was the reason why it was left out in the first place.

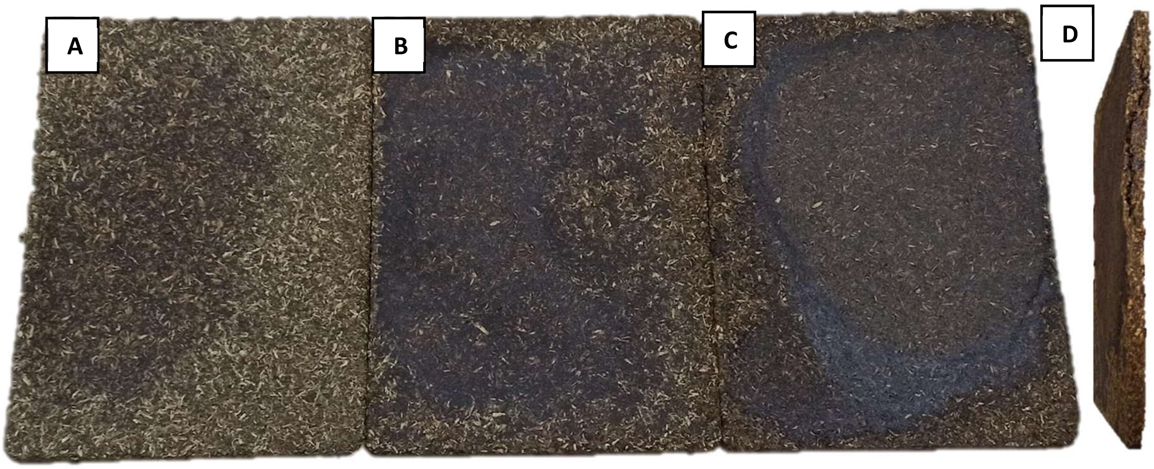

Figure 11: 200 g of 4mm flowerwaste board pressed with binder (A) Control board with only water (B) Board pressed with cutch (C) Board pressed with cutch and sugar (D) side-view of board C visualizing its rupture.

After careful consideration we decided to not use the sugar as binder. We feared that it would serve as a good substrate for fungi and microorganisms outside. Furthermore, the extra drying step was undesirable. The low costs for the sucrose did not weigh up to these problems and we therefore continued using only tannin as binder since it showed such promising results.

A reoccurring problem were the “dark moisture spots” in the boards. Decreasing or increasing the amount of moisture did not elevate these inhomogeneity (data not shown). It might have been possible to solve it with perfectly distributed pressure and a level mould but this was very counterproductive and not possible with the available equipment. It also became clear that on larger scale the steam explosions could pose a real threat to equipment and handlers, therefore most of the presses do not recommend the pressing of material with a moisture content above 10%. The only method that worked partially was to let the board cool down inside the mould (until <60 degrees). However, cooling down of the mould took around 1.5 hours and the mould would then need to be reheated for the next experiment. This enormous waste of energy and time did not sit well with us and after a few break tests (B.2.1 Flexural strength tests) it became clear that the moisture was actually unnecessary. It does seem to facilitate the binding of the materials but the moisture content of the dry rose waste together with the tannin powder is already 9.34% (measured with a Mettler Toledo HB43-S moisture analyser). The tannin, heat and pressure combined appeared to be enough to create a strong enough board. All these reasons ensured that in the final material prototype we only used dry tannin powder as binder (Figure 12).

A.2.3 Optimizing parameters

It became clear that the method of pressing was also of substantial importance for the quality of the resulting board. The optimized temperature and amount of tannin binder was determined by literature[22]. Less tannin did indeed lead to weaker boards (B.2.1 Flexural strength tests). Since the pressing was done in a mould the difference between 8 and 15 tonnes of pressing weight was actually inconsequential. Higher was not feasible with the available manual press and lower resulted in not proper closing of the mould. The density of the boards was mainly determined by feel, lower than the adhered 1.11 g/cm^3 felt significantly less sturdy and more became too heavy. The most significant factor seemed to be pressing time. Pressing too long resulted in cooked and burned fibres, weakening the material. Too short pressing did not allow enough time for the proper flow and binding of the tannin and lignin. Somewhere there has to be an optimum. However, we were able to bypass this problem when we discovered that cooling down under pressure seemed to be the perfect way to circumvent the cooking problem and allow more than enough time for the tannins and lignin to bind and settle, resulting in the strongest board yet (Figure 12B).

Figure 12: Boards pressed with only (dry) tannin as binder. (A) Short pressing time at temperature (B) Piece of a board that was cooled down under pressure after pressing on temperature

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A.2.4 Aesthetics

The boards were destined to be a commercial product, the aesthetics were therefore an important aspect of the material development. The small particles gave the board a bit of a boring bland look without hinting to the origin of the material. A few experiments were performed to improve the appeal of the boards.

In the first experiment shredded dried roses with a particle size around 2 cm were added to the top and bottom of the board before pressing (Figure 13B). The shredded roses on top made the surface of the board uneven and flaky. Another board was pressed with intact rose leaves with stems on the top and bottom of the board (Figure 13A). Adding material to the bottom of the board before pressing proved to be futile. The small rose particles engulfed the bigger material which meant that the added elements became largely invisible. Most of the colours of the added elements disappeared after pressing, probably because any lingering moisture got sucked into the board together with the pigments. In the case of the intact rose leaves, this resulted in some beautifully structured dark spots with the leaf nerves still clearly visible. The effect resembled fossilized leaves and was considered beautiful by a lot of colleagues. The leaves thus became a fixed feature of the boards.

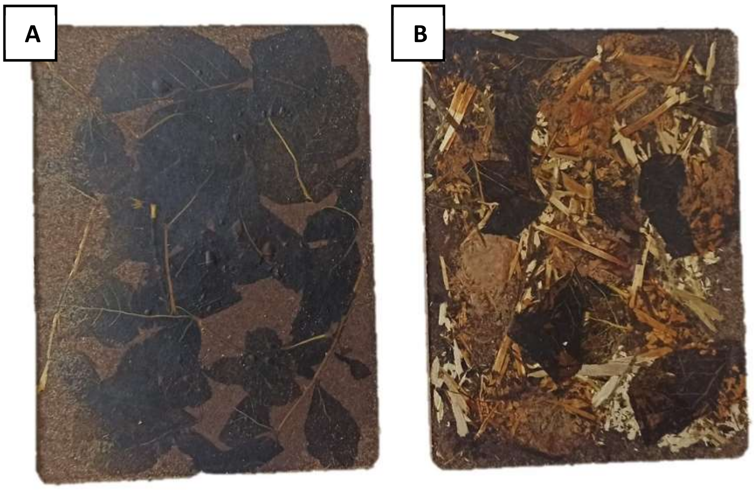

Figure 13: Decorated flower board (A) Board decorated with intact rose leaves before pressing (B) Board decorated with shredded rose waste and flower petals before pressing

In *Figure 14* the difference between before and after pressing is visualized. The decorations were in this case only put on top of the boards and more sparsely distributed to avoid overlap. This way all the individual leaves were clearly visible after pressing. Using whole roses (without pressing them beforehand) did not work (Figure 14B). The voluminous flowers created indents in the board when pressed, locally weakening the plate. After inspection it became clear that the inner petals were also not fully dried yet, the extra moisture caused 'boils' in the petals. It made the surface fragile and a bit soft, which was unacceptable.

The previous boards were at that time still pressed with extra moisture, which as explained by *Figure 12* was not the final pressing procedure. Without the moisture and a bit lower pressure the leaves did not come out as dark as in the previous boards. However, they did preserve more of their green colour, which had its own appeal. The final board prototype therefore looked like *Figure 15A*. Extra colour and dynamics could be achieved by adding flower petals to the decorations (Figure 15B). The resulting yellowish look of the petals after pressing was independent of the colour of the petals before pressing. The boards themselves also have a slightly less reddish look to them because of the use of a different type of tannin. The use of the different tannin is explained in the A.2.5 Scaling up section.

Figure 14: Flower decorations before and after pressing. (A) Intact dried rose leaves. (B) Intact dried roses and leaves.

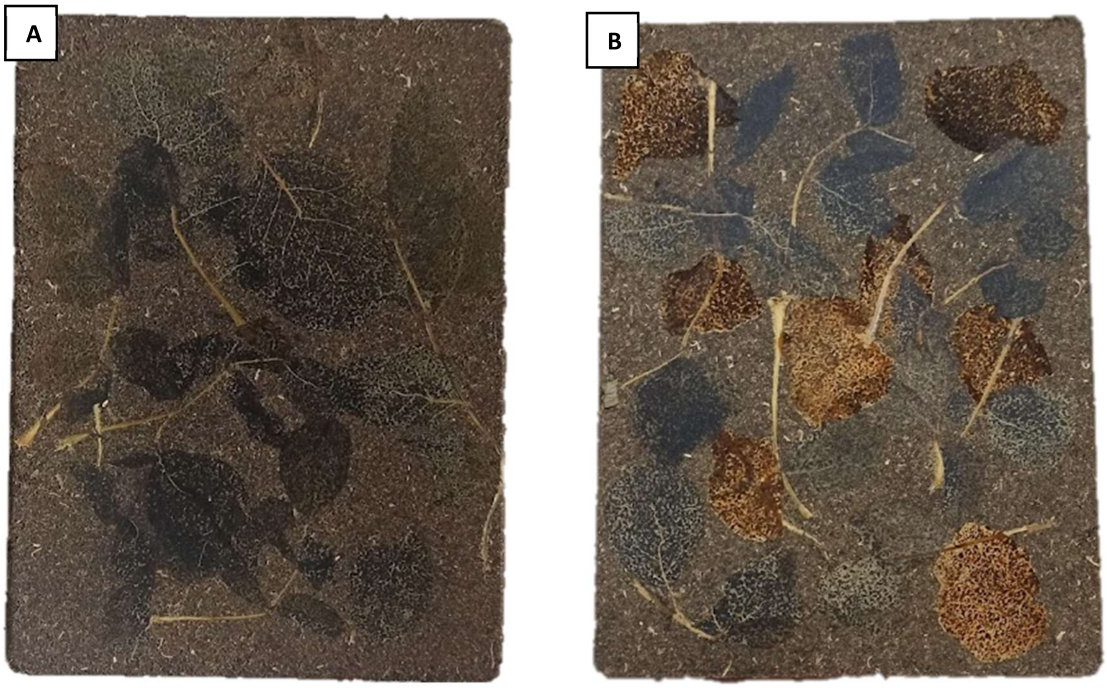

Figure 15: Final flower board prototypes. (A) Flowerwaste bound with tannin powder and decorated with rose leaves. (B) Flowerwaste bound with tannin powder and decorated with rose leaves and petals.

A.2.5 Scaling up

The next challenge was scaling up these findings to a larger, commercially useful board. The first attempt was made in collaboration with Bluecity. They did not possess a mould so a makeshift frame out of wood was created. The size of the resulting board was approximately 180x280x4 mm (Figure 16).

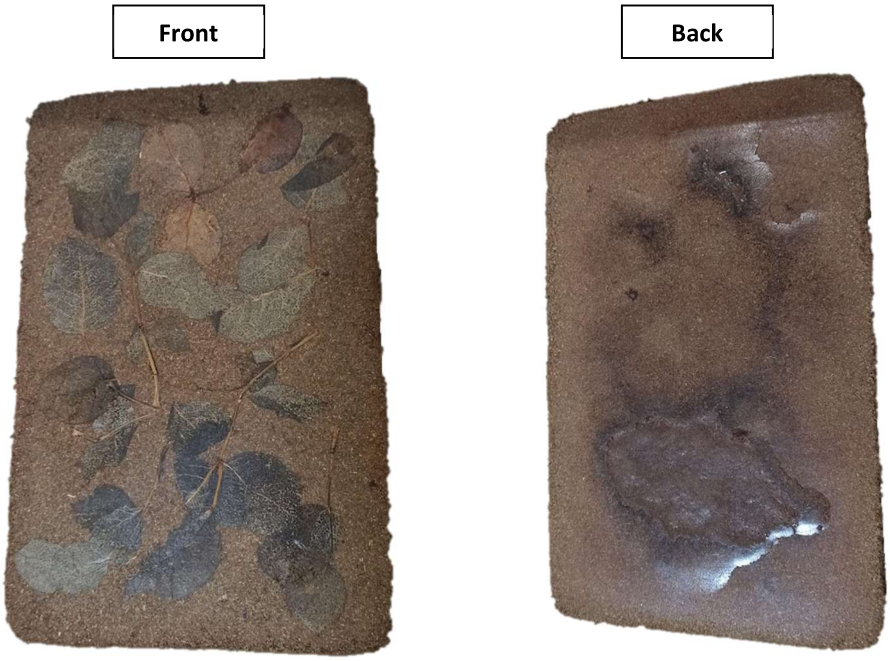

Figure 16: Flower board (180x280x4 mm) pressed without mould in collaboration with Bluecity.

Even though no moisture was added to the raw material a small steam explosion still occurred upon pressure release, resulting in some burned and damaged parts at the back of the board (Figure 16 Back). The surface of the board was also not entirely smooth and even. Probably caused by uneven distribution of the material before pressing. The back of the board was however as smooth as plastic and even though the board was relatively thin it felt quite strong. This experiment emphasized the importance of a good mould for creating a homogeneous board but it also showed that it is possible to create the flower boards without mould. With better raw material distribution and cutting off of the brittle edges the mould might not be necessary. The enabled the use of a variety of heat presses without mould.

Next, we collaborated with Circlefied. With their press we created a flower board with dimensions of approximately 650x650x6 mm (Figure 17A). The board was pressed without frame or mould which made the outer 5 cm of the edges fragile. However when these were cut off the board proved to be very strong and processable (Figure 17B). The top came out perfectly, the back showed some dark spots similar to the board from Bluecity but without the damage. These spots seemed to improve the strength of the board rather than weakening it. This board was the proof of concept that we needed and enabled us to work towards a final product.

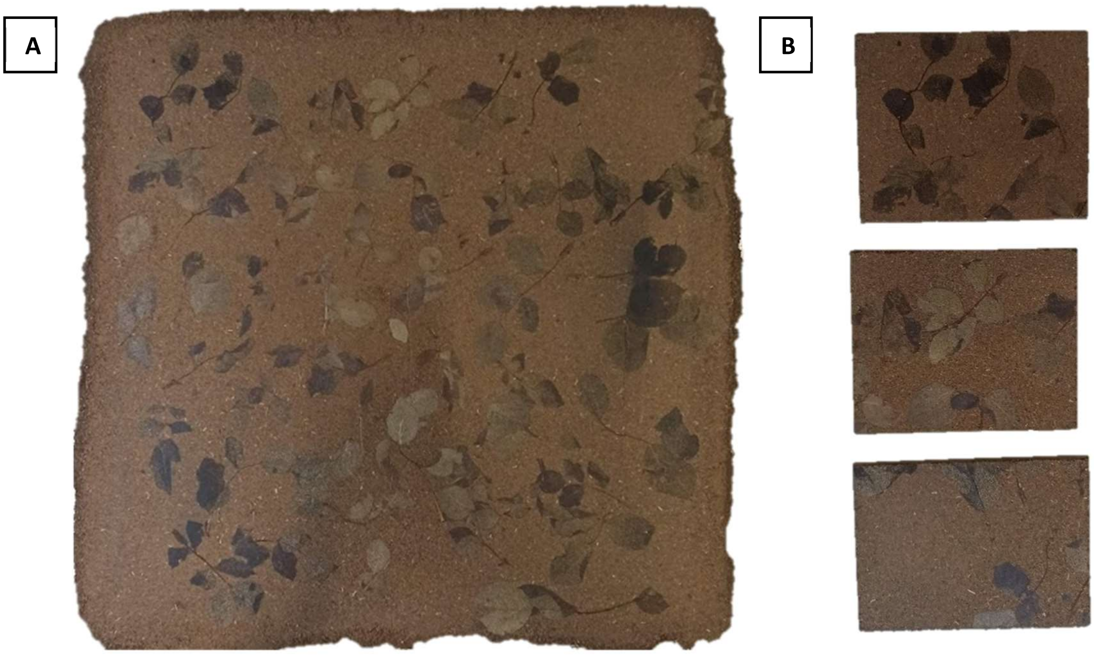

Figure 17: Flower board (650x650x6 mm) pressed in collaboration with Circlefied.

When working towards larger production it was also important to re-evaluate the supply chain. At the moment the cutch of cachou tannin was the limiting factor since it was only available in small amounts. This was not a problem previously since only small boards were pressed. For the upcoming bigger boards we ordered a slightly different tannin, Mimosa tannin from UCL Zuid-Afrika, which was only available in large quantities (20 kg), and therefore only interesting after we validated its potential as binder. This new tannin showed the same promising qualities in the board, the main difference seemed to be a slightly different colour of the final board (Figure 15). Buying the tannin in larger quantities also dramatically decreased the costs of the binder, increasing the feasibility of commercially selling the boards.

A.3 Conclusion

Based on the previous experiments, we were able to conclude that it was indeed possible to make bio-based boards out of flower waste and mimosa tannin with excellent quality.

Important was the particle size of the dried flower waste. A particle size below 0.5 mm yielded clearly better results. Mimosa tannin functioned as an excellent biobased binder of the flower particles. Mixing the flower particles with 8 wt% of dry mimosa tannin powder was sufficient to create strong and smooth boards. Pressing with sugar as binder or added moisture was unsuccessful. Dried flower leaves and petals could be added to the top of the board before pressing to create aesthetically pleasing patterns, adding commercial value to the board. Finally, the quality of the boards improved greatly when pressed shortly at high temperature and long while cooling down. This method proved to be scalable.

Due to limited time not all parameters were tested extensively, improvements could probably still be made by optimizing more parameters. However, for our purposes the quality of the board was enough to continue with the project.

PART B: MATERIAL TESTING

In *Part B* we show the experiments we performed to test a few of the material properties of the flower board. The experiments herein are only indicative and are not conclusive. The goal here was to test if the flower board could potentially survive exterior use and which coatings could increase its lifespan. Important factors that influence the lifespan of the flower board were determined to be moisture, fungi and strength. The experiments were therefore chosen to test these three factors.

B.1 Material and methods

B.1.1 Materials

Boards used

Tests were performed on a variety of boards. During material development, boards with the same pressing method but slightly different ingredients were used for the *B.2.1 Flexural strength tests.* The *Tdry* board mentioned here was the board from *Figure 12B.* The *T8%* board was similar to the board from *Figure 13A.* The *T6%* board was similar to the *T8%* board only with 6 wt% of cutch of cachou instead of 8 wt%. The *T6% low pressure* board was similar to the *T6%* board but pressed with only 2 tonnes of pressure. The *water* board was similar to the *T8% board* but without the cutch of cachou, only the moisture was added. Finally, the control consisted only of flower waste and no added water or cutch of cachou.

For the rain test and miniblocktest we used pieces of the board pressed in collaboration with Circlefied (Figure 17). All boards were cut with a Bosch PCM 8 S cut-off saw. Laser cutting was performed on the board from Circlefied as well as the boards pressed with the UCL Mimosa tannin (Figure 15).

Exterior protections used

Some of the flowerboards were coated to protect against water. The tested bio-based coatings were commercially bought and not altered in any way. The coatings used were: Fungi Force biofinish (Fungi Force), Fungi Force oilfinish (Fungi Force), Linseed oil extra (Allbäck), Verbeterde houtolie (Cokerije), Verbeterde Danish oil (Cokerije), Terpentijnolie (Cokerije) and Bioseal mycelium (Impershield.

They were applied to the flower board with soap-cleaned brushes according to the corresponding instructions. For the oil-based coatings this meant that the upper oil layer was wiped off 20 min after application so that the lower layers could dry as well. The coatings are abbreviated in the following way:

FF: Fungi force coating, the flower board was first coated with a layer of Fungi Force biofinish and after drying sealed off with a layer of Fungi Force oilfinish.

L: Linseed oil extra coating, the linseed oil was heated to 75 degrees before application of a single layer.

C1: Cokerije coating 1, a single layer of Verbeterde houtolie diluted with 30% Terpentijnolie was applied.

C2: Cokerije coating 2, a single layer of Verbeterde houtolie diluted with 30% Terpentijnolie was applied and after drying a second layer of Verbeterde Danish oil was put on top of the first layer.

I: Impershield coating, a double layer of Bioseal mycelium was applied to the flowerboard.

The Yakisugi method (abbreviated with *Y*) was also tested in different experiments. A standard crème brûlée burner was used to gently char all sides of the flower board until the whole surface was blackened.

An additional binder was also tested, a resin called OriBond (Orineo) abbreviated with *OB*. A total of 30 wt% of the resin was added to 4 mm rosewaste particles mixed with 8 wt% of mimosa ME before pressing with the same method as *Figure 12B*.

B.1.2 Methods

Flexural strength test

To measure the flexural strength (also called modulus of rupture, bend strength or transverse rupture) of the flower board a Lloyd Instruments/Ametek LS5 Single Column Bench Mounted testing machine with a 1 kN module was used.

The flower board was cut in 75x20 mm pieces and mounted on the device (Figure 18). Thickness *d* of the pieces was individually determined due to small differences with a digital calliper. The distance *L* between the two lower points of the three-point test was set to 48 mm. The force *F* was applied in 1 kN increasing steps exactly in the middle of the board until the breaking point. Maximum load at breaking point was used in the calculations to determine the flexural strength.

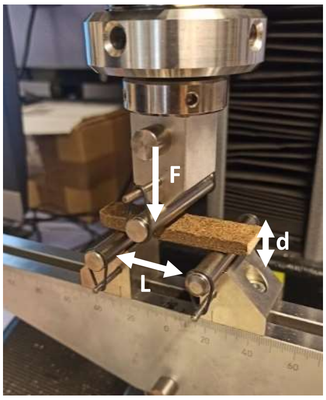

Figure 18: Material testing machine owned by Hogeschool Utrecht. Distance L was 48 mm.

Rain test

To test the effects of rain in a controlled environment a handmade rain simulator set-up was built (Figure 19). Water was pumped around the system with a standard fountain pump. 7 Holes with a 2 mm diameter were drilled 7 cm apart in the upper basin so that a constant stream of water flowed to the lower basin. Flower board pieces with a dimension of 50x20 mm with different coatings were placed under the water stream so that at least half of the pieces was exposed to the water flow. The width and weight of the pieces was measured beforehand and after 24h of constant exposure. The experiment was repeated three times per coating and each time the pieces were arranged in a different order.

Figure 19: Rain test set-up. A constant stream of water flows over 7 pieces of flower board with different coatings.

Durability test

A durability test was carried out on the flowerboard that was created in collaboration with *Circlefied* (Figure 17). This test was inspired by the EN 113 (1996)[27] test which is a standardized test to evaluate the durability of wood against wood destroying basidiomycetes.

A total of 43 flowerboard miniblocks with 10x30x6 mm dimensions were sanded down and sterilized by dry heating in an oven at 170 degrees for 30 min. After sterilization the flowerboard miniblocks were only handled in sterile environments. There were 13 blanco controls and 30 Pieces that were coated so that each coating (*FF, L, C1, C2, I* and *Y*) had 4 replicates and a control. All pieces were labelled and weighed before drying for 6 days in a 60 degrees stove. The dry weight of the pieces was measured after 5 and 6 days in the stove.

Trametes versicolor was grown for two weeks on MEA agar in a 25 degrees climate chamber. Pieces (1x1 cm) of the agar containing the grown fungi were then transferred to new MEA agar plates together with the dried flowerboard miniblocks. There were 4 flowerboard miniblocks per agar plate which contained 3 coated miniblocks and one blanco control. For each coating there was a control without fungi. There was also a plate with two blanco controls and the fungi and a plate with only one blanco control Figure 20.

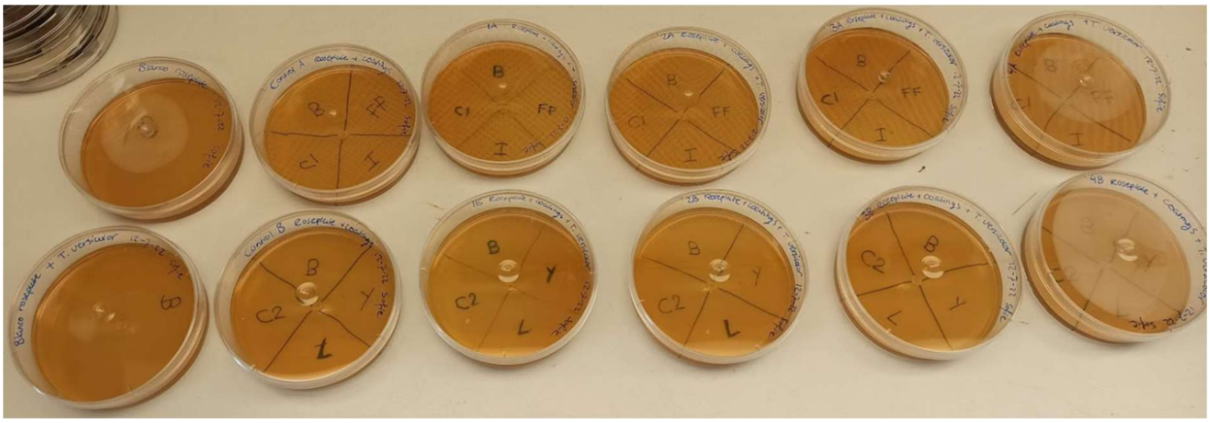

Figure 20: Labelled MEA agar plates before the durability test

T. versicolor was then grown on the flowerboard miniblocks for 8 weeks in a 25 degrees climate chamber. Afterwards, the mycelium was brushed of the flowerboard and the miniblocks were weighed. The miniblocks were then dried for 5 days in a 60 degrees stove before their dry weight was measured again.

Laser-cutting

Laser-cutting experiments were performed with a BRM lasers machine owned by the Living Lab. The board that was tested was a piece from the board that was created in collaboration with Circlefied *Figure 17A.*

B.2 Results and Discussion

B.2.1 Flexural strength tests

To assist with the material development, a few strength tests were carried out. Boards with slightly different ingredients were tested in a three-point bending test were force was applied until the board broke (Figure 21). We tested whether pressing with only water, low pressure or with tannin as binder made any significant differences in the strength.

The first thing we noticed was that the boards samples were not homogeneous in strength. The tested boards were cut up in smaller pieces to fit in the machine, which is how we discovered that specifically the edges of the boards were weaker. For future tests and applications we will therefore need to cut off at least 2 cm of the edges of the board. We also discovered that the boards that contained extra moisture had some random weak spots were the board had exploded internally, recognizable as the graphs were the load does not smoothly increase (Figure 21B-D). The explosions were located in the dark areas mentioned in the *A.2.2 Binder* section. Depending on the amount of damage internally the strength of these board pieces decreased. The method of cooling down the boards inside the mould did therefore not appear as successful in avoiding steam explosions as we first thought.

The flexural strength of each individual board-piece (given the symbol σ) could be calculated using the maximum load applied at the breaking point with the following formula:

$$\sigma = \frac{3FL}{2wd^2}$$

$$where\ \boldsymbol{F}\ is\ the\ maximum\ force\ applied\ before\ breaking\ (load),$$

$$\boldsymbol{L}\ is\ the\ length\ of\ the\ sample\ (set\ to\ 48\ mm),$$

$$\boldsymbol{w}\ is\ the\ width\ of\ the\ sample,$$

$$and\ \boldsymbol{d}\ is\ the\ depth\ of\ the\ sample.$$

The average of the flexural strength (in MPa) per board was then calculated (Figure 22). It has to be noted that the flexural strength is only an indicator of the strength and largely dependent on the particle geometry of the board[28]. More tests should be carried out to determine the real strength of the flower-board.

The averages show that pressing with only dry tannin (*Tdry*) or tannin with water (*T8%*) resulted in boards with similar flexural strength. They were also significantly stronger than the boards pressed with very low pressure (*T6% low pressure*) or the *Control*. Together with the problems caused by adding moisture before pressing we determined that only using dry tannin to bind the rose particles was the best way forward. The corresponding flexural strength of *Tdry* (7.88 MPa) was already quite close to the minimal required flexural strength of particleboard, which is 11 MPa according for the EN 312 (2010)[29] standard and 8 MPa for the JIS A 5908 (2003)[30] standard. The third piece of *Tdry* (Figure 21A) actually did reach the European standard (11.77 MPa). The experiment should be repeated with only pieces from the centre of the board to determine a more accurate flexural strength.

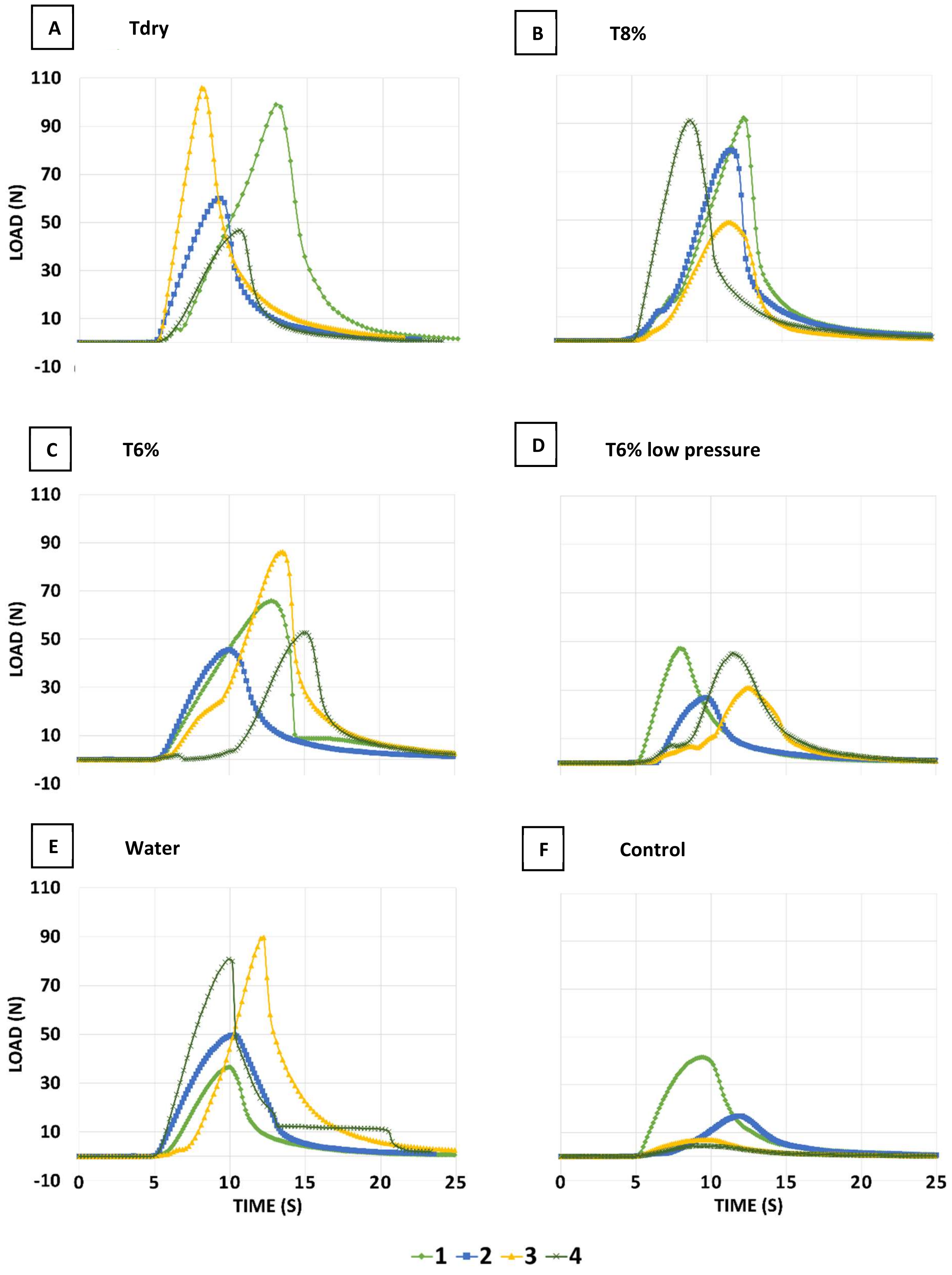

Figure 21: Three-point breaking test curves, 4 pieces per flower-board were tested. (A) Board with 8 wt% tannin added. (B) Board with 8 wt% tannin and 12 wt% moisture added. (C) Board with 6 wt% tannin and 12 wt% moisture added. (D) Board with 6 wt% and 12 wt% moisture added and pressed with only 2 tonnes of pressure. (E) Board with only 12% moisture added. (F) Control without additions.

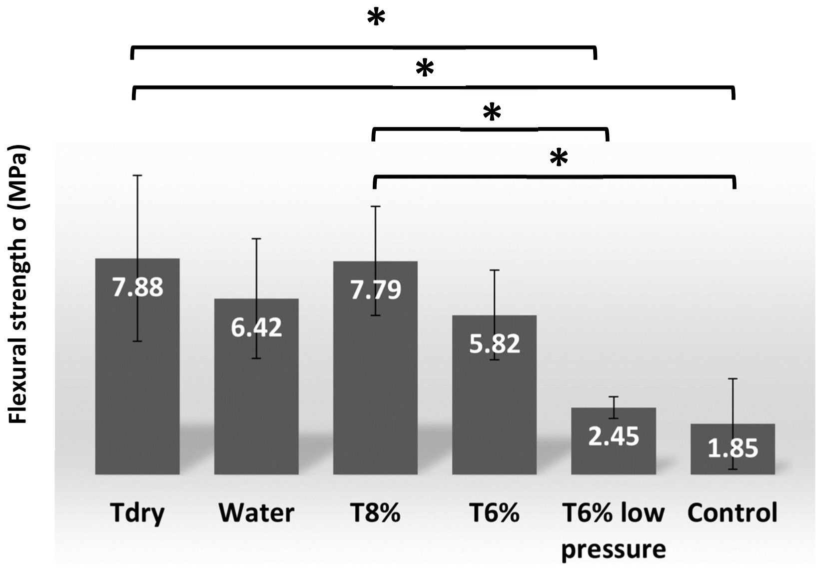

Figure 22: Average flexural strength per flower board. Error bars indicate standard deviation. (One-way ANOVA with Tukey PostHoc test: * ≤ 0.05)

However, it also has to be noted that *Tdry* was pressed with 40 kg/cm^2 which is not possible with larger presses. And since low pressure also seems to result in less strength it is not yet clear if the larger flower boards will reach the same flexural strength. Furthermore, it could also be that applied coatings influence the strength of the board.

Unfortunately, after these initial experiments the testing machine broke down and more tests could not be performed.

B.2.2 Rain test

To determine if the flowerboard could withstand rain we performed a few water resistance tests. The standard test for this is the EN 317[31], where the samples are submerged in water for 24 hours. When the swelling of the samples then stays below 5 percent the material can be considered water resistant. Unfortunately, the flower board disintegrated after 24 hours (data not shown) and can therefore not be considered water resistant. The only boards that stayed relatively intact were the boards that were pressed with extra moisture. This shows that the internal bond strength of the flower boards does seem to improve when extra moisture is present. We also tested 6 different bio-based coatings that are commonly used for wood protection outside, but the results from those were inconclusive as well. However, most of the coatings were oil based. They should be water repellent, not necessarily resistant. Repellence causes water to quickly and smoothly glide from a surface. To properly test the quality of the coatings we had to perform a different experiment.

This is why a rain-simulator set-up was built to test the coatings in a more meaningful way. The set-up meant that a constant singular stream of water flowed over the flowerboard for 24 hours. The thickness swelling per sample was measured after the 24 hours of exposure. In this way we tested 6 different coatings and one different binder for water repellence (Figure 23).

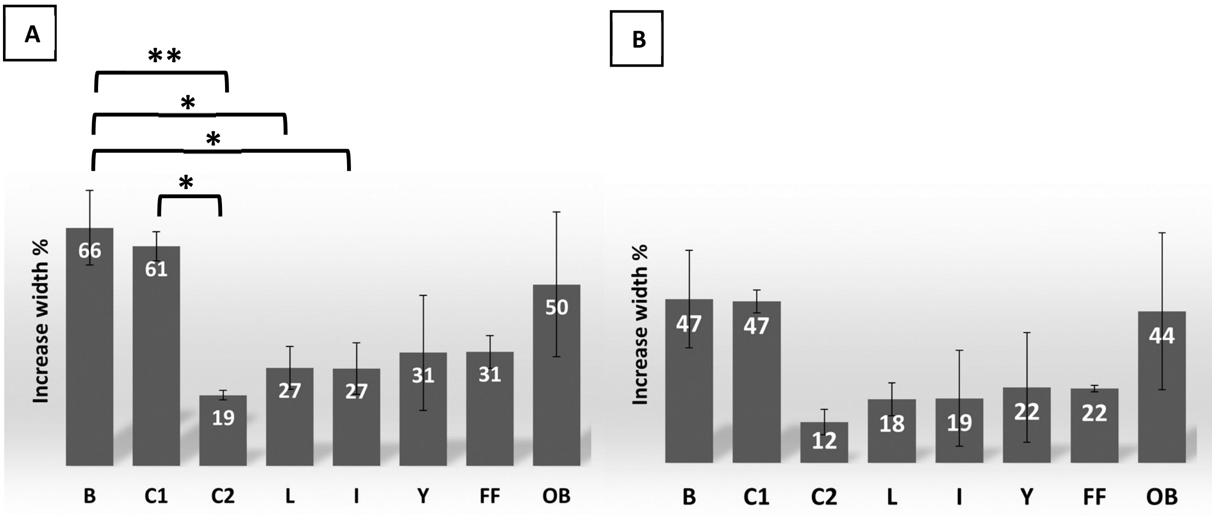

Figure 23: Percentual increase of the thickness of the flowerboard with different coatings after 24 hours of exposure to a stream of water. B is the blanco control. Error bars indicate standard deviation. (One-way ANOVA with Tukey PostHoc test: * ≤ 0.05, ** ≤ 0.01) (A) Measurements directly after the experiment. (B) Measurements after the samples were dry.

From the results we could see that the C2 coating performed consistently the best. Especially directly after the experiment, when the samples were still wet, we could see a high significant difference in thickness swelling compared to the control (<0.01).

What these results do not show is that not all samples maintained their shape and strength. This is also the reason why water absorbance could not be measured since almost all of them were very brittle and lost material over time. Only the L and C2 coated samples consistently maintained their shape and strength, as tested by breaking by hand. Their water absorbance an average was 27 ± 5 wt% and 11 ± 11 wt% respectively as measured by a not very sensitive kitchen weighing scale.

Based on these results, we determined that the C2 coating had the best potential to protect the flowerboard against the rain and weather.

B.2.3 Durability test

In this durability test the basidiomycete *T. versicolor* was grown on small pieces of flowerboard called miniblocks. *T. versicolor* is a white rot fungi that secretes several enzymes that are able to degrade lignocellulosic biomass (LB)[32]. LB is the combined term for the organic compounds hemicellulose, cellulose and lignin. Rose waste is referred to as lignocellulose waste since it consists almost entirely of LB[20], meaning that this fungus is suitable to test on our flowerboard. Only 8 wt% of the flowerboard consists of different material (tannin). The amount of mass loss after 8 weeks of incubation indicates the durability of the flowerboard against white rot fungi.

After incubation the miniblocks reached a moisture content of 30-50% which is generally ideal for the growth of *T. versicolor*[33], and were indeed fully covered by the mycelium of the fungus (Figure 24). This also means that none of the coatings of the material itself was toxic for the fungus. This is an important quality since we want the material to be biodegradable, only we desire the rate of degradation to be as low as possible. The mass loss of the treated miniblocks is visualized in *Figure 25*. The controls also lost some mass, most likely because some tannin got lost in the humid environment. Unfortunately, due to contamination not all controls could be measured (Figure 24B Control). To give an indication of the true mass loss by degradation the average weight loss of the available controls (1.9%) was subtracted from the treated samples. Normally the test should be repeated for the missing data of the controls but due to lack of time this was unmanageable.

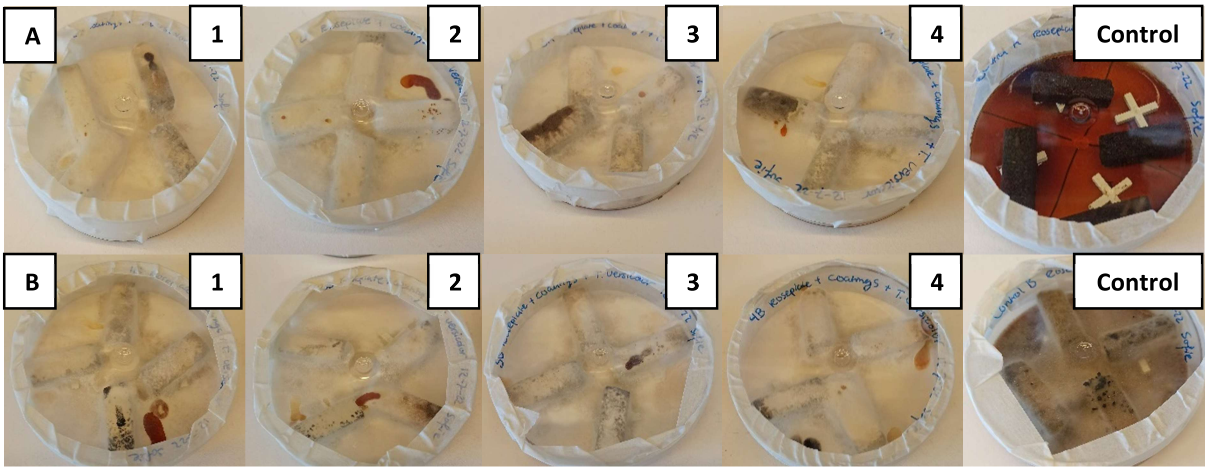

Figure 24: Growth of *T. versicolor* on flowerboard after 8 weeks of incubation. (A) Replicates of blanco and the C1, I and FF coatings and their corresponding control plate. (B) Replicates of blanco and the C2, L and Y coatings and their corresponding contaminated control plate.

There were no significant differences between the different coatings (One-way ANOVA). For all coatings and even the blanco control mass loss was below 5 percent, which indicates high durability against the white rot fungus.[34] This percentage could however be slightly higher since not all of the mycelium could be brushed off during measurements without damaging the miniblocks. Furthermore, all samples maintained their strength and shape (as tested by hand). In comparison, common wood species like pine, beech and spruce wood had a mass loss of 38%[35], 55%[34] and 32%[36] respectively after similar miniblocktests with *T. versicolor*. Since no significance was observed between the coatings, durability was most likely caused by the material itself. The high density of the flowerboard might have made it difficult for the fungi to penetrate. The tannin also has fungi repelling properties, which might have increased the durability of the material. Furthermore during pressing and sterilisation the material is heated at high temperatures, degradation of the extractive components of the material at this heat could also decrease decay[37].

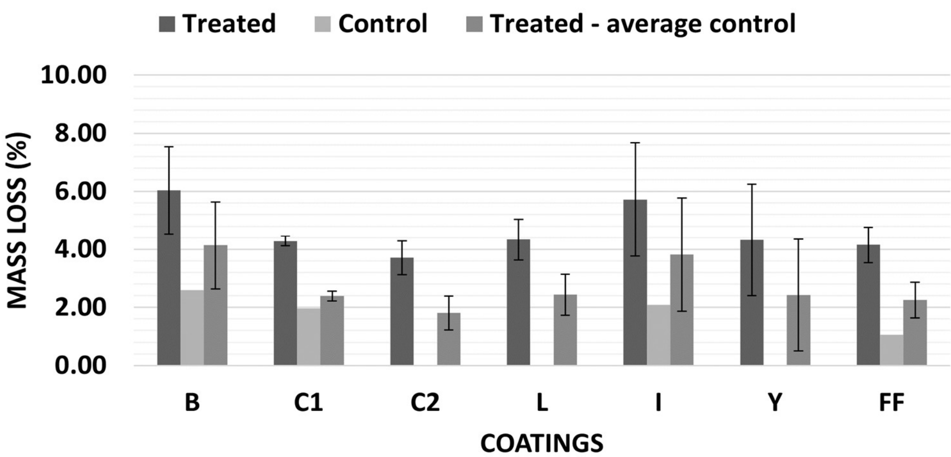

Figure 25: Mass loss of the flowerboard miniblocks after fungal incubation. Error bars indicate standard deviation.

If this were a complete test performed by the EN 113 norms it would easily qualify for an outside material above ground[3734]. However, we knew that the current experiment is incomplete. At least three basidiomycetes would have to be tested, including a brown rot fungi before the material can be officially classified.

B.2.4 Processability

It was important to know whether the flowerboard could be processed with normal equipment. A few tests were performed to find out if there were limitations to the machinery used.

We already knew that is was possible to cut the flowerboard into pieces with a cut-off saw, which is a quite aggressive machine (Figure 26A). To be thorough we also tested the drilling of differently sized holes (Figure 26B) and whether the material could be laser cut.

Drilling proved to be no problem at all. However, laser cutting required more care. A few different laser settings were tested (Figure 27). The boards were very dense and the laser could therefore not cut through the board in a single run. The best settings turned out to be a laser speed of 8 mm/s and 4 runs for a 6 mm thick board. With these settings it was possible to cut through the board. Engraving at a speed of 300 mm/s and a laserpower of 30% was also successful, the letters "TEST SCAN" were clearly visible (Figure 27B).

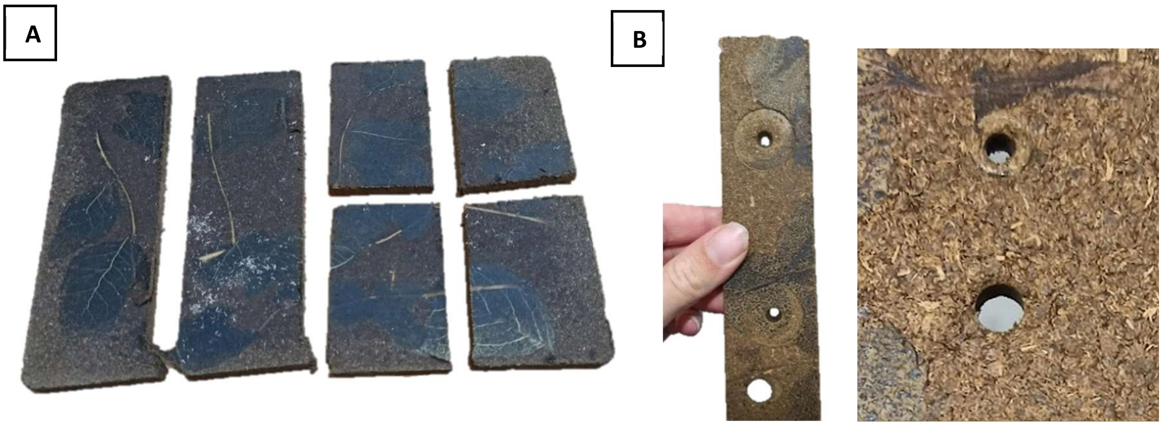

Figure 26: Processability tests of flowerboard. (A) A flowerboard cut in pieces with a cut-off saw. (B) Flowerboard with different sized holes drilled into it.

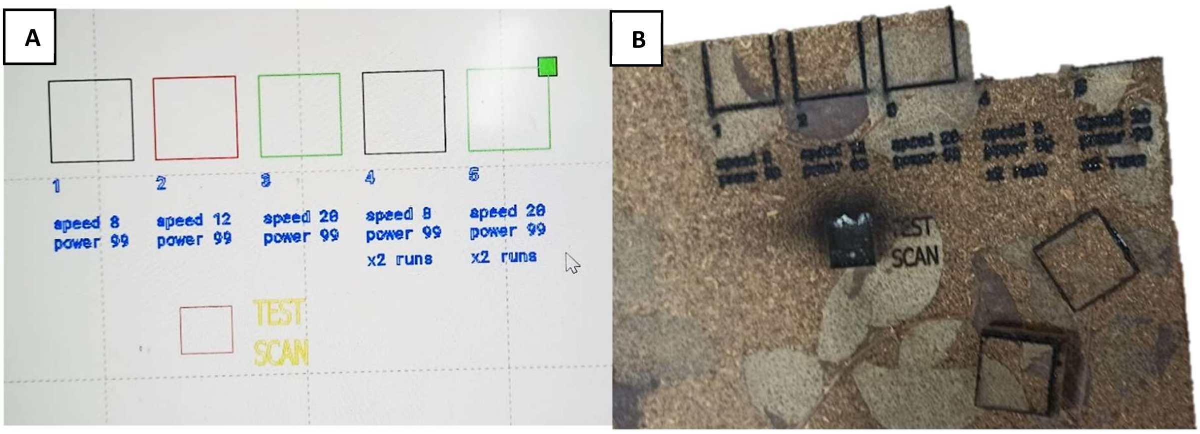

Figure 27: Laser cutting test of flowerboard (A) Program that was run. (B) Result.

B.3 Conclusion

As stated previously, the results from the experiments in this part are only indicative of the real material properties. However, the flowerboard was able to withstand all of the performed experiments. This suggests high potential for using the flowerboard as exterior material.

The flexural strength tests indicate that the material could reach strengths similar to particle board and at least strengths similar to gypsum board (2.5 MPa[38]). Since gypsum board and particle board are excellent building materials the strength of the flowerboard should be sufficient to build a bee hotel.

After the rain test we found that the material without coating is not water resistant enough to survive prolonged exposure to water. However with the *C2* coating, an oil coating form the Cokerije, water repellence was significantly increased. Excellent drainage should be integrated in the final design for this coating to work the most efficient.

From the durability test we could conclude that the flowerboard has a high but not total resistance to the white-rot fungus *T. versicolor.* This indicates that the flowerboard is biodegradable, but also durable. The exact combination we want for our biobased material. Even without coating the flowerboard performs significantly better compared to common wood species like pine and spruce, that are often used to build bee hotel from.

Finally, the processability tests showed that the material is easily handled and can be sawed, drilled or even laser-cut in any desirable form or shape. The flowerboard proves to be a very versatile material.

PART C: DESIGN AND PROTOTYPE

In this part the process that lead to the design an prototype of the bee hotel is laid out. Flowerboard as described in Part A is herein considered to be suitable as building material. Knowledge of the material properties obtained in Part B is incorporated in the design.

C.1 Design Brief

“Create a biobased bee hotel that integrates flower waste as a cyclic material flow”

C.1.1 Relevant background

The Netherlands is one of the biggest exporters of the flower industry, annually creating approximately 300.000 m^2 of flower waste. This waste mainly includes cut off stems and flowers that did not meet the quality standard. *Arena flowers,* in collaboration with *Groot packaging,* wants to make the flower industry more circular. This started by giving more value to this waste stream by integrating it in more valuable products. Eventually, the aim is to make the whole flower industry plastic-free and circular.

C.1.2 Vision of the client

For a new project the client asked to develop a bee hotel from the flower waste that is biobased, circular, and commercially attractive. The relation between the flowers and the bees is a known concept and fitting in this context. The story behind the bee hotel is therefore as important, if not more, as the final design. The bee hotel will function as inspiration and example for how to up-cycle your own waste streams in a regenerative and environmentally friendly way. Green-washing of the bee hotel will not tolerated. All of the requirements and wishes for this project are stated in *Table 2*.

Table 2: An overview of the general requirements as stated by both Arena flowers and Groot packaging for the design of a bee hotel from flower waste. Also including the specific requirements and personal wishes for the final design.

General requirements	Specific requirements	Wishes
The bee hotel is biobased	All materials used in the hotel are 100% biobased.	Material used should also be eco-friendly and ethically sourced.
The bee hotel is biodegradable	All materials used in the hotel are 100% biodegradable.	The hotel is regenerative.
Flower waste should be used	At least 50% of the bee hotel should consist of flower waste.	The flower waste that is used should be visible in the design.
No greenwashing is tolerated	Consumers should be openly and honestly informed about the real eco-costs of the bee hotel.	Greenwashing is not needed since the production is carbon neutral or negative.
The bee hotel needs to sell well	- The price should not exceed 50 euro's per bee hotel - The design needs to be attractive	- The design should appear luxurious and well thought off to cover any high production costs. - The story of the hotel should be inspirational. (visible rose waste) - The bee hotel can be ordered in flat package and self-assembled to reduce production costs and allow for easy ordering by customers.
The bee hotel needs to be of good quality	- The lifespan of the bee hotel should be at least a year - Bees should want to nest inside the bee hotel	- The lifespan of the hotel is at least 5 years. - Multiple species are willing to nest inside the bee hotel to increase its functionality.

C.2 Problem analysis

The largest concern for the production of the bee hotel is the uncertainty of the flowerboards lifespan outside. No tests within a few months could determine this for sure. We will therefore have to design for success, a prototype that has the most potential to survive for a longer period. To protect against the weather and pathogens the design will therefore need to include:

- Excellent drainage, water from rain needs to flow away immediately and not be able to collect somewhere for a longer time period.
- A strong structure with a minimal amount of weak spots.
- A hanging design above ground, to minimize contact with fungi in the soil.

The second concern is that of the bees. Since no experiments with living bees were performed we are not sure yet if the smell or other aspects of the flowerboard deters the nesting of the bees inside the hotel. We did talk with insect-expert Linde Slikboer and she did not foresee any problems. She did however provide us with a few tips how to make the hotel attractive for bees, such as:

- The hotel needs to be placed above ground to prevent fungi from entering the nest.
- A hanging place in urban areas since there are enough nesting places in nature.
- Food sources (flowers) need to be close by.
- Smooth nesting tubes with an inner diameter ranging between 2 to 12 mm.
- The possibility of at least 10 cm long nesting tubes.
- Dry and wind protected nesting tubes.
- The nesting tubes should be able to face the sun.

Since one of the requirements is to make the hotel completely biobased this also means no use of screws, nails or chemical glue. All biobased glue is generally very unresistant against either water, fungi or algae and is therefore not a real viable option. The design will need to be smart to hold itself together.

Finally, if we want to use the equipment at our disposal to save costs, mainly the laser cutter, only 90 degree angles can be achieved. Especially since the material does not bend. This limits the amount of shapes of the hotel. Eventually, in a later stage of the development, different equipment could be used to make more dynamic shapes.

C.3 Biological models

To develop a biobased and nature inclusive design it always pays off to seek inspiration in nature. For instance, how does nature protect against water and the weather? Or against pathogens? During material development we already used a common strategy for waterproofing our material. The strategies and biological models that have been useful in the design process are listed below.

C.3.1 Waterproof

The bee hotel is made waterproof with a biobased coating on oil basis. Lipids are employed as an almost universally strategy in nature for waterproofing. Terrestrial organisms like plants, arthropods, amphibians, reptiles, birds and mammals protect their skin or body surface against water penetration using lipids (Figure 28[39–42]).[43] In some cases, such as the preen waxes in birds, the layer does not only protect against water but also against fungi and microbes.[43] On a more fundamental level, the membrane of cells consists of a lipid bilayer to separate liquids. Finally to stay in theme of the report, even bees make use of waxes to waterproof their nests.

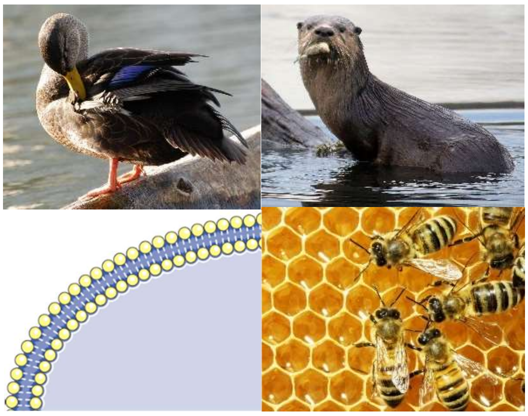

Figure 28: The use of lipids as a biological strategy to become waterproof.

C.3.2 Protection against the weather

Not only oils and lipids are used in nature to protect against water or the weather. It is often the combination with structure what makes the formula so successful. A most common example of this is the structure of fur and coats. Often a top coat with long and bigger hairs protects the more sensitive and insulating undercoat of mammals (Figure 29[44]). Such layering could directly be applied to the structure of our bee hotel design, where larger overarching parts protect more sensitive parts.

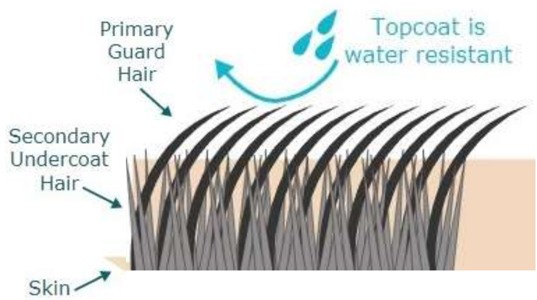

Figure 29: Structure of a topcoat and undercoat to protect the animal against water.

C.3.3 Tree bark and tannin

Similar to the bark of a tree, we will protect the nesting tubes of the bee house with a protective layer made out of flowerboard. Comparing the flowerboard to bark is actually very astute since we directly use tannin from mimosa bark extract in the production process of flowerboard (Figure 30[45]). Tannins are the answer provided by plants to protect their unmoving bodies against pathogens like fungi, bacteria and viruses. And even after the tannins are extracted from the wood or bark of the tree their characteristics remain unchanged.[13] They are so powerful that they even protect aquatic plants like mangroves.

Figure 30: Mimosa bark. Picture from our tannin supplier.

C.3.4 Solitary bee nesting places

Our bee hotel will be based on the natural nesting places of the solitary bees. Solitary bees are very resourceful and find nesting places in all kinds of places (Figure 31[46]). They nest in holes and grooves that occur naturally in wood. However since humans were added to their habitat they also nest, sometimes unwanted, in all kinds of nooks and crannies in our homes. They appear not to be very specific of the material of their nesting places as long as it meets the rest of their requirements. We can use that to our advantage and use a convenient material, like bamboo, that has natural cavities as nesting tubes.

Figure 31: Nesting of solitary bees.

C.3.5 Weaver nests

Humans are not the only ones that are capable of building intricate structures. A prime example is the nest of a weaver bird. To build the nest the bird uses all kinds of different plant fibres. twigs and even string and twine. Strands are knotted to a branch with beak and claw (Figure 32[47]) and threaded through others at opposing angles. The woven nests are strong and beautiful. Natural fibres could help reinforce the structure of the bee hotel.

Figure 32: Weaver bird starting a nest.

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C.4 Idea sketches

C.4.1 Joint connection studies

In *Figure 33* a few sketches of different joint connections that were studied are visualized.

Since the bee hotel has the be 100% biobased, the use of screws, nails or glue for the flowerboard connections is not an option. Different wood joint connections exist, such as the dovetail, mortise and tenon or the half cross lap joint. Especially the Japanese have invented very intricate joints were structure and small wood pieces ensure very stable connections. Since we have to work with a material that is at most 10 mm thick and not as strong as normal wood, it is most likely not possible to work with such delicate joints. Furthermore, to create structures like dovetails, special machinery is needed.

Sliding of two panels together such as depicted in the left bottom of *Figure 33* creates a vulnerable piece that might be easily broken. If such a joint is used at the top of the structure you also make gaps in the nook were rain could enter the structure. Bamboo could be used to protect and enforce these vulnerable places.

In the end, hidden finger joints (top right) in the roof and normal finger joints at the bottom seemed to be the most promising type of joint. This joint can be easily made with a laser cutter and does not create certain vulnerable places in the hotel. However, when the fingers do not fit perfectly the joint is is not very strong. Since our material will most likely change in thickness and slightly in shape when exposed outside, this means that the joints have to be reinforced in a certain way.

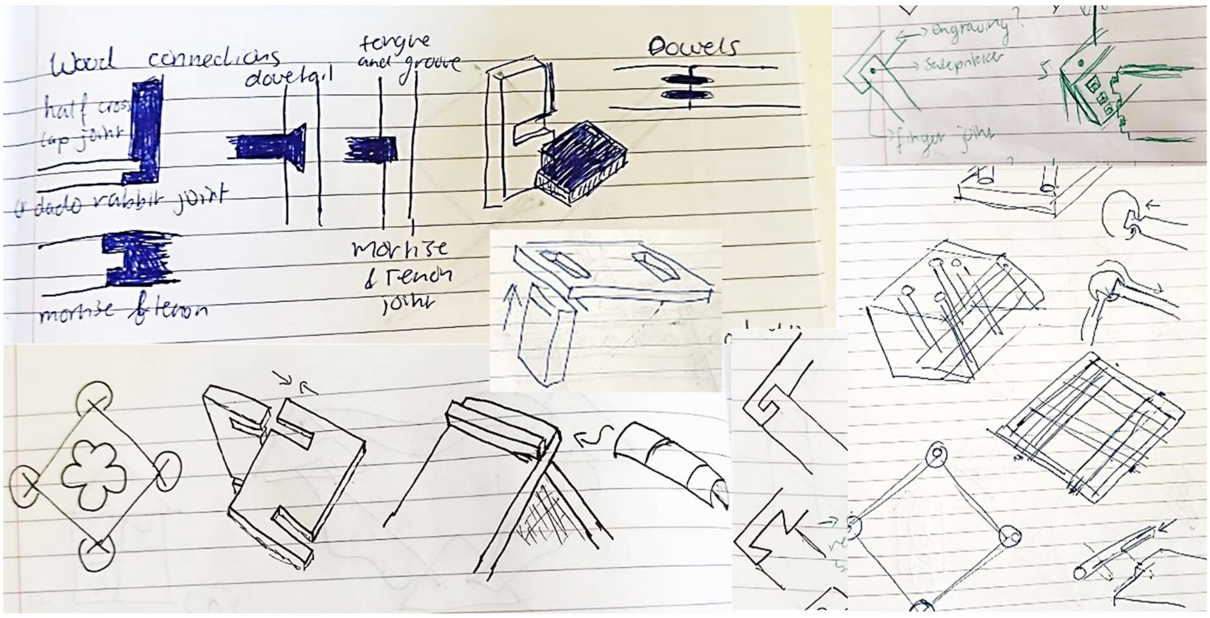

Figure 33: Joint connection study without using screws, nails or glue.

C.4.2 Shape studies

The shape of the bee hotel was also studied (Figure 34).

Different common shapes on the market were considered and discarded. Many used complex angles or would create gaps and holes if no screws or glue would be used to connect the joints. Besides shape, it was also important that the flowerboard material was emphasized and not just an add-on. The most feasible option was to make a square-shaped bee hotel. Joints would then be connected in a 90 degree angle, water would slide immediately of the surface and the flowerboard would have a prominent role as structural material.

A few alterations could be made to the square-shape by creating an overarching roof. With a laser cutter it is also possible to create more intricate patterns. We preferred to use clean and minimalistic lines since it fit more in the rhetoric of a functional design.

Bamboo and natural rope could be used to reinforce the structure. Bamboo has excellent durability and if the diameter is large enough it might be useful to protect vulnerable places of the hotel, like the nook. By using rope to attach the bottom of the hotel to the roof, tension on the rope caused by gravity will then also further strengthen the structure of the hotel.

In the final design phase it was briefly considered to use proportions from the Fibonacci sequence or golden ratio. However, this would result in the addition of large pieces of flowerboard, which felt unnecessary.

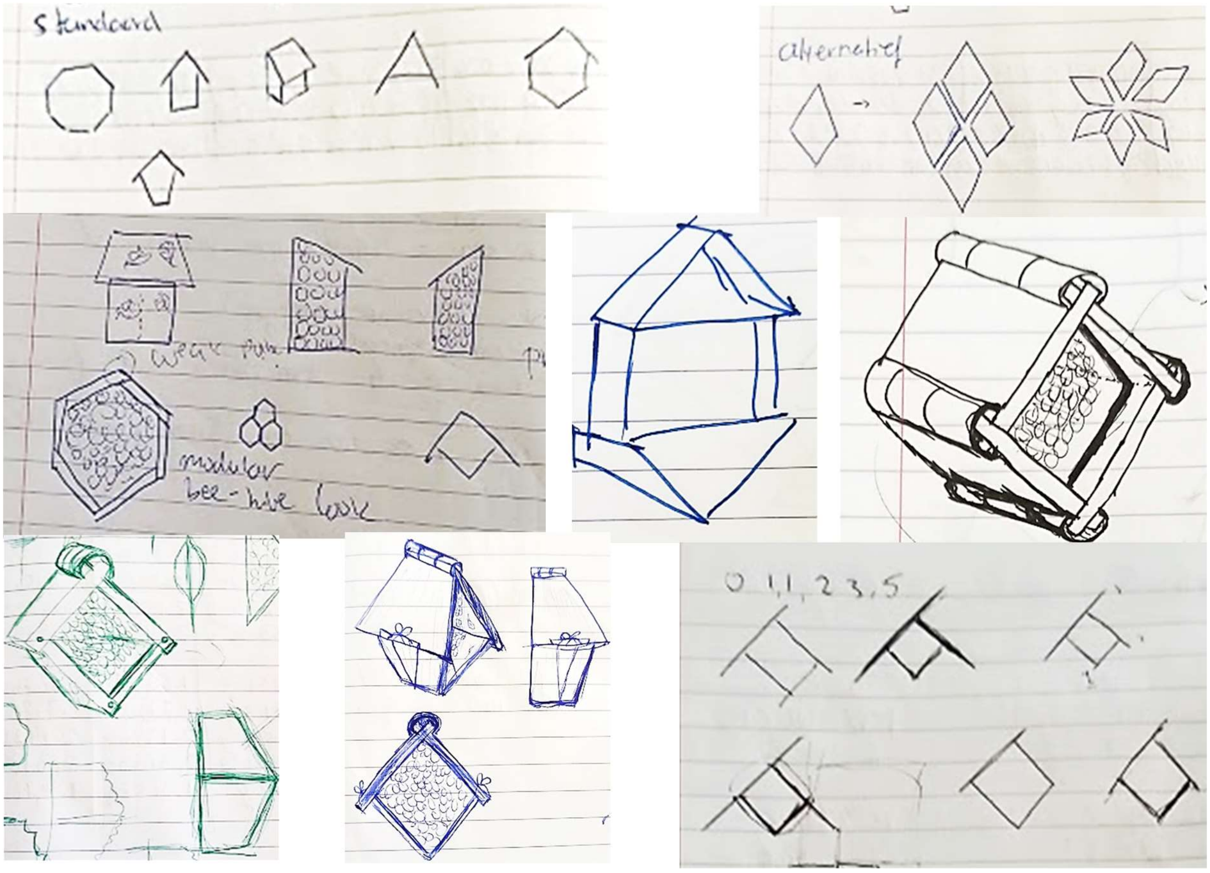

Figure 34: Different shapes that were considered for the bee hotel.

C.5 Final Design and prototype

The final design is connected by (hidden) finger joints and reinforced with natural rope (Figure 35). The material thickness of the flowerboard will be 10 mm, which is slightly thicker than the previously adhered 6 mm. This gives the hotel a more sturdy look and improves the quality of the finger joints. The roof is overarching and asymmetric, protecting the joint on top and the inside from wind and rain. Connections are in a 90 degree angle for easy manufacturing with a laser cutter. Only the hidden finger joints in the roof will have to be made using another machine like a milling cutter. Bamboo nesting tubes can be laid inside (Figure 36). The design is easy to assemble and could be send in a flat package.

Figure 35: Final prototype design (A) Prototype out of MDF. (B) Laser cutting file. (C) Coated flowerboard which will be the building material.

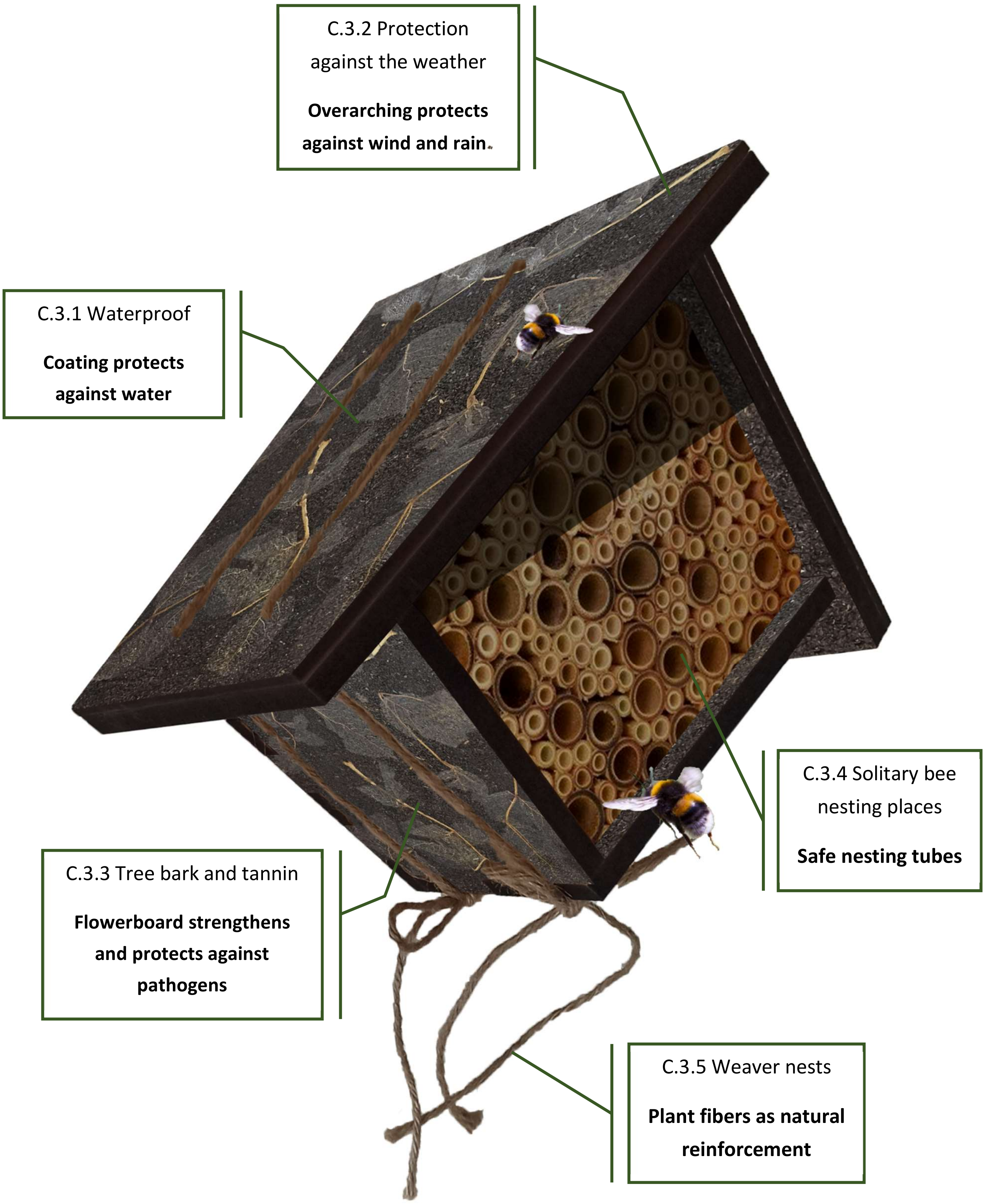

Figure 36: Render of the final prototype, corresponding biological models are explained.

C.6 Design evaluation

In *Table 3* the design is evaluated against the initial requirements. Scores are assigned per requirement (1-5) were 1 means that the design fails to meet the requirement and 5 means a perfect fulfilment of the requirement. Reasonings behind the scores are given in the last column.

Table 3: Design evaluation according to the requirements of the client.

General requirements	Specific requirements	Score (1-5)	Wishes	Score (1-5)	Reasoning
The bee hotel is biobased	All materials used in the hotel are 100% biodegradable.	**5**	Material used should also be eco-friendly and ethically sourced.	**4**	The bamboo, tannin and rope are shipped from a long distance.
The bee hotel is bio-degradable	All materials used in the hotel are 100% biodegradable.	**5**	The hotel is regenerative.	**5**	Will provide nutrients for other organisms and help bees.
Flower waste should be used	At least 50% of the bee hotel should consist of flower waste.	**5**	The flower waste that is used should be visible in the design.	**5**	Only the rope and nesting tubes will not be made from flower waste.
No greenwashing is tolerated	Consumers should be openly and honestly informed about the real eco-costs of the bee hotel.	**5**	Greenwashing is not needed since the production is carbon neutral or negative.	**2**	Production at the moment is quite insufficient and has to be improved before we can reach carbon neutral.
The bee hotel needs to sell well	- The price should not exceed 50 euro's per bee hotel - The design needs to be attractive	**3**	- The design should appear luxurious and well thought off to cover any high production costs. - The story of the hotel should be inspirational (visible rose waste). - The bee hotel can be ordered in flat package and self-assembled to reduce production costs and allow for easy ordering by customers.	**4**	The design is not very innovative and might be more a combination of luxurious and cute. The price is still a bit high for its function.
The bee hotel needs to be of good quality	- The lifespan of the bee hotel should be at least a year - Bees should want to nest inside the bee hotel	**-**	- The lifespan of the hotel is at least 5 years. - Multiple species are willing to nest inside the bee hotel to increase its functionality.	**-**	These requirements are not yet tested, however the expectation is that the hotel will at least meet the specific requirements.

PART D: BUSINESS CASE AND PRODUCT DEVELOPMENT

In this part it is briefly explained what steps were taken to produce the bee hotel and the approximate costs of production. Since the production chain is currently still incomplete the official final cost could not yet be calculated. The expectation is that efficiency and cost of production will significantly improve when the number of bee hotels increases.

D.1 Production chain

In *Figure 37* the production chain is visualized. The raw materials are collected, processed and mixed before delivery to *Circlefied*. There, the flowerboard will be manufactured in square meter dimensions. The flowerboard will be almost entirely processed by the laser cutting machine in the Living lab from *SIGN*, the hidden finger joints in the roof of the bee hotel will need to be cut by a different machine from *Schultenprint*. The pieces have to be coated with oil from de Cokerije and assembled in a package together with the rope and bamboo nesting tubes by *Groot*.

The vital companies of this chain are *Berg Roses, Waardewenders, Circlefied, SIGN and Groot*. *Groot* and *Berg Roses* have an agreement so that rose waste is available for use for *Groot*. *Groot* also has an agreement with *SIGN* over the use of the laser cutter and other machinery in the living lab. *Waardewenders* is specialized in the drying and processing of the rose waste and is vital to obtain the necessary raw material. *Circlefied* is specialized in pressing with many different materials and has a single large press so that reasonable quantities of flowerboard can be manufactured. We do not have the desire the produce more than a few square meters which is not an option with larger particle board manufacturers.

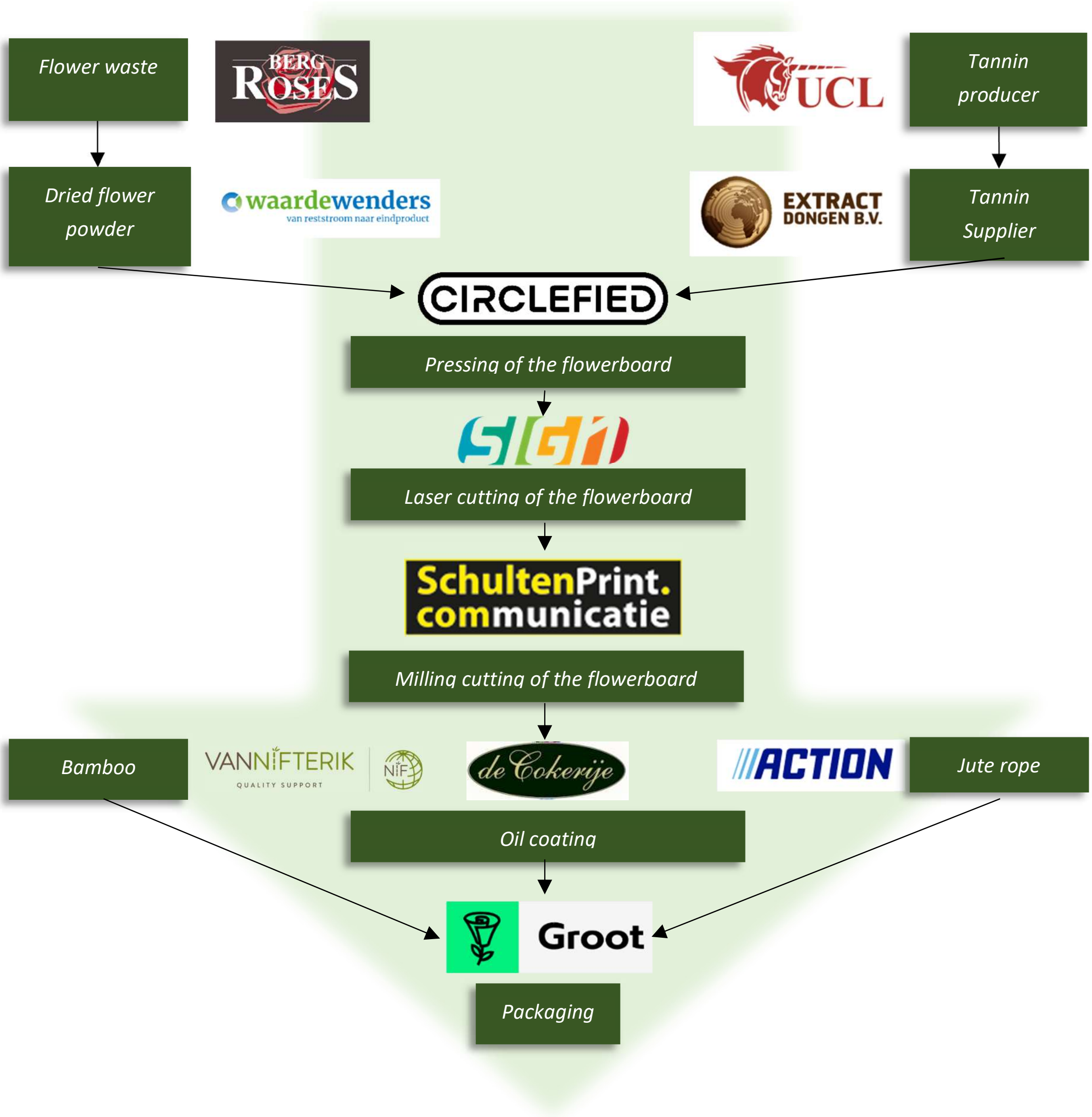

Figure 37: Visualization of the production chain and corresponding companies of the bee hotel.

D.2 Business case

An approximation of the production costs per bee hotel is made in *Table 4.* Some costs are still uncertain, like the production of the flowerboards and milling costs. This is because the companies could not yet predict the amount of time necessary for manufacturing since it is a new material. The total costs could therefore still slightly increase or decrease.

Table 4: Production costs per bee hotel

Matter	Costs per hotel
Drying and grinding flower waste	€ 9,70
Mimosa tannin (binder)	€ 0,50
Flowerboard production cost	€ 11,20
Milling	€ 3,00
Coating	€ 2,00
Packaging costs	€ 2,00
Other material costs (bamboo, rope)	€ 1,50
Total:	**€ 29,90**

In order to profit from the bee hotel it will therefore need to be sold for at least 35 euros per bee hotel. When comparing to the bee hotels currently on the market this is a bit higher than the standard bee hotel from the *Intratuin* (ranging between 10 and 30 euros for a similarly sized hotel, *Figure 38A*[48]*)* but is below the price of quality bee hotels from for example *Crown Bees* (Figure 38B[49]), with a price of 67 euros. Since our product is unique, of good (initial) quality and inspirational we expect that at least a few will be sold as show pieces. Larger production will depend on the lifespan and reviews of the first few hotels.

Figure 38: Bee hotels currently on the market (A) Bee hotel from the intratuin with a price of 12.99 euros. (B) Bee house from Crown bees on the market for 67 euros.

OVERALL CONCLUSION AND OUTLOOK

In this project we discovered that it is possible to use flower waste as a circular material to make a very promising and versatile type of biobased particle board. The final flowerboard met the required strength, processability, cost effectiveness and white-rot and water resistance needed to design a feasible and commercially attractive bee-hotel. The production of the bee hotel is slightly more expensive than the standard hotel but optimization of the product and further testing might improve the final costs. Correct marketing of the hotel as the only completely biodegradable and entirely environmentally friendly hotel on the market should also cover the slightly higher price.

Because of time constraints and some unlucky required reparations of machinery the final flowerboard bee-hotel prototype still has to be produced and tested with bees. It is however clear that at least 5 to 40 hotels will be produced. A few will be showcased by *Groot* and *SIGN* and others will be tested to determine the lifespan of the hotel. Current plans for the hotel are mainly to serve as an example and to inspire the use and exploration of more bio-based and environmentally friendly products.

Since this entire project took place within 6 months there was not enough time for additional material testing and optimization of the parameters. If more interest or funding for flowerboard will be provided it would definitely be interesting to determine the properties according to the European standards and discover more uses for the flowerboard.

The methodology in this project was also tested with meadow grass which yielded promising results. In the future we might expand this project using different lignocellulosic waste materials.

To conclude, we developed a unique and versatile material that has the properties to replace artificial panels. We achieved this by using a previously unvaluable waste stream and in a completely sustainable way. The production chain has the potential to become carbon negative and does not include any toxic- or petrochemicals. Furthermore, the flowerboard is waste-free and will function in a regenerative way, stimulating the bee population and serving as nutrients at the end of its life. We hope that this board will inspire others and show that with the right knowledge and tools, a more environmentally friendly and regenerative future is just around the corner.

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Last but not least I would like to thank my fiancé Tristan van Ham for drawing the laser-cutting file and rendering the image of the final prototype.

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LAYMEN’S SUMMARY

This research project was brought by *Groot Packaging*. *Groot* wants to help create a waste-free floral industry and has developed several circular and biodegradable products from flower waste. In this project we used flower waste as a circular material to create a new type of biodegradable particle board, which we called flowerboard.

The flowerboard is made out of flower waste that was cut into small pieces, which were then bound together with a natural adhesive. This adhesive has been used in the wood panel industry as a substitute for the toxic glues that are normally used. It consists of tannins that occur in natural abundance in wood and bark and which protect the trees against bacteria, parasites, viruses and fungi. By using these tannins as adhesive, this protection is also transferred to the flowerboard.

We tested a few of the properties of the flowerboard to see if it was suitable for use as a bee hotel. As a bee hotel it would need to survive storms, fungi and rain. We therefore tested the strength, fungi- and water resistance of the flower board.

The strength of the flowerboard is similar to common wood particle board and stronger than gypsum plate. We considered this strength sufficient for building a bee hotel. The flower board was also very resistant against a common fungi, probably because of the properties of tannin and the heat pressing of the flowerboard. The flowerboard was not very resistant to water and therefore needed an additional coating. For this we used natural oils that repel water, with these oils the flowerboard was able to survive 24 hours of constant simulated rain.

Because of these promising properties we designed a bee hotel where we use flowerboard as the construction material. Since the lifespan of the flowerboard is unclear we designed the hotel to be as efficient as possible, without compromising our ideals of a fully biodegradable and functional hotel. The final design is attractive and commercially feasible to produce and sell.

In the coming months a few of the hotels will be produced and tested outside. After these tests we will evaluate if we want to produce more or if they will serve as a show-piece and inspirational product only.

If interest in the flowerboard arises we will continue to perfect and test the properties of the board. As well as find new functions and designs. We already successfully tested our method of production with other organic waste materials, which means that we might also expand this project with different waste streams.

To conclude, we were able to create a unique and versatile material that has the properties to replace harmful artificial panels. We achieved this by using a previously unvaluable waste stream and in a completely environmentally friendly and sustainable way. As an added benefit, by using the flowerboard as a bee hotel, we also help repopulation of the bees. We hope that this board will inspire others and show that with the right knowledge and tools, a more environmentally friendly and regenerative future is just around the corner.