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A Framework for Growth

Strategies for a detachable and biobased vegetative façade

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Strategies for a detachable and biobased vegetative façade

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Abstract:
The perception of living walls shows great benefits but also critical challenges. This research intends to change the latter view by highlighting quantifiable performance benefits as well as the other qualitative benefits providing evidence of its unique value and service to people and the building. The catalogue of biobased materials and processes of manufacturing as well as detachability methods go even further to reimagine the existing walls more sustainably, to eliminate waste and increase adaptability. This paper highlights the properties of selected biobased materials from a set of criteria specifically aimed at detachable living walls. It reveals coconut as the highest scoring material closely followed by hemp, then miscanthus, flax straw and timber. The most noticeable material applicability difference are bioplastics with the lowest scores, largely due to their unnatural aesthetic.

Keywords:
Adaptability, biobased materials, vegetation, living wall, prefabrication, biodiversity, building performance, detachability, future-proof architecture, lifespan (important definitions can be found in Addendum A)

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I. Introduction

Architecture is often imagined as something permanent which extends into the design, planning and construction of a building and its components (Lifschutz 2017). Most modern buildings lack adaptability even though there is so much social, economic, technical developments and environmental change happening around them. Some of these changes include trends in aesthetics, changes in property value, innovations in materials and techniques, a new use for a building and rising temperatures. These buildings have a linear life with the typical end-of-life resulting in demolition as the "prefabricated components (are) designed to be mountable, but not demountable" (Durmisevic 2006). This leads to excessive waste in the building industry.

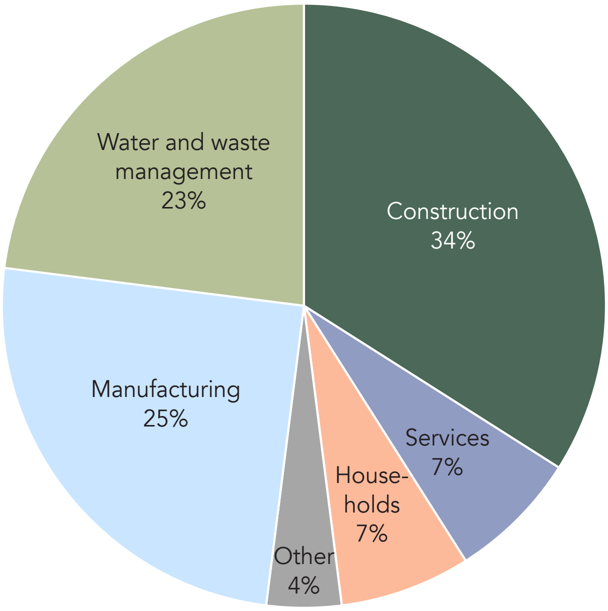


Figure 1: Diagram showing the waste by sector in the Netherlands in 2018 predominantly coming from construction. (Eurostat 2020)

In addition the world is experiencing a loss in biodiversity for many reasons largely due to population growth and subsequent increase in built land including land developed for agriculture (Rafferty 2019). The loss of biodiversity breaks down the functioning of an ecosystem and is critical for human survival. Notably, the biodiversity in the Netherlands is under serious decline. The Netherlands' single biggest use of land is pastures. 24% of the country is predominantly used for grazing livestock (Raven-Ellison 2019). Agriculture is the main human-driven cause of biodiversity loss as it converts a terrestrial ecosystem into a single crop over a vast amount of land (Rafferty 2019).

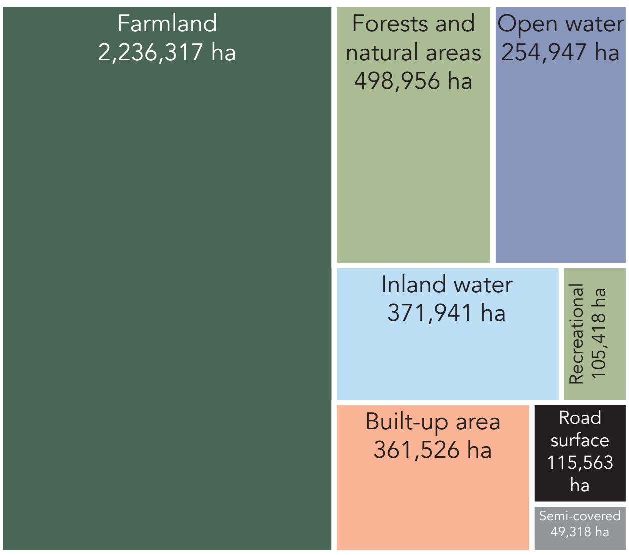


Figure 2: Diagram showing the land use in the Netherlands predominantly being farmland and a lot being built-up area. (CBS 2020)

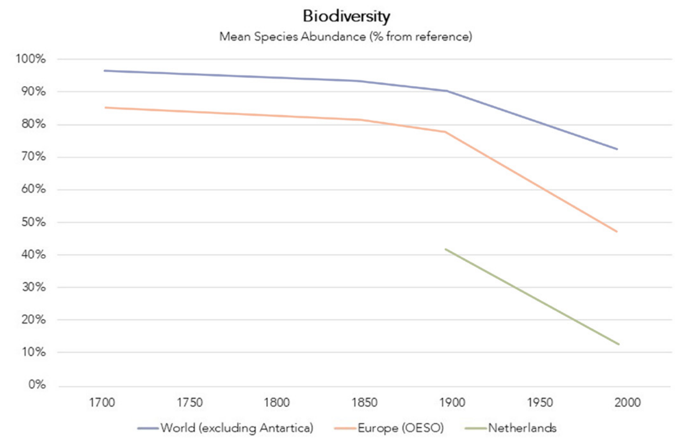


Figure 3: Biodiversity mean species abundance between 1700 and 2000 showing the Netherlands in relation to the world and Europe. (Original from PBL, 2010)

If we arguably need to increase our building stock to support a lack of housing, then any new elements on the façade of the building should consider its impact on waste and its opportunity to increase biodiversity.

The shearing layers model by Steward Brand in his book, How Buildings Learn, defines 5 separate layers of the architecture of the building according to life span: site, skin, structure, services and space plan (Brand 1994). Vegetation is, however, missing and could be a part of this model too, hosted by appropriate elements.

According to the shearing layers model, the skin of the building has a rough lifespan of 20 years, dependent on the materials involved. The lifespan of vegetation varies immensely but lasts longer under congenial conditions. To create a sustained vegetative façade, the detachability of the system is essential. In this way, the façade can either adapt to the plants, or the plants can be relocated, to the site (for example) – an eternal layer in the shearing layer model.

In addition, biobased materials are a possible solution when it comes to lowering waste in the entire life cycle of the material as they are fully renewable. Biobased materials have a timeline for biodegradability: when removing or replacing materials, the materials are put back into the cycle of decomposition thus too, minimising waste.

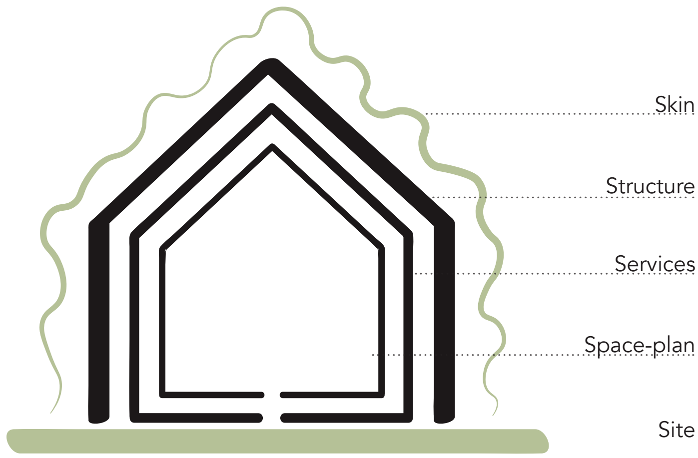
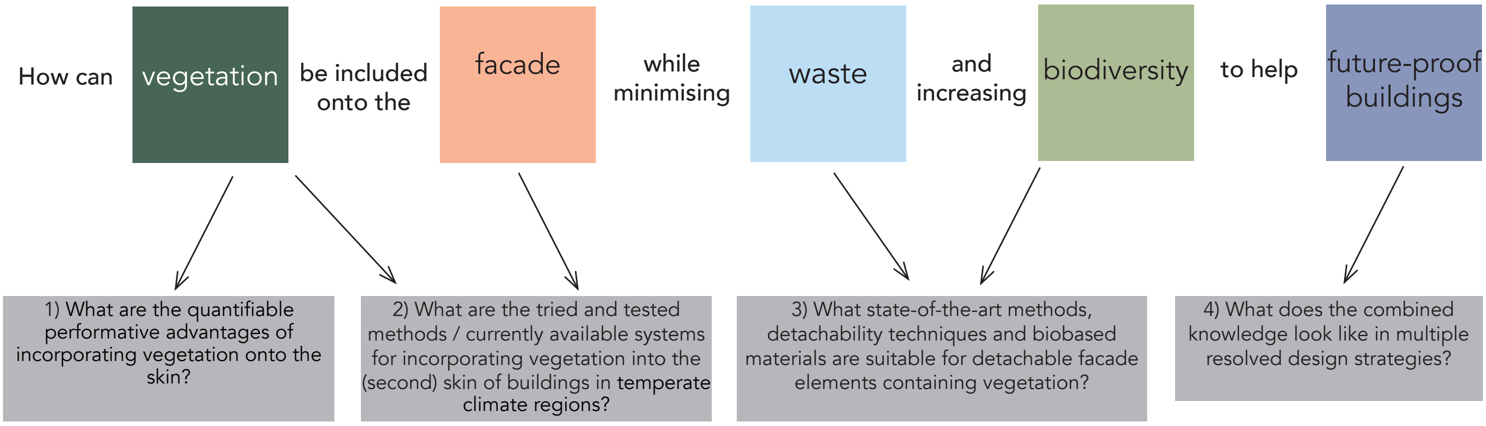


Figure 4: An adapted shearing layers model diagram where the layers of skin, space plan and site are highlighted as potential green vegetative layers. (Brand, 1994)

This research question is: *How can vegetation be included onto the facade while minimising waste and increasing biodiversity to help future-proof buildings?* Sub questions serve as a structure to the research.



II. Methodology

This research methodology uses analytical and systematic methods applied from product development. This helps to perform a quantifiable reasoning for the chosen living wall systems under investigation, biobased materials and consequent new strategies.

This research forms a base of knowledge for the following design goal: A living wall made from **biobased materials** (originally from any location) for a temperate climate, Cfb, with a **variety of vegetation** providing quantifiable performance benefits and social/ecological benefits. The living wall is **detachable** as a whole from the building envelope, with detachable elements of varying lifespans and includes the detachability of the plants to be replanted or replaced.

The measurement of the success or applicability of the living wall types and chosen materials stems from a set of criteria. Each criterion has a number of importance ranging from 0 to 4. 0: not important, 1: relatively unimportant, 2: less important, 3: important, 4: mandatory. An explanation of each criterion and their points can be found in Addendum B. They are as follows:

- Type of vertical garden: A living wall (4)
- A variety of vegetation (4)
- New bio-based materials (4) (Sub categories: accessibility in the Netherlands and growth time of the plant)
- Waste as a resource (3)
- Natural/nature aesthetic (3)
- Adaptability: detachable (4)
- External durability (4) (Sub categories: lifespan and water & humidity resistance)
- Manufacturing process (4) (Sub categories: making process & energy, prefabrication potential and weight)
- Cost/affordability (2)
- Performance (4) (Sub categories dependent on component: acoustic, insulation, air quality, fire resistance, tensile strength, elongation at break and moisture retention)

These criteria are chosen in accordance with the problem statements highlighted in the introduction. That is to reduce waste and increase biodiversity. In addition their exterior durability, their natural aesthetic and low energy use are also vital to its sustainability and user appeal. The performance value differs from type of component and therefore has its own score at the end of Addendum F. The criteria applies throughout the investigation when determining suitable living wall types, vegetation, biobased materials and manufacturing processes. These criteria would be carried through to the design process.

The biobased materials that were researched are explained in Chapter V. These materials were studied extensively mainly through scientific papers and product technical sheets. They were given the following scores for each category: 0: does not meet the requirements, 1: poor, 2: satisfactory, 3: good and 4: outstanding, to determine the quantifiable best option. Some of the categories had subcategories and then the average score was determined. Once each score was assigned then the scores were multiplied by the level of relevance score of each category to determine the best option from each category.

III. Living Walls

Sub question: *What are the tried and tested methods / currently available systems for incorporating vegetation into the (second) skin of buildings in temperate climate regions?* Living walls are a type of facade system containing vegetation with integrated irrigation. It contains a separate substrate for a variety of plants therefore it can cover tall buildings. It differs from a green façade, which has climbing plants growing from the ground or planters. This research focuses on living walls because their modularity allows structural elements, components and the vegetation to be removed or replaced. This independence ensures the system can be maintained according to the plants' and materials' varying lifespans and desired adjustments. The living wall type also allows for variation in plants scattered across the wall increasing biodiversity. The types of plants are only limited to not having invasive tendencies. They can be low-growing shrubs, ferns, perennials, grasses and either native or adapted to their environmental context. Their growth is limited by how deep their roots can grow in the substrate controlling the weight of the system. For a more detailed list of desirable plants see Addendum D.

The perception of living walls shows great benefits but also critical challenges. This research intends to change the latter view by highlighting quantifiable performance benefits as well as the other qualitative benefits to provide evidence of its unique value and service to people and the building. The design strategies from this research would go even further to reimagine the existing walls more sustainably, with the use of biobased materials, to eliminate views on its superficiality or as ornamentation.

The challenges living walls impose include the following:

1) The critical need for a well-working water system to provide nutrients and hydration to the plants.
2) In return, the risk of condensation damaging the building.
3) The costs involved in maintaining, monitoring and needing labourers with specific skills.
4) The concern of inconsistent or patchy greenery during different seasons, orientation or if plants become unhealthy.

These remarks can be addressed by the following:

1) Firstly, a sustainable solution is to not think of a living wall in isolation but as a part of the building system with a fully integrated rainwater harvesting and storing system. Perhaps, also utilising the wall's ability to attenuate water. By absorbing water, purifying it and slowly releasing it back to the ground it stabilises the water level, puts less strain on sewage systems and reduces flood risk.
2) Secondly, a waterproof membrane is a key component to the wall and in addition the system acts as a weather barrier prolonging the life of the building's façade.
3) The system can be prefabricated which enables quick or easy assembly on site which reduces labour costs. The irrigation system would need to be handled by a specialist.
4) In Addendum D, one can see the needs of vegetation to make an informed decision for a healthy flourishing living wall. Careful monitoring can test the substrate and assess the state of the plants.

Living walls have been proven to increase health and wellbeing, in particular increasing productivity and reducing stress (SemperGreenwall 2021). It reduces the heat island effect by cooling down dense built environments. The natural appearance increases property value, adds value to neighbours and can uplift an area by bringing people to it. It becomes a sustainable image reminding people of nature's beauty and the need to protect it. In dense urban environments the living wall is a chance to have a large garden but save on valuable space while creating even more biodiversity. The quantifiable benefits of vegetation are discussed in Chapter IV.

There are two categories of living walls: soil-cell and hydroponic. Soil-cell systems have individual compartments filled with soil with a drip-irrigation feeding the plants water and nutrients. The concerns are soil compaction, excess mineral salts and plant stress due to soil loss from wind or water-aided erosion. Soil-cells allow plants to grow vertically mimicking the ground and hydroponics mimic a mountain or cliff face.

Hydroponic systems use a dense mat or geotextile type material as a growing medium for roots to grow between eliminating problems with soil. Both irrigation systems could potentially have a recirculating pump for reuse of water.

Within these two categories 5 types of living walls meet the criteria in Chapter II. These types can be found on the exterior façade of a building and are detachable, therefore modular. The 5 systems are namely, pocket, geotextile rail, framed boxes, panel and carrier systems. 3D drawings and a description of each with regards to their materials and process of making can be found in Addendum E. From these systems the key components of a living wall can be identified:

1) **The support structure:** For stability to hold the panels and plants separate from the wall's structural system. This also includes a backing board if necessary.
2) **Waterproof layer:** This guarantees that the moisture in the substrate does not pass to the wall, so it is protected from the roots and the humidity.
3) **The substrate:** The substrate can be an inert substrate or an organic substrate. This includes fibrous panels and double layered geotextiles. The substrate can also be carried by felt-like materials for pockets or stable troughs.
4) **Irrigation:** This is critical for the health of the plants to get enough nutrients and water and should be the longest lasting or most durable element of the system. It consists of tubing and other elements that depend on the type of system (drip, hydroponic or recirculating).
5) **Connections:** For example, adhesives, rails, screws and plates to join the components together and securely fix them to the wall.
6) **Air cavity:** To provide ventilation to the plants and avoid a build-up of moisture. It also creates a thermal insulative later for heating and cooling of the building.
7) **Plants:** Conveniently selected for desirable traits such as native or adapted to the climate, its orientation, a favourable condition and performance value or benefit.

IV. Vegetation

Sub question: *What are the quantifiable performative advantages of incorporating vegetation onto the skin?* A living wall can be more than a screen of beautiful plants. The vegetation when considerably selected has quantifiable benefits. Their effect on thermal balance, sound absorption, the air quality and shading can reduce the need for expensive installations and save on energy and materials while ensuring a healthy living environment. The vegetation's characteristics of leaf shape, stage of development, coverage percentage, colour, form and solar transmittance all play a role on their performance contribution in particular their thermal effect (Manso and Castro-Gomes 2016). The other effects on performance are the components of the living wall system such as substrate type, moisture level, air gap from the wall as well as the orientation of the building and climate conditions.

The measurements gathered for this paper are from similar climate zones to the Netherlands. On the Köppen climate classification chart that is Cfb (temperate oceanic climate). The 'C' means the temperature of the warmest month is 10 °C or more, and the temperature of the coldest month is between –3°C and 18°C. The 'f' refers to the rain and means it is distributed evenly through the year. The 'c' means the warmest month's average temperature is less than 22°C (Britannica 2020). These conditions are important to bear in mind when designing for healthy vegetation and choosing the suitable species. The benefit to this climate is the consistent rainfall; a key need of the plants and an opportunity to harness water effectively. The concern for this climate is during the colder months when changes may occur in the colour and foliage consistency of the vegetation, meaning the wall behind needs to be visually appealing and natural looking.

There are many scientific articles quantifying the performance of the vegetation on living walls. A full table can be found as Addendum C.

According to the scientific papers vegetation can reduce temperatures in the summer months by between 2°C and 10°C, it lowers the thermal transmittance (U-value) by at least 12%, reduces the thermal conductivity (K-value) and can improve its thermal resistance (R-value) by 31%.

The noise reduction values of living walls are dependent mostly on the thickness of the substrate and leaves of plants as well as the size of rooms and ceilings behind. It can reduce noise by between 1dB and even up to 15dB.

Vegetation are natural air purifiers as they absorb pollutants such as NO_2, particulate matter PM_{10} and other heavy metals. This is called biogenic regulation (Biotecture 2021). Plants convert CO_2 into oxygen for us to breathe. A green wall can remove an average of 2.3kg of CO_2 from the air per meter squared (Technische Universität Darmstadt 2016) and produce 1.7kg of oxygen in return (SemperGreenwall 2021).

When a living wall is designed strategically it can have optimal shading benefits. In the changing seasons it can also let light in in winter and shade windows in the summer without mechanical intervention, this reduces the energy consumption for cooling by 11,5% (Zheng, Dai, and Tang 2020).

V. Biobased Materials

Sub question: *What biobased materials are suitable for detachable facade elements containing vegetation?* The biobased materials investigated in this paper fully originate from plants, therefore they are renewable resources. Their greatest benefit is their being CO_2 neutral or even CO_2 negative. Unlike recycled materials these materials can always be available when they have good growing conditions and do not perpetually decrease in quality through recycling processes. Biobased materials are often much lighter in weight. When used in conjunction only with biobased adhesives or natural processes the materials are most likely to be non-toxic. In addition, their natural aesthetic is hugely appealing, tactile and blends into natural environments.

The major concern for biobased materials is their lifespan or biodegradability. It would be ideal if they could withstand external application, while still ultimately being compostable and not adding to our waste streams. Currently, there is an expectation that buildings and their components should last for a very long time. To meet this expectation, biobased materials need to be combined with other inorganic finishes or treatments to increase their external durability. Alternatively, there should be a shift in mindset to be able to replace things more often and a shift in systematic procedures to make this feasible.

A full table of the properties based on the criteria can be found for selected biobased materials in addendum F and how they rank in addendum G. The information is given with regards to the criteria in Addendum B, as well as with a few subcategories.

The materials have been given a relevant living wall component which they could be used for. These components are listed and explained in chapter III. There are 20 researched biobased materials. At least three materials for each component type were investigated and some materials apply to multiple components. The substrate varies in nature (geotextile, carrier or panel) and has the largest use in terms of amount of material for the system, therefore more substrate materials were looked into.

Some of the performance qualities are only relevant to certain categories and are highlighted in grey. This performance table is also ordered according to highest score. It is interesting to note that the only critical factor when trying to get a material approved in practice is fire resistance.

Addendum G shows the total scores of the materials according to the set of criteria explained in Addendum B. Coconut received the highest score closely followed by hemp, then miscanthus, flax straw and timber. The points often vary only slightly but the most noticeable difference are bioplastics with the lowest scores, largely due to their unnatural aesthetic.

The support structure needs to be strong and stiff and weather resistant so hardier materials with a high lignin content are needed. The researched options were timber (larch being the most readily used in the Netherlands so this was the focus type), bamboo and board made from agricultural residues such as straw or reeds. The structural material with the highest score was timber mainly due to its accessibility in the Netherlands.

The waterproof layer would go unseen but is critical for the system to protect the envelope of the building from the moisture in the living wall. It needs to be continuous and durable. Bioplastic options made from potato starch, cellulose, sugarcane or vegetable oils and resin are investigated mainly for this component. Although they scored low they would be the most durable option.

One type of substrate for a living wall is fibrous panels to host the vegetation. They are exposed if the vegetation is not thriving so how they look is important. They are also exposed to water and other weather conditions so would need to be resilient. The materials researched are hemp, flax straw, miscanthus, straw, wood fibres, coconut, cork, manila hemp and sisal. The top four materials are coconut, hemp, miscanthus and flax straw. Their scores differ very slightly and could be used almost interchangeably or even in combination as a composite depending on one's design.

These materials could also be used in other means perhaps as carrier systems with soil or sphagnum moss to hold the roots of the plants. Bioplastics could be produced as carriers, but they do not have a natural aesthetic.

Another substrate is geotextiles. They are usually permeable synthetic textile materials generally made from polypropylene or polyester polymers. They can however be made from natural fibres. Their key properties are a good tensile strength, water absorbency and long-term durability (a tendency not to break). They also need good mechanical properties, resistance to biodegradability and a higher lignin content. Natural fibres come in three classifications: bast (stems of plants), leaf and seed/fruit. Leaf fibres prove to be the best option as they have a good lignin content and high crystallinity therefore they are less biodegradable. Coconut has the highest tensile strength and elongation at break percentage. Along with meeting the other criteria it would be the best geotextile option. Manila hemp and sisal would also be viable as they are both leaf fibres. Biodegradability is the main challenge and blending these fibres may be a good option currently.

The biobased materials appropriate for the irrigation system tubing are bioplastics, directly mimicking the current systems or bamboo with its natural cylindrical shape.

Connections include fixings, connectors, adhesives and rails. Mycelium is researched as a biobased adhesive. From the roots of mushrooms, a natural binding process occurs to glue fibres together resulting in a 100% natural composite without synthetic additives that can remain biodegradable. The material is the roots of the mushroom, and the process is explained further in addendum H. Other connections are discussed at the end of the next chapter on detachability.

Separately to the criteria chosen for this research some materials have additional notable strengths. Coconut flesh can be used as a natural adhesive for its own fibres. Cork is the only commercially tried and tested existing example used in a living wall as a panel substrate. Cork score reflects its limitations due to accessibility and growth time and it being a limited resource. It's performance is really good and therefore should be used but sparingly. Hemp removes heavy metals in soils when it is grown enabling it to be a good rotational crop. It can absorb 20% of its own weight without any deterioration. Miscanthus, like bamboo, has a very high yield and it also requires very little fertiliser.

VI. Processes and Detachability Methods

Sub question: *What state-of-the-art methods and detachability techniques are suitable for detachable facade elements containing vegetation?* A full catalogue of methods that can be applied to the biobased materials discussed in this paper can be found as Addendum H. These methods are arranged according to the type of process they use. These are subtractive, forming or additive. Each process evidently differs in production of waste and energy use. Subtractive processes remove part of the material which can be used in a different application but may also be lost. Forming does not waste the material directly but often uses extra materials for moulds and high energy for heating. Additive processes do not waste material as it is precisely allocated to its need or applied to a material directly. Electrical energy is also needed for these digital processes. Included in the additive processes are finishes that traditionally are not fully biobased but are necessary for extending the life of materials.

For a system to be detachable it requires mechanical or dry joints, as opposed to wet joints such as synthetic adhesives like glue. Mechanical assembly includes tangling, crossing, stacking (interlocking), wedging, nailing, screwing, pegging and complementary metallic elements such as inserts, rings and brackets (Kula and Ternaux 2013). Sewing is also a form of dry attachment for fabrics and textiles. The methods for sewing are slip stitch, zigzag stitch and overlock stitch. These methods can be unpicked with a bit of effort, and threads can also be sourced from plants.

When it comes to the detachability of a living wall it is challenging to be 100% biobased. The building industry relies heavily on metal connectors such as plates, screws and nails. These dry fixings are durable and can be easily removed.

There are however some alternatives. Firstly there are many techniques for dry joining wood (beautifully illustrated in *Materiology: The Creative Industry's Guide to Materials and Technologies* (Kula and Ternaux 2013)). These include edge-to-edge joints such as tongue and groove, end-to-end, scarf joints, crosspiece assembly, mortice and tenon. Dovetail and dowel or tabs and dowels. These methods can be used to put panel frames together and connect elements to their adjacent counterpart.

Secondly natural fibres can be braided into rope to hold carrier systems and secure them by making ties or loops. Natural ropes include coir (from coconut), flax or hemp, sisal and cotton. Manila rope is the best option as it is durable for 10 years. It also shrinks when it is wet making knots tighter and stronger and is fire retardant.

Lastly, bioplastics can be formed, extruded, printed or moulded into for example railings, plugs, clips and hooks.

VII. Conclusion

This paper answers the research question: "*How can vegetation be included in the building's skin to minimise waste and increase biodiversity, creating future-proof buildings?*" by analysing existing living wall types that are modular therefore detachable and host a variety of vegetation that provide several benefits. The critical factor is further imagining these walls from optimal biobased materials with the use of relevant mechanical processes. The tools are thus provided for a low waste, biodiverse and detachable vegetative skin.

In addition to providing qualitative benefits, the vegetation provides quantifiable benefits in the form of thermal balance, sound absorption, increasing air quality and shading. This can reduce the need for expensive installations and save on energy and materials while ensuring a healthy living environment.

The research reveals coconut as the highest scoring material closely followed by hemp, then miscanthus, flax straw and timber. The most noticeable difference are bioplastics with the lowest scores, largely due to their unnatural aesthetic.

It is important to note that this decision-making has a subjective aspect to it and further experimental research may be necessary to compare materials and design strategies in application. Furthermore, any additional noteworthy results not part of the criteria can be mentioned to promote value or warn against an attribute.

Biobased materials are an outstanding solution to waste reduction as they are 100% natural coming from renewable resources and can biodegrade. They are perfect for shorter-use applications. Currently, there is an expectation that buildings and their components should last for a very long time. To meet this expectation biobased materials, need to be combined with other inorganic finishes or treatments to increase their external durability. Alternatively, there should be a shift in mindset to be able to replace things more often and a shift in systematic procedures to make this feasible.

The processes of making these materials can be optimised to reduce waste especially through additive processes instead of forming or subtractive processes. Mechanical fixings or dry joints must be used for detachability. It is challenging to be 100% biobased as the building industry relies heavily on metal connectors such as plates, screws and nails. These dry fixings are durable and can be easily removed. However, timber dry joints have been traditionally used for years, manila rope is a viable option and bioplastics can be formed, extruded, printed or moulded into connectors of one's choice.

This research is aimed for external application on the façade in temperate oceanic climatic regions. It is challenging but not impossible for biobased materials to remain durable in these conditions for more than 10 years. However, interior application would provide for a longer lasting wall. Performance benefits of a living wall will also be more significant in warmer climates.

The perception of living walls shows great benefits but also critical challenges. This research intends to change the latter view by highlighting quantifiable performance benefits as well as the other qualitative benefits providing evidence of its unique value and service to people and the building. The design strategies from this research would go even further to reimagine the existing walls more sustainably, with the use of biobased materials, to eliminate views on its superficiality or as ornamentation.

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Definitions

Adaptability: "The capacity to be modified for a new use or purpose" ("Adaptability" 2021)

Autoclave: "A strong heated container used for chemical reactions and other processes using high pressures and temperatures, e.g. steam sterilization." ("Autoclave" 2021")

Biobased materials: Materials fully originating from living organisms therefore are a renewable resource. This does not only include for example, wood but also for example, plant based compostable plastics.

Biodiversity: "the variety of plant and animal life in the world or in a particular habitat, a high level of which is usually considered to be important and desirable" ("Biodiversity" 2021)

Biodegradable: "susceptible to decomposition by living organisms" (Barrett 2019) Biodegradability refers to a process that starts without human intervention and where the residue is not necessarily compost.

Building performance: How well it functions according to its prescribed criteria (Designing Buildings 2020) such as the environmental benefits; air quality improvement, thermal conductivity, shading and noise reduction.

Compostable: "act or process of separating the constituent elements of a compound body" (Barrett 2019) Composting refers to a process started by human intervention and where the residue may be defined as compost.

Detachability: The independence of elements by having separable joints or dry connections.

Environmental Quality: "the sum of the properties and characteristics of a specific environment and how it affects human beings and other organisms within its zone of influence" (Terrapin Bright Green 2014)

Future-proof (building): "an assessment process aimed at maximising whole-live value in the face of unpredictable, ongoing change" (Designing Buildings Ltd 2021). It is a building that is adaptable and resilient.

Geotextiles: Usually permeable synthetic textile material generally made from polypropylene or polyester polymers.

Living wall: A type of facade system with vertical vegetation and irrigation. It contains a separate substrate for a variety of plants therefore it can cover tall buildings. It differs from a green façade, as that is made of climbing plants growing from the ground or planters.

Prefabrication: "A building manufactured in sections to enable quick or easy assembly on site" ("Prefabrication" 2021)

Vegetation: "Plants considered collectively, especially those found in a particular area or habitat." ("Vegetation" 2021)

Criteria Description

Type of vertical garden: A living wall A type of facade system with vertical vegetation and irrigation. It contains a separate substrate for a variety of plants therefore it can cover tall buildings. It differs from a green façade, as that is made of climbing plants growing from the ground or planters.	**4**
A variety of vegetation The wall should be able to host +-100 healthy flourishing plants to increase biodiversity. These plants can be native or adapted to the temperate climate (Cfb) (perennial plants, grasses, shrubs, succulents, edibles as long as they are not invasive).	**4**
New accessible biobased materials Materials sourced 100% from plants from anywhere around the world but accessible in the Netherlands. Consideration is made for the plants' yield and a short growth time of the plant the material is based on.	**4**
Waste as a resource The system uses as few materials as possible. The materials at their end-of-use are either compostable or recyclable.	**3**
Natural/nature aesthetic The attached plants are already grown so growth looks continuous over the wall. However, the system should look good without plants. That is to say, as natural looking as possible (colours, textures).	**3**
Adaptability: Detachable Modular with the use of dry connections and joints, the system should be able to be detached as a whole, in its elements and as well as its plants.	**4**
External durability The lifespan depends on the temperate climate (Cfb) conditions therefore, it should be water and humidity resistant. It should last longer for example for the irrigation system and shorter for example for the plant substrate (preferably 15+ years). The system should be securely fixed without the worry of it falling over.	**4**
Manufacturing process Desirable to be prefabricated to ensure its scalability, ease of maintenance, simplicity, quick, reduced labour and efficiency. Three things to look for to reduce environmental impact: 1) the use of an autoclave should be avoided. 2) using other materials such as vacuum bags, moulds should be avoided. 3) Any emissions from evaporation should not be harmful.	**4**
Cost/affordability Of the plant-based material in its manufactured condition as a competitor to non-renewable materials (either now or feasible in the future)	**2**
Performance* Air quality (non-toxic), thermal comfort, acoustics, fire resistance, shading Moisture retention for the plants' roots (only applicable to substrate) Tensile strength, elongation at break (only applicable to textile)	**4**

* It is to be noted that the living wall is a second skin and does not constitute the entire building envelope's performance. It can still aid in reducing materials, insulation and expensive installation costs of the building.

Vegetation Performance

Thermal properties:

Vegetation or system type:	Quantified Measurement:	Notes:	Source:
Green facade with cold-green plant layer of 35cm	Reduces the heat transfer coefficient (U-value) by about 12%	Influences operational costs therefore energy usage/bills can be lowered	#31
Living wall pocket with "fytotextile"	31% improvement to a traditional brick facade. U-value with living wall: 0.77Wm2K U-value without living wall: 1.12Wm2K		#10
Living wall: Air cavity (thickness of 0.05m), concrete blocks (0,40m), aluminium living wall frame, PVC + felt living wall support panel, vertical garden vegetation	0,7Kc	See table of source for exact vegetation and detailed coefficients	#23
Living wall with planter boxes of 22cm (4 cm gap to wall)	5°C surface difference between bare wall and living wall facade. 2°C at night to 9°C in the afternoon. 100% reduction of sun radiation due to materials.		#19
Living wall with planter boxes of 22cm (4 cm gap to wall)	The wind velocity profile: decrease from 0.56 m/s to 0.10 m/s (ΔW ¼ 0.46 m/s)	The thermal transmittance (insulation properties) is affected by the wind velocity that goes over the building's surface.	#19
Living wall (planter) (10cm shrubs, 22cm planter, 5cm air cavity)	A temperature difference of 8,4°C compared to bare wall (after 8 hours of heating). winter temp difference of 2.1°C. An improved R-value.		#17
Three plant species, west facing, climbing movable screen	0,94 - 0,61 Kc		#33
General green façades and living walls	Indoor temperature reduced by 10°C	Depends on climate, building skin type and density of plant coverage, shading, insulation and vegetation	#21
General green façades and living walls	Reduced energy consumption up to 20%		#32
Exterior living wall: Green over Grey	Reduces indoor air temperatures by up to 7°C. Electricity savings of up to 20% by reducing air conditioning requirements.	The air between the living wall system and the wall also provides insulation.	#12
Exterior living wall: Green over Grey	A green wall can be up to 10°C cooler than an exposed surface.		#12
Green facade vegetation	In the UK an air temperature reduction of 3-5°C . Wall surfaces can be up to 10°C cooler and wall cavities 5°C cooler.	During the winter vegetation can convey an average energy cost saving of 38% because of the plants and the wall surface trap heat in between.	#6
Exterior green walls on southwest façade on the second-story.	Stabilized indoor wall temperatures of 2°C cooler in summer and 2°C warmer in the winter.		#33
Geogreen cork vegetated surface (wall & roof)	Reduces indoor maximum temperature and increases minimum temperature up to 7°C. Reduces maximum income heat flux by 75% and outgoing heat flux by 60%.	These aspects can lead to reduce and shift air-conditioning power loads and to improve buildings thermal performance.	#15
Vegetation (Singular green)	They reduce up to 5°C the interior temperature of a building in summer as well as maintain it in winter.	Saving up to € 500 / m2 per year.	#25

Sempergreen Living Wall (outdoor living wall)	Plants absorb sunlight, 50% is absorbed and 30% reflected; so this helps to create a cooler and more pleasant climate. For the indoor climate this means that 33% less air conditioning is required, which in turn means energy savings.		#24
Sempergreen Living Wall (outdoor living wall)	An outdoor living wall also has a positive influence on the heat-island effect in the city. Overall, it means a 3°C reduction in the city.		#24

Sound Absorption:

Vegetation or system type:	Quantified Measurement:	Notes:	Source:
Green façades	Reduce sound intensity up to 10dB		#32
Green façades	Noise reduction of 15dB		#10
Living walls	Living walls provide a noise buffer which significantly reduces outside noise and vibration (up to 40 dB) inside the building and close areas		#28
Framed boxes modular living wall	Living wall has a weighted sound reduction index of 15db and weighted sound absorption coefficient of 0.40, and concludes that living walls are significant sound insulators of buildings		#21
A thin layer of vegetation (20–30 cm) in a pre-cultivated, modular-based system and double-skin green facade.	An increase of 1dB in the sound insulation for traffic noise	Greening of the upper storeys in the street and (full) façades in the courtyard itself is most efficient to achieve noise reduction	#21
Framed boxes modular living wall	Insulation increase 2 dB for a pink noise		#21
Exterior living wall: Green over Grey		Leaves of plants attenuate sound by reflecting, refracting and absorbing acoustic energy in small amounts	#12
Exterior living wall: Green over Grey		Barriers against traffic and other urban noise pollution, absorb the echo bouncing off buildings	#12
Vegetation (Singular green)	Plant insulation reduces noise pollution by up to 10 decibels		#25
Sempergreen Living Wall (outdoor living wall)	Based on test results the SemperGreenwall Indoor absorbs 85% of the ambient noise.	The precise acoustic value always depends on factors such as the size of the room and ceiling height.	#24

Air Quality:

Vegetation or system type:	Quantified Measurement:	Notes:	Source:
Green walls with resistant species		Absorption of gaseous pollutants through stomata in plant leaves	#31
Green walls with resistant species		Settling / sticking solid particles to the leaf surface	#31
Green walls with resistant species		Passive accumulation of pollutants on the plant's root-soil system	#31

Green walls exposed on proper sun lighting	CO_2 content in the air can be reduced by 250 μmol m2/s		#31
Green walls	Particulate matter PM10 level may be reduced up to 50%		#31
Green walls	NO_2 in the air may be decreased about 60%		#31
Green wall	A green wall can remove an average of 2.3 kg of CO_2 from the air per square metre		#27
Living walls		Smaller leaved species with a high LAI were found to have a higher PM removal potential compared to species with wider leaves	#30
Green façades and living walls	Reduced in canyon concentrations of NO_2 and PM10 by as much as 15% and 23%		#20
Vegetation (Singular green)	1m² of vegetation cover generates the oxygen required by a person throughout the year.		#25
Vegetation (Singular green)	1m² of vegetation cover traps 130 grams of dust per year.		#25
Vegetation (Singular green)	A 4-storey building (60m²) with a green façade can filter out per year 40 tons of harmful gases.		#25
Vegetation (Singular green)	It is capable of trapping and processing 15 kg of heavy metals		#25
Sempergreen Living Wall (outdoor living wall)	The plants in a living wall filter particulate matter from the air and convert CO_2 into oxygen. 1m² of living wall extracts 2.3 kg of CO_2 per annum from the air and produces 1.7 kg of oxygen		#24
Outdoor living wall	The following plants have the following mean density of PN10 capture: Convolvulus eneorum: 2.75g.m², stachys byzantina: 1.5g.m², acorusgramineus: 1.3g.m², carextestacea: 1.25g. m², erysimumbicolor: 1.2g. m², hebe odora: 1.15g.m², lavendulaangustifolia: 1.15g. m², prunuslaurocerasus: 0.9g. m², euonymus fortune: 0.8g.m², geranium maculatum: 0.7g.m², henchervillosa: 0.65g.m², aucuba japonica: 0.65g.m², viburnum tinus: 0.6g.m², berberisjulianae: 0.4g.m², hedera helix: 0.25g.m²	Plants capture toxins, gases and particulate matter through natural processes (this is called biogenic regulation). This cleans the air of which we breathe.	#20

Shading:

Vegetation or system type:	Quantified Measurement:	Notes:	Source:
Three plant species, west facing, climbing movable screen	0,28 shading coefficient.		#34
Three plant species, west facing, climbing movable screen	Cooling energy consumption reduced by 11,5%		#34
Three plant species, west facing, climbing movable screen	Heat flux transferred through the window glass reduced by 64,7%		#34
Living wall in a Mediterranean climate	In the summer season: for more than 60% of the hours, the difference of outside surface temperature of the wall before and after the application of the green system ranges from 6 to 11°C	The heating and cooling need comes down 10%. The lifespan of the building façades is prolonged: reduced maintenance, less wear and tear. and fewer replacements.	#3
Living wall in a Mediterranean climate	Shading reduces energy consumption for air conditioning systems by up to 19%		#26
Living wall in a Mediterranean climate	Air temperature to 21.2°C from 37.4°C. Relative humidity to 46.4 from 68.1%.		#14

Vegetation for Green Façades

Species:	Decidius (D) Evergreen (E) Annual (A)	Orientation Bold: preferred Light: tolerated	Growth Rate	Soil	Native (N) Adapted (A) Exotic (E)	Benefits:
Euonymus fortune	E	**N E W**	Slow	Any	E	0.8m2 (mean density of PN10 capture)
Hedera helix	E	**N** E S W	Slow	Rich	N	0.25g.m2 (mean density of PN10 capture)Excellent wildlife plant. Good nesting site for robins and wrens, and hibernating butterflies – esp brimstone. Nectar and pollen for bees and hoverflies.
Parthenocissus quinquefolia	D	N **E** S W	Average	Any	E	Useful for nesting birds if grown on a trellis. Provides nectar and pollen for bees. May attract nesting spotted flycatcher.
Parthenocissus tricuspidata	D	N **E** S W	Fast	Any	E	
Hydrangea petiolaris	D	**N E W**	Average	Loamy	E	Good for nesting birds and produces nectar for bees and other insects.
Polygonum bauldschianicum	D	N E **S** W	Fast	Any	E	Good for nesting birds.
Lonicera Periclymenum	D	**E** S **W**	Average	Good Loam	N	Must be kept bushy for nesting birds. Excellent for insects, especially moths, due to nightscented flowers. Bark from older stems used by nesting birds. Berries eaten by birds.
Lonicera spp.	D-E	N **E** S **W**	Average	Good Rich	E	"Several varieties are useful nectar and seed plants. Evergreen honeysuckly trained up a trellis makes a good bird roosting site."
Clematis vitalba	D	E S W	Fast	Prefers Alkaline	N	Seeds for birds. Nesting sites. Nectar for insects.
Clematis spp.	D	**E W**	Fast	Various	E	Useful nectar and/or seed providers. Useful for nesting sites if trained thickly on a trellis.
Humulus lupulus	D	**E** S **W**	Fast	Rich moist	N	Good for bees.
Aristolochia spp.	D	**N** S **W**	Average	Most	E	
Jasminum officinale	D	**E W**	Fast	Well drained	E	Night-scented, attracting moths and other night-flying insects.
Vitis spp.	D	E **S** W	Average Fast	Rich Loamy Moist	E	Provides fruit for birds and nectar and pollen for bees.

Vegetation for Green Façades

Species:	Decidius (D) Evergreen (E) Annual (A)	Orientation Bold: preferred Light: tolerated	Growth Rate	Soil	Native (N) Adapted (A) Exotic (E)	Benefits:
Wisteria spp	D	E **S W**	Average	Rich, moist, loam	E	Excellent nectar and pollen for bees. Can be used by nesting.
Capsis radicans	D	E **S W**	Slow	Rich, well drained	E	
Passiflora caerulea	D	E **S W**	Fast	Any	E	Nectar and pollen for bees.
Lathyrus odoratus	A	**S** W	Fast	Rich, well drained	E	
Tropaeolum spp.	Mainly A	E **S** W	Fast	Poor	E	Nectar/pollen for bees and beetles. Seeds eaten by birds and small mammals. Food plant of small and large white butterflies.
Rubus fruiticous	E	N **E** S W	Average	Most like acid	N	Provides pollen for bees and nectar for bees and butterflies. Berries for birds and small mammals, Night-scented and attracts moths.
Jasminum nodiflorum	D	N **S** W	Average	Most	E	
Rosa canina	D	E **S** W	Average	Good	N	Night-scented for moths. Nectar for insects, rosehips for birds and small mammals. Good nesting cover for birds.
Rosa spp.	D	E **S** W	Average	Most	E	Excellent nectar for bees. Nesting sites for birds.
Forsythia suspensa	D	N E **S** W	Average	Most	E	Nesting sites for birds, as above
Cotoneaster spp.	D Some E	**N E**	Slow	Any	E	Thick growth may be used by nesting blackbirds and brushes. Berries for birds, especially blackbirds and small mammals. Nectar and pollen for bees.
Pyracantha atalantiodes	E	**E** S W	Slow	Most, well drained	E	Good for nesting birds e.g. thrushes, and provides nectar and pollen for bees and berries for birds, particularly blackbirds.

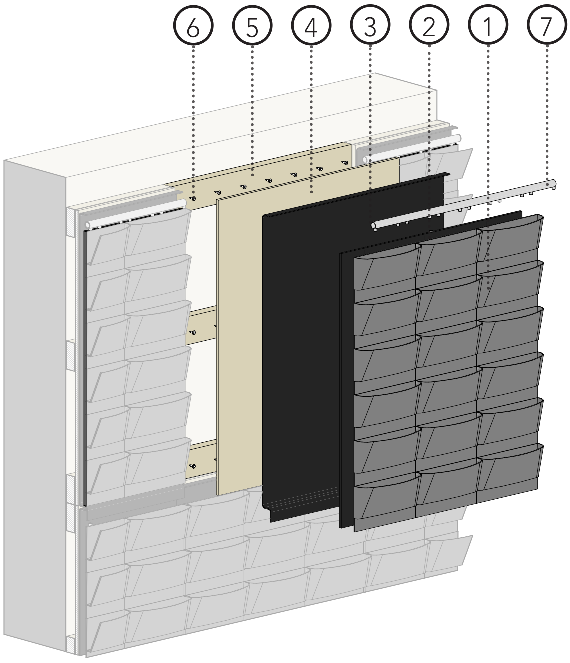
This text is taken largely from Timur, Ö.B.; Karaca, E. Vertical Gardens (CHAPTER 22). In Advances in Landscape Architecture, 1st ed.; Ozyavuz, M., Ed.; IntechOpen: London, UK, 2013; pp. 587–622.

Vegetation for Green Façades

Other types (Scientific name):	**(Common name):**
Convolvulus eneorum	Silverbush
Stachys byzantina	Lamb's-ear
Acorusgramineus	Japanese sweet flag
Carextestacea	Prairie Fire
Erysimumbicolor	Bowles' perennial wallflower
Hebe odora	New Zealand Gold
Lavendula angustifolia	English lavender
Prunus laurocerasus	Cherry laurel
Geranium maculatum	Wild geranium
Heuchera villosa	Hairy alum root
Aucuba japonica	Spotted laurel
Viburnum tinus	Viburnum
Berberis juliana	Chinese barberry
Dracaena marginata	Dragon tree
Dracaena warneckii	White stripes
Dracaena craig	Janet Craig
Dracaena sanderiana	Lucky Bamboo
Dracaena deremensis	Corn plant
Phalaenopis spp.	Moth orchids
Hibiscus spp.	Hibiscus
Gardenia spp.	Cape Jasmine
Schefflera spp.	Dwarf umbrella tree
Nephrolepsis spp.	Tuberous sword fern
Asparagus sprengeri	Asparagus fern
Hoya Kerrii	Sweetheart Hoya
Sansevieria hani	Bird's nest snake plant
Chamaedorea elegans	Parlor palm
Begonia tuberhybrida	Tuberous begonia
Syngonium podophyllum	Arrowhead vine
Philodendron giganteum	Giant philodendron
Ficus elastica	India rubber plant
Hatiora salicornioides	Dancing Bones Plant
Soleirolia soleirolii	Baby's tears
Haworthia attenuata	Zebra Haworthia
Kalanchoe spp.	Flaming Katy
Tradescantia zebrina	Wandering Jew
Asplenium nidus	Bird's Nest Fern
Chlorophytum spp.	Spider plant
Fittonia spp.	Nerve plant
Scindapsus aureus	Hunter's robe
Siderasis spp.	Brown Spiderwort
Tillandsia spp.	Ball moss
Aucuba spp.	Spotted laurel
Nidularium spp.	Bird's Nest Bromeliads
Maranta spp.	Prayer plant
Fatsia spp.	False castor oil plant
Ctenanthe spp.	Never never plant
Cordyline spp.	Ti plant

Current Living Wall Types:

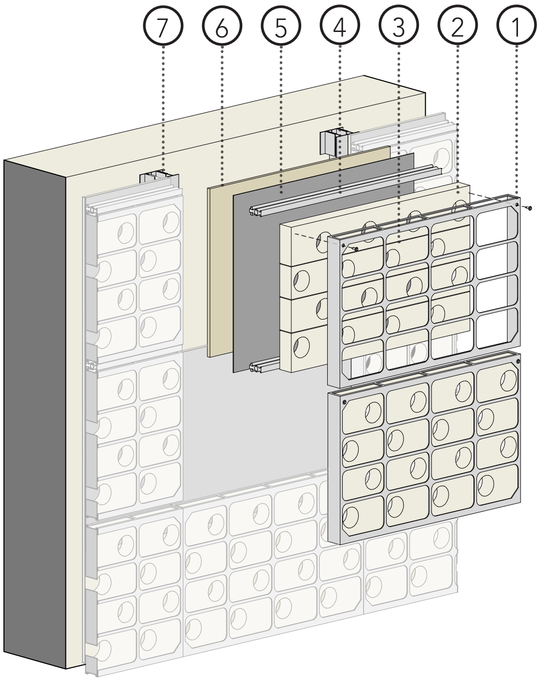
Pocket System:



Component:	Material:	Technique:
1) Individual hanging pockets - Substrate	1) 100% recycled P.E.T. plastic felt pockets - Soil or felt squares	1) Non-woven stitching
2) Panel	2) Rigid plastic panel (polyethylene)	2) Plastic calendering
3) Waterproof layer	3) EPDM rubber	3) Curing/.Vulcanisation
4) Support board	4) Plywood	4) Gluing veneers & hot pressing
5) Structure	5) Treated timber	5) Sawing, staining
6) Fixings	6) Staples, bolts, deck screws	6) Heading machining
7) Irrigation tubing	7) Plastic (PVC or polyethylene)	7) Extrusion

Irrigation type: Drip irrigation recirculating from tank below

Geotextile Rail System:

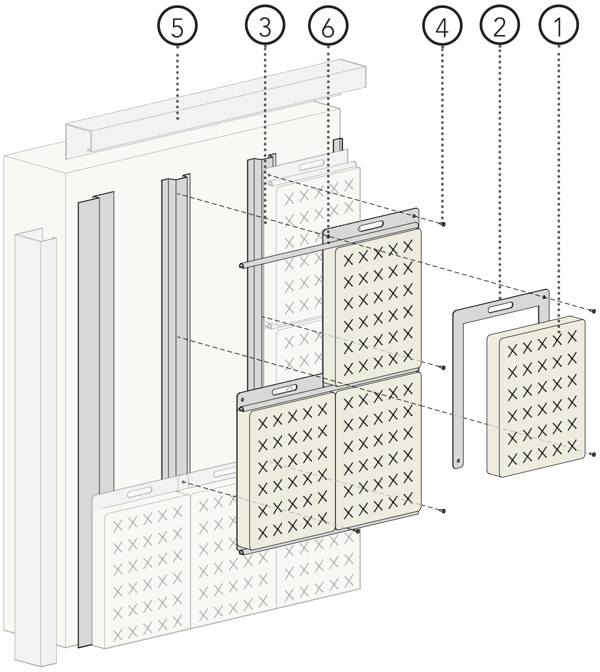


Component:	Material:	Technique:
1) Panel frame box	1) polypropylene compound (from recycled polymer)	1) Co-injection moulding
2) Substrate growing medium	2) Stonewool (high alumina, low silica wool)	2) Melting with iron ore slag and spinning, coating forming
3) Capillary break	3) HDPE, PP, PE/EVA	3) Plastic extrusion
4) 'T' profile rail	4) Aluminium	4) Metal extrusion, anodised, powder coated, mill finish
5) Drainage layer	5) HDPE, geotextile filter	5) Woven
6) Waterproof Backing board	6) Cement bonded particle board (wood chips, Portland cement, additives and water)	6) Autoclave (bonding)
7) Structure	7) SS 'T' profile	7) Laser cut, CNC bending
Fixings	Rail & cam-lock, screws	Extrusion, heading machining

Irrigation type: Hydroponic system

Current Living Wall Types:

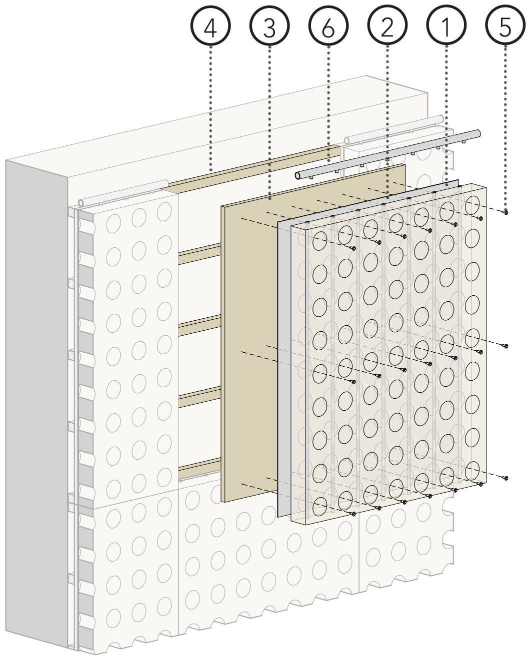
Framed boxes:



Component:	Material:	Technique:
1) Substrate panel with cross-openings	1) Synthetic compressed mat	1) Polymerisation
2) Support panel	2) (Thermoplastic Polyolefins (TPOs) - polypropylene based	2) Injection moulding
3) Structure	3) Stainless steel omega profiles	3) Laser cut, CNC bending
4) Fixings	4) Dry bolts and screws, steel plates	4) Heading machining, melting, heating, casting. forming
5) Edge	5) Aluminium	5) Metal extrusion, anodised, powder coated, mill finish
6) Irrigation tubing	6) Plastic (PVC or polyethylene)	6) Extrusion

Irrigation type: Intelligent irrigation drip-line (remote control monitoring)

Panel System:

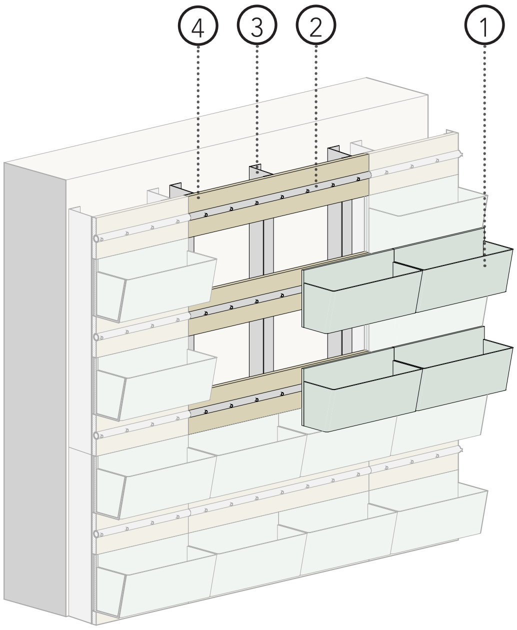


Component:	Material:	Technique:
1) Modular panel substrate with holes	1) Organic (cork & either sphagnum moss or soil around plants) or inorganic (plastic pots placed in holes)	1) Mould, heat-pressed. plastic pots: injection moulded
2) Waterproof back layer - Cloth to transfer water	2) Expanded PVC - polyester & polyamide	2) Polymerisation - woven
3) Barrier board	3) Plywood or PVC foam board	3) Sawmill or polymerisation
4) Structure	4) Treated timber	4) Sawing, staining
5) Fixings	5) Spax screws, galvanised zinc washers	5) Heading machining, hot-dip galvanising
6) Irrigation tubing	6) Plastic (PVC or polyethylene)	6) Extrusion

Irrigation type: Hydroponic system either with centralised timer system or recirculating with pump

Current Living Wall Types:

Carrier System:



Component:	Material:	Technique:
1) Planter/troughs - Substrate	1) 100% recycled polymer plastic - Organic (soil)	1) Co-injection moulding
2) Hollow rail for irrigation conduit	2) Anodized stainless steel	2) Extrusion
3) Structure	3) Stainless steel furring strips	3) Laser cut, CNC bending
4) Support backing	4) Treated timber or metal or plastic	4) Sawing, staining or CNC bending or extrusion
Fixings	Stainless steel screws	Heading machining
Irrigation tubing	Plastic (PVC or polyethylene)	Extrusion

Irrigation type: Drip irrigation tubing with flush valve system to equalise water flow

Living Wall Component	Material name & plant	Accessibility (Netherlands)
Support Structure, Fixings	Timber (larch being optimal, pine or spruce)	Grown widely in Europe, large timber industry, processes in place
Support Structure, Fixings, Tubing	Bamboo	Now cultivated in Europe but mostly imported. Grown best in tropical and subtropical regions in South America, Asia and Africa. An abundance in natural forest but also in plantations in China.
Support Structure/ Backing board	Board from agricultural residues - straw or reeds	Transport CO2 measures are not significant in comparison to other savings (produced in Europe: - -0,984 Co2/Kg compared to produces in Asia plus transport is -0,618 + -0,367 = -0,985 CO2/Kg)
Substrate	Hemp (panel, or textile)	Netherlands is one of the main producers
Substrate	Flax straw (Flaxseed plant) Insulating rolls, panels (boards & sheets), fleece (felts), strips, shives & infill	Available in the Netherlands
Substrate	Miscanthus (Insulation, composite materials, fiberboard, miscanthus biocomposites.)	Native to Africa, Eurasia & Pacific Islands, similar properties to reed & bamboo, grows in diverse conditions, high biomass yields, needs very little fertilisation. Grown particularly in the UK. Available for import. There is already efforts being made to link South Africa's miscanthus industry to the Netherlands.
Substrate	Straw (dry stalks from wheat, rice barley, oats, rye, hemp etc.)	Abundant in the Netherlands
Substrate	Sphagnum moss (moss)	Abundant
Substrate	Eelgrass	Abundant in the northern hemisphere. Eelgrass still grows in the Netherlands but in diminished amounts after the afsluitdijk in 1930s dammed off the Wadden Sea.
Substrate	Wood fibres (eg. pine & spruce)	Grown widely in Europe, large timber industry, processes in place
Substrate	Rice husk bioplastic carrier	90% grown in Asia but also in parts of Europe. There is so much of it in abundance.
Substrate, Waterproof layer	Coconut board (coconut husks) or coconut baskets/ pots with coir liner	Native to Africa, Eurasia & Pacific Islands, similar properties to reed & bamboo, grows in diverse conditions, high biomass yields, needs very little fertilisation. Coconut producing countries: Sri Lanka, India, the Philippines (15 million tonnes per year, 5 million tonnes of husk are discarded or burnt), Indonesia
Substrate Waterproof layer	Cork (carbonised, expanded & board) (bark of the cork oak tree)	Portugal & Spain. Or recycled cork. Needs to be used sparingly.
Substrate Connections	Manila hemp (from the leaf sheath around the trunk of the abaca plant) - textile or board or rope	Native to the Philippine Islands, Russia, Central America and Australia
Substrate Connections	Sisal (leaf fibre) for geotextile or rope	Angola, Brazil, China, Cuba, Haiti, Indonesia, Kenya, Madagascar, Mozambique, Mexico, South Africa. Tanzania and Thailand. In sur[plus (estimated 300 000 tonnes world wide)
Adhesive for substrate	Mycelium based composite (mushrooms)	99 mushroom farms in the Netherlands
Support Structure, Waterproof layer, Tubing, Connections	Bioplastic (sugarcane)	Grown in warm, temperate tropical regions (India, Southeast Asia) in abundance. Importing is an option.
Support Structure, Waterproof layer, Tubing, Connections	Bioplastic (potato starch)	Grown widely in the world including the Netherlands, Germany, Poland & France
Support Structure, Waterproof layer, Tubing, Connections	Bioplastic (cellulose from trees & straw)	"Trees: Grown widely in Europe, large timber industry, processes in place Straw: Abundant in the Netherlands"
Waterproof layer	Waterproof membrane from vegetable oils & resin	Product of Utrecht, Netherlands

erial Catalogue

Growth time (plant)	Waste as a resource
60 - 80 years	The whole tree can be completely used. Compostable & recyclable if non-chemically treated. Reusable.
60 days	Compostable & recyclable if non-chemically treated. Reusable.
Varying depending on crop 4 - 8 months	Agricultural residues. 95% biobased. Reprocessable.
3 - 4 months	Whole plant can be used. Compostable if binded by natural resins, mycelium etc. Does not rot or degrade over time - 100% recyclable
1 to 3 months after flowering, 2 weeks after seed capsule forms	Compostable & 100% recyclable.
3 - 5 months (can be cultivated for 10 - 22 years) Lifespan with annual harvest 15 – 20 years	Compostable if bound by natural resins, mycelium etc. 100% recyclable.
Varying depending on crop 4 - 8 months	Waste by-product: compostable, recyclable & reusable
8 - 22 years to regrow after harvesting	Dried & processed new growth of moss. Compostable. Not recyclable as it has a short life-span.
Grows around 2-5m each year. Can regrow in as little as 10 days	Eelgrass is compostable and very good as fertilizer for potatoes if binded by natural measures. 100% recyclable.
Depending on source. Pine (25 - 40 years)	When uncoated can be composted. Can be from pre-consumer wood waste (by-product). 100% recyclable.
3.5 - 5 months	Waste by-product from rice (coating of grain), compostable, recyclable but also 100% biodegradable
Lifespan of 60 - 100 years. up to 150 nuts per year.	Coconut is used in its entirety. Compostable. 100% recyclable No glue required. Low crystallinity (more biodegradable)
Tree needs to be 25+ years and then harvested every 9-12 years for on average 150 years	Needs minimal support. Impermeable so takes longer but can grind it up to help the process along and add 'green' materials like fibres and kitchen waste. 100% recyclable
18 - 24 months (2 - 3 plant stalks are ready) & 4-6 months after (2-4 stalks are ready)	100% recyclable
Harvested after 2 years from planting. It produces for up to 12 years, (180 to 240 leaves) 1 - 4 tonnes per hector	High crystallinity (less biodegradability). It's waste an generate bio-energy, be used as animal feed or fertiliser.
Variable 2 - 3 weeks for mushrooms	No waste (method to reducing agricultural waste fibres & stalks) by establishing a new use. Excellent compostability. Potential to be reusable as organic fertiliser
9 - 24 months depending on climate (needs rain)	At end of useful life aided by fungi, bacteria and enzymes to compost. Takes time to compost if not directly assisted. 100% recyclable.
60 - 80 days	At end of useful life aided by fungi, bacteria and enzymes to compost. Takes time to compost if not directly assisted. 100% recyclable.
Trees: Varying depending on tree (25+ years) Straw: Varying depending on crop 4 - 8 months	At end of useful life aided by fungi, bacteria and enzymes to compost. Takes time to compost if not directly assisted. 100% recyclable.
Unclear	Cradle to cradle (Silver). Uses oils from the vegetable oil industry and reintroduces it into the process of fabrication. 100% recyclable but not entirely biodegradable.

Living Wall Component	Material name & plant	Natural Aesthetic	Detachability
Support Structure, Fixings	Timber (larch being optimal, pine or spruce)	Yes. Depends on species.	With dry joints
Support Structure, Fixings, Tubing	Bamboo	Yes. Round, segmented, jointed, hollow, light yellowish brown	With dry joints
Support Structure/ Backing board	Board from agricultural residues - straw or reeds	Yes. Smooth but looks textural, resembles processed chipboard	With dry joints
Substrate	Hemp (panel, or textile)	Yes. Light brown, shiny, slightly course and thicker than flax	Modular panels or textile for pockets
Substrate	Flax straw (Flaxseed plant) Insulating rolls, panels (boards & sheets), fleece (felts), strips, shives & infill	Yes. Slender, colour ranges from buff to grey (best quality when creamy white)	Modular panels
Substrate	Miscanthus (Insulation, composite materials, fiberboard, miscanthus biocomposites.)	Yes. Fibrous, similar to straw	Modular panels
Substrate	Straw (dry stalks from wheat, rice barley, oats, rye, hemp etc.)	Yes. Light yellowy orange, shiny, course	Modular panels
Substrate	Sphagnum moss (moss)	Yes. Shades of green, grey or brown, fluffy	Loose material than can decompose or be removed
Substrate	Eelgrass	Yes. Often described as shaggy or ugly by individuals, the appearance of thatched eelgrass is very organic and natural looking	Eelgrass thatch is able to be disassembled and stripped from the main structure. A modular construction is possible under the right conditions and with the right craftsmen. It is possible to repair and replace sections of eelgrass thatch as needed.
Substrate	Wood fibres (eg. pine & spruce)	Yes. Varying colour according to species, usually mixed	Modular panels
Substrate	Rice husk bioplastic carrier	No. Slightly see through with fibres but still resembles plastic	Can be moulded into any form for detachability
Substrate, Waterproof layer	Coconut board (coconut husks) or coconut baskets/ pots with coir liner	Yes. Thin, yellow-brown	Modular panels or baskets/pots with coir liner
Substrate Waterproof layer	Cork (carbonised, expanded & board) (bark of the cork oak tree)	Yes. Cellular structure with pentagonal or hexagonal shaped cells of different shades of brown	Modular panels, dense board but plant roots can penetrate only into tiny gaps
Substrate Connections	Manila hemp (from the leaf sheath around the trunk of the abacá, plant) - textile or board or rope	Yes. Fine, matte, light beige.	Modular panels or textile for pockets
Substrate Connections	Sisal (leaf fibre) for geotextile or rope	Yes. Smooth, straight and yellow.	Modular panels or textile for pockets
Adhesive for substrate	Mycelium based composite (mushrooms)	Yes. Fibrous, white fluffy-looking	N/A
Support Structure, Waterproof layer, Tubing, Connections	Bioplastic (sugarcane)	No. Closely resembles petroleum based plastics	Can be moulded into any form for detachability
Support Structure, Waterproof layer, Tubing, Connections	Bioplastic (potato starch)	No. Closely resembles petroleum based plastics	Can be moulded into any form for detachability
Support Structure, Waterproof layer, Tubing, Connections	Bioplastic (cellulose from trees & straw)	No. Closely resembles petroleum based plastics	Can be moulded into any form for detachability
Waterproof layer	Waterproof membrane from vegetable oils & resin	No. White in colour, reflective and synthetic looking	Should not be pierced (loses waterproof integrity) therefore requires overlapping (a challenge with dry joints) or would require wet joints

erial Catalogue

Lifespan	Water & humidity resistance
With treatment: 40 - 100 years Without treatment: 10 - 60 years	Low permeability high density (larch) Cannot contact ground (deterioration by fungi) withstands wetting with drying
With treatment: 50+ years Without treatment: 10 - 12 years"	More water resistant & resilient than hardwood
Mainly suitable for domestic interior conditions (but alternative to plywood)	Moisture resistant (but suitable for humid indoors)
Textile: 20 - 30 years	Acceptable resistance to water
If protected it has a low degradability but a higher lifespan	Resistant against moisture & mould (cannot be permanently wet or will decay)
High lignin content therefore among the most durable natural fibres	Naturally water resistant with low moisture uptake
If protected it has a low degradability but a higher lifespan	Moisture content to be kept below 14% by weight
It fragments, compacts & properties change as it ages (faster process when kept wet) therefore fungi and bacteria break down the cells (8, 12, 16 months)	N/A
If plants die in the sea-grass and are not removed, they will begin to rot away the construction. Eelgrass must be periodically replaced to prevent this from happening.	Naturally water resistant
20 - 30 years	Depends on product and treatment but can be waterproof.
Very biodegradable	Dissolves in water
High lignin content (35%) therefore among the most durable natural fibres	Naturally water resistant with low moisture uptake
50+ years	Suberin and ceroids contained in the cork cell walls, impermeable to liquids and gases making them resistant to moisture which enable them to age without deteriorating
High lignin content (15%) At least 10 years	Shrinks when wet so becomes tighter and stronger in a way
10% lignin content.	Not waterproof and absorbs water therefore needs to be protected or dried often
Unknown. One source says 20 years.	Requires waterproofing
Manufactured to last long	Waterproof
Manufactured to last long	Waterproof
Manufactured to last long	Waterproof
45 years	Water & humidity resistance

Timber (larch)

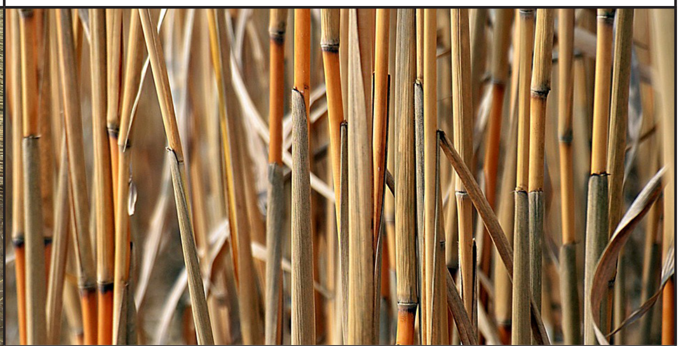
Bamboo

Board from agricultural residues - straw or reeds

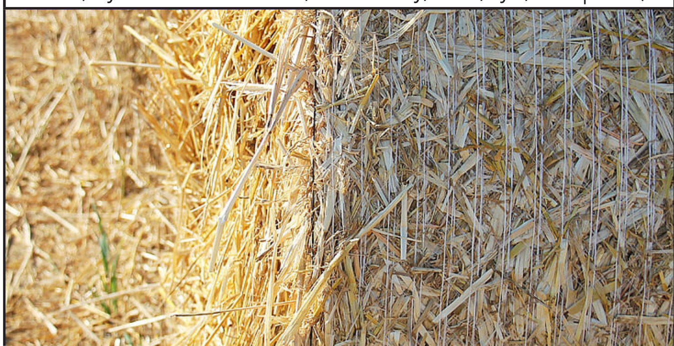
Hemp

Flax straw

Miscanthus



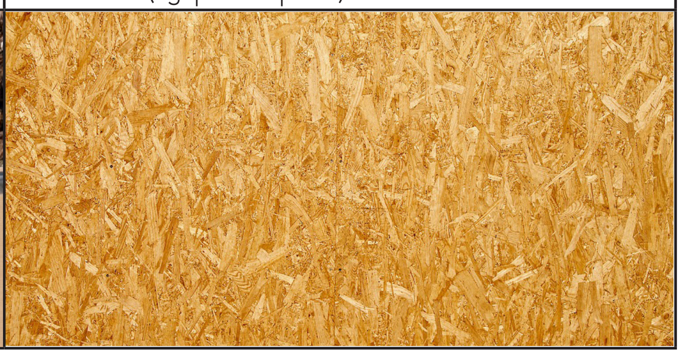
Straw (dry stalks from wheat, rice barley, oats, rye, hemp etc.)



Sphagnum moss (moss)

Eelgrass

Wood fibres (eg. pine & spruce)



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Rice husk bioplastic carrier

Coconut

Cork

Manila hemp

Sisal

Mycelium based composite (mushrooms)

Bioplastic (sugarcane)

Bioplastic (potato starch)

Bioplastic (cellulose from trees & straw)

Waterproof membrane from vegetable oils & resin

Living Wall Component	Material name & plant	Making process & energy
Support Structure, Fixings	Timber (larch being optimal, pine or spruce)	Sawing, drying, milling, treating, machining: CNC milling, wood routing, finishing, mechanical assembly
Support Structure, Fixings, Tubing	Bamboo	Harvesting (drying), cutting
Support Structure/ Backing board	Board from agricultural residues - straw or reeds	Negative Carbon Footprint
Substrate	Hemp (panel, or textile)	Fibres are brought together by mycelium or natural adhesive such as lignin.
Substrate	Flax straw (Flaxseed plant) Insulating rolls, panels (boards & sheets), fleece (felts), strips, shives & infill	Fibres are brought together by mycelium or natural adhesive such as lignin.
Substrate	Miscanthus (Insulation, composite materials, fiberboard, miscanthus biocomposites.)	Binderless fiberboard: Steam explosion of miscanthus, hot press (with lignin as adhesive), some studies with addition of lignin for better binding
Substrate	Straw (dry stalks from wheat, rice barley, oats, rye, hemp etc.)	Straw baling, forming via compression within a frame
Substrate	Sphagnum moss (moss)	No process. Used as is.
Substrate	Eelgrass	Low energy manufacturing when utilizing local eelgrass can simply combine by mixing with water, casein glue or bone glue.
Substrate	Wood fibres (eg. pine & spruce)	The wood fibres are soaked in water producing pulp. Pulp is fed onto a moving wire mesh conveyor (a forming box) as a continuous fibre matt where the excess water is removed by suction (vacuum pumping) and pressure (light rolling) which causes the fibers to felt together.
Substrate	Rice husk bioplastic carrier	Firstly the rice husk is attained and sieved to assure quality then it is dried. Secondly the base bio-polymers & natural additives are mixed and fed through a main feeder & then the dried husk is fed through the side feeder into the compounder. The pellets are formed and put into the injection moulding process
Substrate, Waterproof layer	Coconut board (coconut husks) or coconut baskets/ pots with coir liner	Fibres are separated and flesh contains lignin: suitable as adhesive for coconut fibres
Substrate Waterproof layer	Cork (carbonised, expanded & board) (bark of the cork oak tree)	Harvesting (barking, drying), crushing, moulding gluing, heat processing (300°C), forming, cutting.
Substrate Connections	Manila hemp (from the leaf sheath around the trunk of the **abacá** plant) - textile or board or rope	Harvesting is labour intensive: the stalk is cut into strips and the pulp removed by scraping, washed and dried. Fibres are brought together by mycelium or natural adhesive such as lignin.
Substrate Connections	Sisal (leaf fibre) for geotextile or rope	Harvesting: fibres are removed quickly from in the leaves by scraping away the pulp (mechanical decortication or hand stripping). Fibres and natural resin are combined in a hot compression moulding machine (85°C)
Adhesive for substrate	Mycelium based composite (mushrooms)	Moulds needed (but can be machined to use for a lengthy period of time) no energy required just the natural growth of mycelium to create a composite
Support Structure, Waterproof layer, Tubing, Connections	Bioplastic (sugarcane)	Biotechnology: The process is a biological transformation from feedstock to monomers and then an enzymatic polymerissation (with lignin and cellulose) to produce co-polymers. Low energy consumption. Processing: injection moulding, sheet extrusion for thermoforming and vacuum forming, blown film, lamination, extrusion coating and mono-filaments.
Support Structure, Waterproof layer, Tubing, Connections	Bioplastic (potato starch)	Same as above
Support Structure, Waterproof layer, Tubing, Connections	Bioplastic (cellulose from trees & straw)	Same as above
Waterproof layer	Waterproof membrane from vegetable oils & resin	Vegetable oil from the vegetable oil industry is processed like petroleum would be so there is still a lot of machining involved.

erial Catalogue

Prefab potential	Light weight	Cost (now or future potential)
Yes	Yes (compared to structural steel & concrete)	Cheaper than steel for construction Larch cladding (58€/m²)
Yes	Lightweight	3 times cheaper than steel
Yes	High strength to weight ratio	Fluctuates but generally lower than for example plywood
Yes	9.6kg/m² (panels) 7.2kg/m² (rolls)	3.69-5.88€/kg 3.88 - 33.66€/m²
Yes	4.73kg/m²	2.64 - 5.40€/kg 4.97-16.71€/m² (40-140mm)
Yes	50–130 kg/m3 (13.6-25.7m²)	Feasible in the future.
Yes	128.70kg/m²	Cheap 0.05 - 1.83€/kg 2.74-24.40€/m²
Yes	Lightweight	Cheap: 0.60 Euros for a litre
Yes	You need a thick eelgrass construction to have a successful construction	40kg of building quality eelgrass is 300 Euros. The challenge comes from the labour costs associated with assembling this material. Only a few people in the world know how to thatch with eelgrass.
Yes	9kg/m²	1.46 - 3.74 €/kg 5.13 - 52.40€/m² Geotextile: 0.49 - 0.97€/m²
Yes	Lightweight	Unknown but more expensive than fossil fuel plastics
Yes	Lightweight 400 - 900 g/m²	Inexpensive, source of income for farmers in developing countries (also countries within the Netherlands union) 0,80 - 1.95€/m²
Yes	Lightweight (19,44kg/m²)	Price is expensive because of harvesting limitations: 2.4 - 12 EUR/kg 6.25 - 66.10€/m²
Yes	Lightweight (800g/m² of a thin fabric)	Feasible in the future.
Yes	Lightweight 1000 g/m²	Growing in non-traditional markets as a valuable and diverse resource
Yes, good	Lightweight, 60 - 360 Kg/m3	Slightly higher price to synthetic competitors but potential to invest in scaling up to enable a lower price. 1000,- - 100,- /m3
Yes	Lightweight	2 to 3 times more expensive (will change when demand changes and the produce higher yields)
Yes	Lightweight	2 to 3 times more expensive (will change when demand changes and the produce higher yields)
Yes	Lightweight	2 to 3 times more expensive (will change when demand changes and the produce higher yields)
Yes	34 kg per roll (10m x 1m (3mm thick)) Much thicker than EPDM	Unknown

Plant Material Name	**Acoustic** (alpha w (αw) of 0.70-0.90 between 500-2000Hz)	**Insulation** (The lower the W/mK (U-value) the better)	**Air Quality**	**Fire resis**
Waterproof membrane from vegetable oils & resin	Poor	Temperature lowered by minimum of 5°C in summer	Halogen free	Class B
Mycelium based composite (mushrooms)	High acoustic absorption. 0,6 - 0,9 absorption coefficient, 20 - 30 Rw (dB) at 7 centimeter thickness	Variable according to density - higher density = higher thermal conductivity. 0,040 – 0,060 W/m.K	Non-toxic	Flame ex chitin Fire Clas
Cork	Good sound absorption & reduction (39 - 56 dB) 0.8 αw @ 500Hz	0.038 - 0.070 W/m.K	Non-toxic	Non-flam self-extin combust
Board from agricultural residues - straw or reeds	N/A	Properties close to foamed plastics. 0.065 Lambda Ω(m*K)	No Formaldehyde or chemical emissions	120 min
Timber	N/A	Much better than other materials such as glass, marble, metal and concrete.	Depends on treatment	Usually t
Bamboo	Fibre equivalent to glasswool	Much better than other materials such as glass, marble, metal and concrete.	Depends on treatment	Naturally
Sphagnum moss	N/A	N/A	Non-toxic	Flammab
Coconut	Good 0.95 αw @ 1600Hz	Good	Non-toxic	Compara medium Class 4.1
Hemp	0.65 αw @ 500Hz	0,039 - 0,048 W/m K	Non-toxic	Flammab behaviou resistanc
Flax straw	(Good) Can absorb vibrations 0.95 αw @ 500Hz, 37-39 dB	7°C lower in summer & 16°C higher in winter	Non-toxic	Flammab behaviou
Manila hemp	Good 0.95 αw @ 1600Hz	Good	Non-toxic	Moderat
Miscanthus	Good	0.157 W/m.K	Non-toxic	Euroclass
Sisal (leaf fibre) for geotextile or rope	0.95 αw @ 1600Hz	0.042 W/m.K	UG or equivalent (R and D from Madagascar) and SSUG	Flammab
Straw	(Good) Can absorb vibrations	Good insulating thermal properties. 0,050 - 0,100 W/mK	Non-toxic	Loose st flammab resistant not aerat
Eelgrass	Dampens acoustics	Good	Non-toxic	Naturally on fire b acts as a
Bioplastic (sugarcane)	N/A	N/A	Similarly toxic to conventional plastics, they most often contain some toxic chemicals.	No. Nee
Bioplastic (potato starch)	N/A	N/A	Similarly toxic to conventional plastics, they most often contain some toxic chemicals.	No. Nee
Bioplastic (cellulose from trees & straw)	N/A	N/A	Similarly toxic to conventional plastics, they most often contain some toxic chemicals.	No. Nee
Wood fibres (eg. pine & spruce)	Fibre equivalent to glasswool 7.64 - 16.49 dB	0.3w/m2k U-value (120mm)	Non-toxic	Class E. (spread o

talogue | Performance

stance	**Tensile Strength** (kN/m)	**Elongation at break %** (higher elongation at break required)	**Moisture retention for plants' roots**	**Performance Score (ave.)**
	N/A	N/A	N/A	**4**
tinguishing property - s C or D	N/A	N/A	N/A	**4**
mable, fire retardant, guishing, slow ibility	N/A	N/A	Moisture resistant	**3.75**
fire rating	N/A (7.8 N/mm)	N/A	Water absorption 2 hour (3.1%)	**3.67**
reated	N/A	N/A	N/A	**3.33**
because of silica	N/A	N/A	N/A	**3.33**
ble	N/A	N/A	Retains moisture in potted plants, allows airflow to prevent root rot	**3.33**
able to or better than density fibreboard (MDF) (flammable solid)	7.66 - 8.76kN/m	high extension at break (ratio between changed length and initial length after breakage) (41 - 45%)	Moisture regain at 20 °C 10%	**3.29**
ble material / Acceptable ir in fire / moderate fire e	N/A	N/A	Natural moisture control - the fibres absorb & release moisture in dry periods	**3.2**
ble material / Acceptable ir in fire	N/A	N/A	Water absorption: 20 – 40% (will decay if wet and not dried)	**3.2**
e fire resistance	7kN/m	2.6 - 2.8 %	Moisture 20%	**3.14**
s E	6.5 - 8.4kN/m	2.8 - 4.8 %	Moisture 7%	**3.14**
ble especially if thin	5.2 - 6.8kN/m	1.9 - 4.5 %	Moisture regain at 20 °C 11–14%	**3.14**
raw is extremely le. Non-flammable & fire (when compacted and ted)	N/A	N/A	Can retain water & therefore mould	**3**
fire resistant (it will catch ut not flame, as the salt natural fire retardant)	N/A	N/A	Moisture resistant	**3**
ds chemical additives.	N/A	N/A	N/A	**2.5**
ds chemical additives.	N/A	N/A	N/A	**2.5**
ds chemical additives.	N/A	N/A	N/A	**2.5**
(Charing slows down the f fire)	N/A	N/A	Can allow water vapour to pass through	**2.4**

Living Wall Component	Material name	New biobased materials	Natural Aesthetic	Waste as a resource
	Relevance Ranking:	*4*	*3*	*3*
Substrate Waterproof layer	Coconut	12	12	12
Substrate	Hemp	16	12	12
Substrate	Miscanthus	14	12	12
Substrate	Flax straw	16	12	12
Support Structure, Fixings	Timber (larch being optimal, pine or spruce)	12	12	12
Substrate	Straw	16	12	12
Substrate Waterproof layer	Cork	10	12	12
Adhesive for substrate	Mycelium based composite (mushrooms)	16	9	12
Support Structure, Fixings, Tubing	Bamboo	10	12	12
Substrate	Wood fibres (eg. pine & spruce)	12	12	12
Substrate Connections	Manila hemp (leaf of abacá plant)	12	12	12
Substrate Connections	Sisal (leaf fibre)	12	12	12
Support Structure/ Backing board	Board from agricultural residues - straw or reeds	14	9	9
Substrate	Eelgrass	14	12	12
Substrate	Sphagnum moss	12	12	12
Support Structure, Waterproof layer, Tubing, Connections	Bioplastic (potato starch)	16	0	9
Support Structure, Waterproof layer, Tubing, Connections	Bioplastic (cellulose from trees & straw)	14	0	9
Support Structure, Waterproof layer, Tubing, Connections	Bioplastic (sugarcane)	12	0	9
Substrate	Rice husk bioplastic carrier	14	0	12
Waterproof layer	Waterproof membrane (vegetable oils & resin)	12	0	9

aterial Points

Detachability	External durability	Average Performance Score	Manufacturing process	Cost	Total Score with weighting: (/108)
4	*4*	*4*	*4*	*2*	
16	16	13,16	16	8	**105,16**
16	14	12,8	14	7	**103,8**
16	16	12,56	14	7	**103,56**
16	10	12,8	16	7	**101,8**
16	14	13,32	14	8	**101,32**
16	10	12	16	6	**100**
16	16	15	14	5	**100**
16	10	16	14	7	**100**
16	14	13,32	14	8	**99,32**
16	14	9,6	14	8	**97,6**
16	12	12,56	14	7	**97,56**
16	10	12,56	16	7	**97,56**
16	10	14,68	16	8	**96,68**
8	12	16	16	5	**95**
12	4	13,32	16	8	**89,32**
16	16	10	12	7	**86**
16	16	10	12	7	**84**
16	16	10	12	7	**82**
16	4	8	12	7	**73**
4	16	16	14	4	**75**

Subtractive processes:

Process	Methods	How it works	Advantages
Cutting	Laser cutting	A digital process which uses lasers (concentrated beams of coherent light (energy)) to cut through various materials including pieces that are fragile and fine.	- Precision, neat and quick - Thin, unnoticeable cut marks - Can cut through strong materials
Cutting	Utrasound cutting	A mechanical process with vibration, friction, and overheating to create local fusion. In this process welding and cutting happen at the same time.	- Fibres do not unravel after they are cut - Cheaper with no humidity
Cutting	Punching/ Piercing	A steel band is shaped to cut through material (like a cookie cutter) either with a manual or hydraulic press. The process is similar for punching but with a solid die punch for the cutting	- Allow for complex cutting forms, on malleable thin materials - Economical but only for one type of cut for one specific material. - A quick process
Machining	Drilling	A spiral tool that is only sharp vertically is rotated at a speed dependent on the material (slower for harder material) to make a hole by removing material. A coolant or lubricant is required to prevent overheating and distortions. The drill but is made from treated steel, tungsten carbide. The cylindrical holes can go all the way through or stop part of the way and threaded to get a screw.	
Machining	Milling	The endmill is the cutting tool. It moves horizontally and rotates and the material it is working on is also moving. In contrast to a drill it milling machines work in all directions to varying requirements.	- Produces accurate grooves, profiles, surface finishes and patterns. - One can mill finely to create engraving.
Machining	Routing	Like forming routing is a manufacturing process which is linear. It is only used for wood work to make grooves, mouldings and rebates. It has an arm that rotates creating the profile one requires by removing material. Fore example to make 'mortise and tenon' joints. It has tools and heads that can be changed. It can also be used for planing.	
Machining	Spark Erosion (injection moulds)	Removes loose edges after injection moulded	

* The text is taken largely from Materiology: The Creative Industry Guide to Materials and Technologies, Chapter 3: Processes

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Disadvantages	Biobased Material	Relevance to Living Walls	Notes & Source
	Timber, plastics (bio), paper & cardboard, textile	To get a correct and accurate form for the panels for example cutting holes from material	(Kula and Ternaux 2013, 262)
- Can be dangerous and requires specific protection when handling the machines	Fibrous materials, thermoplastic textiles, etc.	To shape fibrous materials if they are the substrate	(Kula and Ternaux 2013, 262)
- A minor flattening at the lip by the cut of the material may occur.	Paper, cardboard, and sheet plastics (bio), (textiles) Harder materials (timber)	To cut shape or make an opening for vegetation	(Kula and Ternaux 2013, 263)
	Almost all materials with the right tool (different drill bits & hole saws) Timber	To aid the fixing of elements	Machining: Precise, highly mechanised, sharp edges, flat surfaces, low dim tolerances (Kula and Ternaux 2013, 269)
	Timber	More for aesthetic finishings and details	Milling machines are currently mostly a digital process also know as caM (computer-aided Manufacture) automated machines. This in combination with several other machining processes, are under improvement and allow for complex 3D shapes. (Kula and Ternaux 2013, 269)
	Timber	To aid the fixing of elements or joints such as mortise and tenon	(Kula and Ternaux 2013, 270)
	Plastic (bio)	To finish off edges of bioplastics	(Kula and Ternaux 2013, 270)

Forming processes:

Process	Methods	How it works	Advantages
Cast moulding	Open mould Closed mould	A cavity is made from a model that resembles the inverse of the desired product's shape. The mould has a release agent to prevent sticking. Usually liquid matter that solidifies. The one side of piece in the mould is exposed to air. Similarly, this products can be casted but with moulds with two halves. The air escapes through vent when the matter is poured through a casting hole in the mould. The mould is opened and the drying process finishes solidifying in the air.	- Simple procedure - Economical - Can be done on a non-industrial scale
Resin moulding	Contact moulding Dry Compression moulding Vacuum or bag moulding	A negative mould is required to make the shape. Firstly there is a layer called a gelocoat then layers of textile or non woven fibres are impregnated with resins. The bubbles in the layers are removed by a vacuum or using rollers. Resin can be applied with a brush or spray gun. A Sheet Moulding Compound or Bulk Moulding Compound presses the resin/ fibre composites. It uses high temperatures for effective compression and impregnation with resin. This creates layers without only a positive mould and the substance to be moulded in a sealed plastic bag. Pressure is created by vacuuming and all bubbles are eliminated.	- Low initial outlay - Great mechanical strength - Flexibility of production (from unique pieces to small runs, to make small or large pieces)
Calendering	Plastic calendering	The plastic is heated and rolled through rollers (usually metal) to create a continuous sheet.	- High productivity - Can be applied to multi-layered products - Continuous thickness's
Injection	Plastic injection moulding Co-injection moulding (with e.g. recycled plastic)	With heat and friction in an injection screw, plastic granules are melted then injected at high temperature and pressure (500 - 1500 bars) into a mould that is close with the aid of motors and hydraulics. The mould contains an integrated cooling system to solidify the substance consistently as well as a strong clamping force. The mould is reused several times and has an angle of 2% to help remove the finished pieces.	- High work rates (in terms of production, injection moulding remains viable from 100,000 up to 1,000,000 pieces - Productivity - Complex forms - Precision
Extrusion	Plastic extrusion	Granules of thermoplastic are poured through a funnel called a hopper into a heated cylinder. The matter is pushed by an Archimedes screw to extrude it, compress it, soften it and homogenise it. Is profile can be formed into a pipe, rod or flat sheet with the help of die. The product is cooled as it comes out of the machine usually by means of a water bath. Finally a circular saw cuts them to their desired lengths.	- Economic production technique - Continuous productivity - Extrusion of many types of thermoplastics (flexible, rigid, expanded)
Rotational moulding	Thermoplastic rotational moulding	A liquid or fine powder is measured and poured into a steel or aluminium two-part mould that is welded together. The mould rotates around 2 axes to spread the matter equally inside and then put into an oven until the matter joins together. It is then cooled and removed	- Large pieces - Hollow bodies - Strong thickness's are possible - Small production runs are viable - Procedure is economical

* The text is taken largely from Materiology: The Creative Industry Guide to Materials and Technologies, Chapter 3: Processes

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Disadvantages	Biobased Material	Relevance to Living Walls	Notes
-Low production rates - Filling difficulties - Impossible to create thin pieces - Matter cannot be compressed highly in the mould	Plaster for casting plaster or resin and thermoset resin reinforced with fibres for casting resin and plaster.	To mould desirable bioplastic shapes	(Kula and Ternaux 2013, 299)
- Non recyclable - Does not offer high productivity - Badly-controlled thickness	Plastics (bio), wood, composites	To mould desirable bioplastic shapes	Thermoset resins for architectural decoration Structural elements (Kula and Ternaux 2013, 301)
- Matter becomes orientated	Plastics (bio), textiles	To make waterproof layers and coatings	(Kula and Ternaux 2013, 303)
- Large initial investment for the machines and moulds - Currently reserved for mass-production	Plastics (bio)	To form desirable bioplastic shapes for example pots/ troughs	(Kula and Ternaux 2013, 305)
- Not viable for thermoset (cannot be reheated) plastics - Not suited to small-scale production - Mediocre dimensional tolerances after direct extrusion - The matter becomes orientated	Plastics (bio)	To make a pipe or rod for tubing of the irrigation system	(Kula and Ternaux 2013, 309)
- Thickness's of pieces cannot be guaranteed - The inside surface is often poor - Slow production - Inferior mechanical properties compared to injected or blow-moulded pieces	Plastics (bio)	To make waterproof layers and coatings	Hollow pieces, either open or closed, are made in this way. (Kula and Ternaux 2013, 313)

Forming processes (continued):

Mycelium	Preparation Growth Finishing	First you mix the substrate with water. The mix is pasteurise or sterilise which is with heat, PH, vacuum and pressure. The fungus is inoculated then colonised in a controlled environment with the correct temperature and amount of oxygen. After this preparation phase comes the growth phase where the substrate and fungus is shaped in a mould until the desired form is achieved. Finally it is heated to ensure it is dry and no longer grows.	- 100% natural (no artificial adhesives)
Stitching	Non-woven (geotextiles)	In applications that require higher filtration capability & large widths. Fibres that are randomly directionally oriented and connected in a flat structure. This connection can be obtained by mechanical means (such as interlocking of the filaments by needles in the case of stitching), chemicals (the connection is made by bonding fibres using resins or emulsions) and thermal (the connection is made by partially melting fibres and achieved by the joint action of temperature and pressure exerted by two heated rollers)	- High absorbency of non-woven geotextiles promotes adhesion to road surfaces and flow resistance to water.
Weaving	Woven (geotextiles)	In applications that require lower filtration capability & smaller widths. Interlacing, usually at right angles, two filaments of several bundles of filaments or bands	- Requiring higher strength and structural stability than is obtainable with non-woven geotextiles

* The text is taken largely from Materiology: The Creative Industry Guide to Materials and Technologies, Chapter 3: Processes

- Better for interior use as exposure to elements causes degradation	Fibres & agricultural waste (straw, hemp, flax), cellulose, hemicellulose and lignin. Straw, Sawdust, cotton, hemp, flax, softwood, straw (loose, chopped, dust, pre-compressed, tow), woodchip & sawdust, sugarcane & casave roots, cotton, hemp (particles, mat, fibres), wood chips, Alaska birch & wheat bran	To combine fibres into a panel with 100% natural means	(Kula and Ternaux 2013, 313)
	Fibres	To combine textiles to make pockets	
	Fibres	To combine fibres to make geotextiles	

Additive processes:

Process	Methods	How it works	Advantages
Digital processes	Stereolith-ography	A computer aided process moves a laser beam with a mirror. It is directed onto a surface with a tank containing photosensitive resin (epoxyacrylate). When the beam makes contact with the resin there is local polymerisation. After the path solidifies the process begins again by a thickness of 0.07m. The designed object is thus created in layers and can be complex.	- Freedom of form - Simple to make a prototype or an object (without a mould)
Digital processes	3D printing	Also a process that works in layers but alternates between powder and glue by a thickness of 0.01m.	- Freedom of form - Simple to make a prototype or an object (without a mould) - Faster, scalable, more economical
Finishes	Paint	Paint consists of a blend of binder, pigments, additives & solvents. Binder: 10 to 40%. Polmer resin. Cohesion & resistant properties Pigments: 5 to 40%. Colour, metalic or organic Additives: 0 to 70%. Silica, chalk, kalin, talc& carbon: greater coverage, limit shrinkage & matt. When less than 5% are chemical agents: controls viscosity, anti-streaking, wetting agents, anti-rust, UV absorbers, insecticides, fungicides, flame retarders . Solvents: 15 to 30%. Volatile, water-based, white-spirit-based, make binder workable, viscosity, evaporate when dried (can be toxic)	Finishes in general: - Protection - Against humidity, mould - Decoration
Finishes	Varnish	Varnish helps make a protective envelope for wood to be more water-tight. When damaged or on impact this effects the protection efficiency.	
Finishes	Stains	Alkyd resins are impregnated into wood internally absorbed and changes the look of the wood slightly. This helps protect the wood from rotting, sun and moisture making it more durable.	- Stained pieces can be quickly and lightly sanded before recoating
Finishes	Coating	An external layer is added to the surface by calendering, scraping, immersion, or spraying with a plastic film. This makes textiles water-proof, stain-resistant, shiny, etc.	

Further processes:

Recycling	Chemical Mechanical Organic	Wastes are chemically treated in order to separate the various constituents. Wastes are treated mechanically by machines which may beat, pulp, grind or crush them. Suitable wastes are composted to produce fertiliser compost or fuel (biogas for example)	- Waste reduction - Preservation of natural resources - Alternative source of supply

* The text is taken largely from Materiology: The Creative Industry Guide to Materials and Technologies, Chapter 3: Processes

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Disadvantages	Biobased Material	Relevance to Living Walls	Notes
- Still slow (creation time is just about as long) - Price - Surfaces are not perfect - Limited materials	Plastics (bio)	To design print precise and integral bioplastic connnectors or prototypes	(Kula and Ternaux 2013, 317)
- Still slow (creation time is just about as long) - Price - Surfaces are not perfect - Limited materials - Grainier finish	Plastics (bio), fibres	To design print precise and integral bioplastic connnectors or prototypes	(Kula and Ternaux 2013, 318)
Finishes in general: - Often expensive - Surface needs to be treated (de-greased, sanding, sandblasting, shot-blasting, flaming, layer of primer) - Needs chemical compatibility - Hard to recycle	All	To make more durable (but not always naturally sourced from a plant therefore non-renewable)	(Kula and Ternaux 2013, 325)
- Varnished pieces need stripping before re-varnishing.	Timber, (and (bio) plastics)	To make more durable (but not always naturally sourced from a plant therefore non-renewable)	(Kula and Ternaux 2013, 326)
- Less efficient - Much less durable than classic varnish (as a rough guide, they last for about one year outside)	Timber	To make more durable (but not always naturally sourced from a plant therefore non-renewable)	(Kula and Ternaux 2013, 326)
	Textiles	To make more durable (but not always naturally sourced from a plant therefore non-renewable)	(Kula and Ternaux 2013, 327)

- Logistics (collection, sorting, etc.) - Profitability has to be assessed	All	To give the component another life	(Kula and Ternaux 2013, 331)

Detachability:

Process	Methods	How it works	Advantages
Assembly	Mechanical	Tangling, crossing, stacking (interlocking). Wedged, nailed, screwed, pegged, sewn. Complementary metallic elements (inserts, rings, brackets)	For all wood joints see pages 272, 274-5 of Materiology: The Creative Industry Guide to Materials and Technology: Edge-to-edge (Tongue & groove) End-to-end Scarf joints Tabs or dowels Crosspiece assembly (90degrees) Mortice & tenon Dovetail & dowel
Sewing	Slip stitch Zigzag stitch Overlock stitch	Two stitches on the front followed by one stitch on the back, this machine stitch is very solid and difficult to unpick. A machine stitch used on borders and edges to avoid unravelling. A stitch used to prevent unravelling at the borders and edges of fabric. Hems are often oversewn in this way.	
Tying	Rope	Braided fibres by spinning/twisting fibres into yarn then bunched into cords or strands then twisted into rope (laying)	

* The text is taken largely from Materiology: The Creative Industry Guide to Materials and Technologies, Chapter 3: Processes

Disadvantages	Biobased Material	Relevance to Living Walls	Notes
- Different for two pieces of the same material, compared to the assembly of two different materials because of different shrinkage rates - Splits or lack of durability in joint - Chemical compatibility & intrinsic sticking power	Timber	These methods can be used to put panel frames together and connect elements to their adjacent counterpart.	Delaminating, tearing, twisting must be analysed, largest possible surface of contact (Kula and Ternaux 2013, 273)
- Can be challenging to unpick	Plastics (bio) & textiles	A form of dry attachment for fabrics and textiles.	(Kula and Ternaux 2013, 289)
- Not great in water & humidity	Natural fibres: Manila (Abaca plant): 10 years Coir (coconut): 4 years durability Flax or hemp - 1-2 years Sisal - 142 days Cotton - 1 year Jute (bark of the white jute plant) - unknown years		