Wageningen University and Research Centre

# A feasibility study on the usage of cattail (*Typha spp.*) for the production of insulation materials and bio-adhesives

## Report

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# A feasibility study on the usage of cattail (*Typha spp*.) for the production of insulation materials and bio-adhesives

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# Abstract

Peat meadow areas in North Friesland face severe water management problems. Because of climate change, they will have to cope with periods of heavy rainfall, but also long dry periods. Additionally, current water management practices have led to dewatering and subsequent land subsidence. The Better Wetter project aims to search for alternative business models and link those with regional economic development. A proposed solution is the cultivation of cattail (Typha spp.) in low-lying flooded land areas for its use as raw material for insulation materials.

Exploration of the current research has shown a growing Dutch interest in usage of Cattail for insulation material in academic research, companies and organisations. In Germany and Austria, a market for cattail insulation has already successfully established. Market conditions require a small scale start of production to improve the knowledge on material characteristics and output volumes. When these requisites are met, several market partners will have concrete interest in purchasing the Cattail material. The research for the development of cattail-insulation materials should be designed towards the compliance of different technical standards specific to the intended market of the product. Thermal conductivity, as well as other important parameters such as moisture absorption, ecological quality, and mould and fire resistances should also be considered. Cattail-based insulation materials can be promoted in the construction of BREEAM-certified buildings if specific conditions are met.

It is important to understand the cultivation practices for cattail in order to better understand how to increase the yield and quality of the final product. To achieve the best product as fast as possible, it is advised to transplant rhizomes for the production of cattail. Growing the plants in a low density showed to possibly increase the quality of the product, however this does have an impact on yield. The harvesting methods showed to be in a rather premature state at the moment and more research is needed to fully explore all the options.

For insulation materials, an experiment performed in collaboration with Bouwgroep Dijkstra Draisma revealed the potential of using cattail as blow-in material, as well as some issues that should be considered when using cattail for this application. Firstly, the moisture content should be checked as the material must be dry enough. Secondly, a cold or heat pre-treatment may be needed to avoid the outbreak of pests. Finally, special attention must be paid to the shredding and mixing processes. Production of particle boards with cattail material is also recommended as it has been proven the suitability of this plant for producing this type of insulation.

It was also shown that multiple components of cattail have potential in the production of bio-adhesives, particularly the rhizomes with their high concentration of starch and the leaves for lignin and cellulose. However, starch extraction is cumbersome and leaves are required for the insulation materials.

At the end of this report, the main conclusions are addressed, together with advice for further development of cattail-based insulation materials.

# Table of Contents

# 1. Background

## 1.1 Water management

Current water management practices in the agricultural sector of the Netherlands have resulted in highly productive soils. Specifically, a region of major importance for water management is North-East Friesland with its rural and (wet) peat meadow areas. Unfortunately, these peat meadow areas are facing severe problems. Agriculture on peat meadow areas is based on water drainage of the lands, which is needed for e.g. ploughing, sowing and harvesting. After these dewatering practices, $O_2$ can reach the soil and can convert (oxidize) the carbon from old plant remains into $CO_2$, which causes land subsidence. In the peat meadow areas in the Netherlands, this results in around 1-2 cm/year (Osinga et al., 2014; Wichtmann et al., 2016). Because of the land subsidence, the soils have to be dewatered again. This management practice is currently reaching its limits, since North-East Friesland is one of the lowest regions in the Netherlands (Figure 1). Additionally, the emission of $CO_2$ from dewatered soils is harmful to the environment. Peat soils are only 10% of the agricultural soils in the Netherlands, but they produce over 50% of the greenhouse gases from soils. One hectare of dewatered peat soil emits 20-25 ton $CO_2$-equivalents yearly. This equals driving 3 rounds around the world with a car (Fritz, et al., 2014).

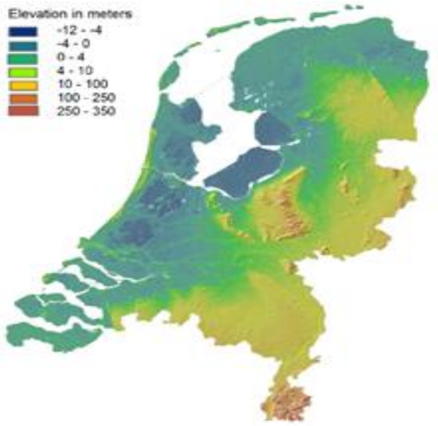


Figure 1. Elevation map of the Netherlands in meters (Rijkswaterstaat, 2013).

Another water management problem that the region of North-East Friesland faces is water storage. Due to its location the region has to store a lot of water during heavy rainfall. On the other hand, there are still regular dry periods in spring and summer causing water shortage. Climate change is worsening the problems by rising temperatures and heavier rainfalls (Osinga et al., 2014).

## 1.2 Paludiculture

The abovementioned issues cause a loss of agricultural and economic value of these lands as fewer crops can sustain these new conditions. A proposed solution to the problem of further land subsidence is elevation of the water level. This solution would drastically reduce the emission of greenhouse gasses. The grey area in Figure 2 indicates a water level of -20 cm to a little bit above surface level would result in the lowest emission. The wet cultivation on peat areas is called paludiculture ("palus," Latin for "swamp"). It was developed in the 1990s in Germany and enables an (economic) sustainable use of previously degraded, but now rewetted peatlands (Wichtmann et al., 2016).

In North-East Friesland, a program was set up called "Better Wetter". This program tries to link the culture of marsh plants with regional economic development to create new business models. The program is a cooperation between the agricultural sector, local governments, entrepreneurs, and education systems. These parties work on finding solutions for a better water management, to retain the peat meadow areas, and for finding sustainable uses for these lands in the future.

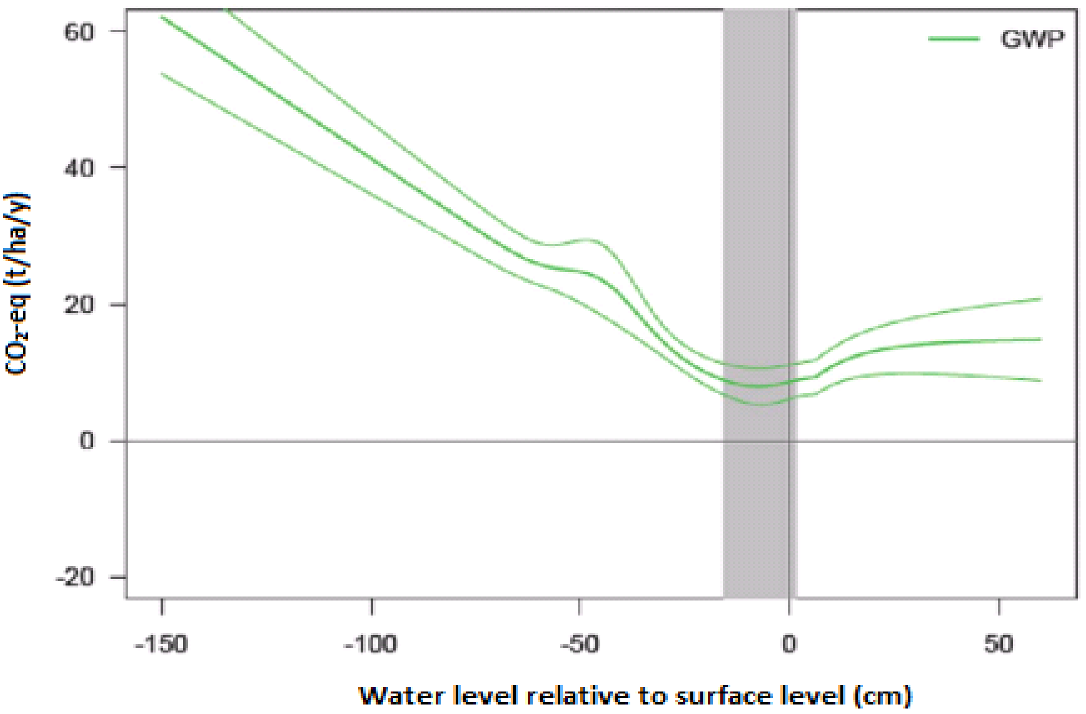


Figure 2. Greenhouse gas emissions in peat soils (in ton $CO_2$-eq/ha/year) at different water levels (Wichtmann et al., 2016).

## 1.3 Cattail

One of the promising plants for paludiculture is the marsh plant cattail (*Typha spp.)* (Abel et al., 2013). Therefore, cattail has been proposed as wet crop for cultivation peatlands in the North-East of Friesland (ACT, 2015). Cattail is a monocotyledonous, hydrophilic crop that can grow on high water levels. Cattail has long and big leaves and its flowering time is from June to July. It grows from seeds that are stored in its seedheads, while it can also grow from a rhizome that survives in the soil during winter (Figure 3). After maturing the seedheads become a fluffy cluster of wind-dispersible seeds. Cattail's height is around 1 to 3 meters, but it can also grow up to 4 meters (Soortenbank, 2017). Cattail grows at a high density, especially the narrowleaf cattail (*T. angustifolia*), which grows up to 20 shoots per $m^2$ (Krus et al., 2014), and the southern cattail (*T. domingensis*), which has been found to reach up to 140 shoots per $m^2$ (Glenn et al., 1995). Biomass production is around 5-15 ton dry weight (DW)/ha/year (Wichtmann et al., 2016). Once planted, cattail grows as ongoing culture and the aboveground parts can be harvested each year. This will be further addressed in chapter 3. Because of its dense canopy and fast growing period the crop is often a dominant competitor in wetland areas (Keddy, 2010). These characteristics make it an excellent crop for wet cultivation on (purposely flooded) peatlands (Wichtmann et al., 2016). Cattail grows in wet peatlands and marshes throughout most of the world, and therefore has developed a natural high resistance to moulds (Krus, 2013).

Cattail has a high nutrient removal ability of phosphorous and nitrogen. Therefore it can be excellently used in the first stage of a transition of dairy farming in peatlands towards wet agriculture (Figure 4). After wetting the soil by raising the water levels, many stored nutrients from the soil will be released into the water. In a first stage, cattail cultivation can be used to remove the nutrients by harvesting cattail biomass. With little nutrients left, a next phase could be sphagnum cultivation (Riet et al., 2014).

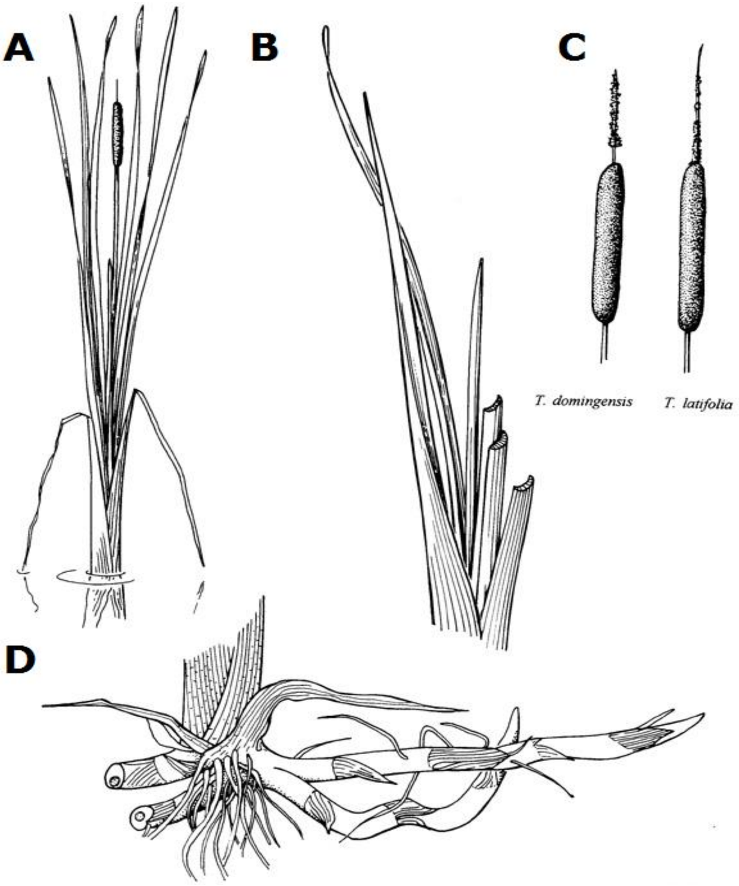


Figure 3. Schematic representation of different parts of cattail (*Typha spp.*). Where A shows the whole plant, B the leaf blades, C different seedheads with on the left *T. domingensis* and on the right *T. latifolia*, and D the roots and rhizomes (adapted from IFAS, 1990).

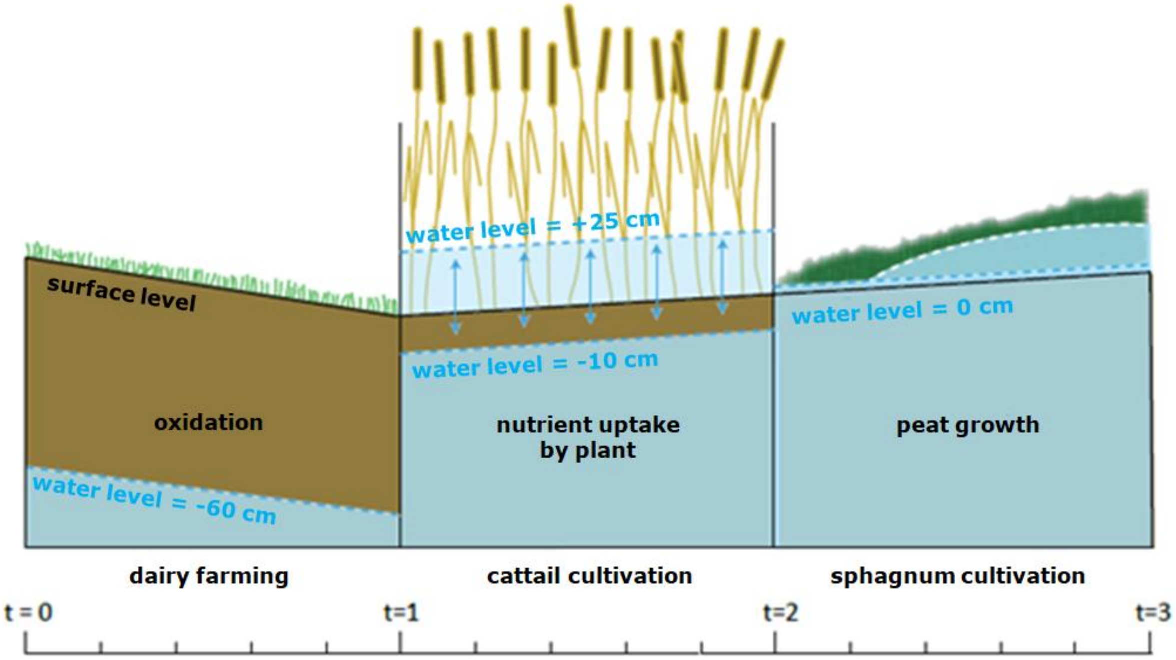


Figure 4. Schematic overview of a possible transition strategy from dairy farming in peatlands towards paludiculture (adapted from Riet et al., 2014).

Traditional applications of cattail range from thatch production, paper production, and weaving (Schwemmer, 2010). In China, cattail pollen are being used for medicinal tea (Geurts, personal communication, 2017). Several ecological and agronomical uses for this crop are being considered, for example using the crop for bioenergy, as it has an excellent heat value that is comparable to that of commercial wood (Grosshans, 2014). Using cattail for bio-energy production is mostly used in the U.S., Canada, Switzerland, and Italy (Geurts, personal communication, 2017). However, as of currently the most potential application seem to be the usage of cattail for insulation material. This application is being used mostly in Germany, Austria, and Switzerland (Geurts, personal communication, 2017). Cattail has a high potential for insulation material because it has a high amount of the "air space" tissue "aerenchyma" in its leaves and stem. This aerenchyma provides material with a low heat conduction and thus excellent insulation value. The high amount of aerenchyma is a primary adaptation of wetland plants to be able to grow in water. Aerenchyma consists of air spaces that move oxygen from plant leaves and stem towards the roots and rhizome. The aerenchyma tissue can occupy up to 60% of a wet plants cross sectional volume, whereas normal plants may only have 2-7% cross sectional aerenchyma volume (Batzer et al., 2014).

This report will be mainly addressing the feasibility of using cattail to create insulation material. Different aspects will be considered, including cultivation practices, extraction, processing, and specific requirements for insulation material. The use of cattail dry biomass for blow-in insulation will be tested by an experiment performed in collaboration with Bouwgroep Dijkstra Draisma. The results of this experiment will provide evidence on the feasibility of using cattail as insulation material. Also, the feasibility of using cattail as a source for bio-adhesives will be assessed. Different parts of cattail will be discussed on their suitability for bio-adhesive applications. Recommendations on each of aspects will be given in order to obtain the best achievable products.

# 2. Current Research

The first patent for using cattail parts to produce thermal insulation was already filed in the early 1900s. Results from feasibility studies have shown promising results. However, there is hardly any scientific literature available for the technical processing on industrial scale (Schwemmer, 2010). This chapter will be focussing on the current state of research and industry of cattail insulation and bio-adhesives. Additionally, the financial potential of cattail cultivation for insulation production will be discussed.

## 2.1 Research and companies

One of the first pilots of using cattail for paludiculture has started since the late 1990s in South-Germany (Donaumoos, Beieren). Current research for using cattail as insulation material focuses only on the leaves/stem, and sometimes shredding of the whole plant. Insulation material can be produced as blow-in insulation material or as insulation boards (Figure 5). One of the major players on the insulation market is the Austrian company Naporo. Naporo was founded in 2009, and since then they have filed around 8 patents and have done initial research for both insulation plates and blow-in insulation (Naporo, 2012).

Figure 5. Blow-in insulation material from 100% cattail in a display case, and construction panels made of cattail (adapted from Wichtmann et al., 2016).

The Fraunhofer Institute for Building Physics (Germany) has developed *Typha* based insulation panels that use a fundamental, relatively uncomplicated production process, of randomly arranged, magnesite-bonded particles of *Typha* leaves (Krus, 2014). According to the manufacturer, there are no products of comparable quality on the market for building markets. The magnesite-based *Typha* boards distinguish themselves by a high load-bearing capacity and insulation performance. In Thailand, cattail has been also used as insulation material by binding the leaves with methylene diphenyl diisocyanate (MDI) and hot pressed to produce thermal insulation boards (Luamkanchanaphan, 2012).

Another German company, Typha technik, has multiple types of insulation boards with different thermal conductivities available for sale. Rainer Nowotny, from the German company Hanffaser Uckermark, claims that cattail has a high potential as a regional, sustainable insulation material. Their blow-in insulation material from cattail consists of 100% renewable material. According to Rainer Nowotny, the cattail biomass of one hectare is sufficient to insulate the roofs of 4 houses. Farmers can both produce the products and market the insulation material. Hanffaser Uckermark offers advice and technical support to farmers (Wichtmann et al., 2016).

From the abovementioned companies, little information is known about their exact processing procedures (e.g. pretreatments, additives, processing machinery). In general, it should be noted that there are multiple factors that have an effect on quality and the final application of the cattail. The quality of raw cattail material is dependent on water and nutrient supply, cattail composition and management practices. These biomass properties can, in their turn, be altered and optimised for further processing by conditioning. The type of processing (i.e. type of defibration, mixing ratios, additives) creates different products for different applications (Schwemmer, 2010).

The application of using cattail for creating bio-adhesives has been proposed in several (Dutch) papers (Gerwen et al., 2017; Gerwen, 2016; Riet et al., 2014). However, the current state research for using cattail as a bio-adhesive is underexplored. The only company that is working on bio-adhesives, and seems to be the source of these papers, is the company Naporo. Naporo has already been mentioned as one of the major players in the insulation market. Naporo has produced a protein-based adhesive, which is called Naporo Natglue® (Naporo, 2012).

## 2.2 Dutch pilots

Currently there are several ongoing Paludiculture pilots in the Netherlands. The pilots that are cultivating cattail are: Bufferzone Bargerveen, Buitenveld, Ilperveld, Deurnese Peel, Park Lingezegen, and Zegveld (Fritz et al., 2016). Within these pilots, the following applications are considered for cattail:

1) insulation material (Zegveld, Buitenveld, Deurnese Peel).
2) fodder (Zegveld, Bargerveen).
3) insect feed in biological control, using cattail pollen (Zegveld).

From those applications, insulation material (either blow-in or construction panels) will be the most valuable for regional usage in the Netherlands. In Zegveld, the developmental phase of the pilot is the furthest. There, the first cattail corporation between 8 farmers and a regional company that makes insulation material has been established (Geurts, personal communication, 2017).

## 2.3 Financial potential

In 2014, a research was published by Riet et al. that investigated the potential of paludiculture in the Netherlands (specifically North-Holland) (Table 2). In their research, they made estimations about the costs and gains of setting up a paludiculture in the Netherlands.

One of the major aspects of the overall gains will be the biomass yield per hectare. In table 1, biomass yields are shown from multiple researches, with different cattail subspecies, harvest periods, site types, and countries. Values range from 4.6 till 15 ton DW/ha/year. In the table, it can be seen that the narrow-leafed cattail tends to have the highest yields. Therefore, this species has been recommended for the usage for building material (Duursen et al., 2016). A ton DW of cattail has a profit of €100-200. After processing (separating of fibres) the profit will be €300-500/ton DW, according to Schwemmer, R. Naporo (Riet et al., 2014). Selling the processed product has reduced transportation costs (less volume), which is an additional advantage. This could potentially result in an average turnover of €2000 (raw material) to €4,800 (processing) per year.

Another source of income in the cultivation of paludiculture crops could be the marketing of Carbon Credits. Between 2012-2020 the Netherlands has the objective of reducing greenhouse gasses by 16%. Therefore, the government determines a maximum amount of greenhouse gasses that big industrial companies and power plants can emit. These amounts are called emission rights. If a company emits more than its emission rights, it risks fees. Therefore, a company can also buy emission rights, such as Carbon Credits. There are two types of markets for Carbon Credits: Compliance markets and voluntary offset markets. Compliance markets are regulated via mandatory (inter-) national reduction schemes, such as the European Union’s Emissions Trading

Scheme (EU-ETS). However, currently the Carbon Credits from peat-rewetting projects can only be marketed on voluntary offset markets. These function outside the compliance markets and allow companies to buy Carbon Credits on a voluntary basis. In this way, companies that want to become climate neutrally can buy these Carbon Credits to neutralize their carbon footprint (Fair Climate Fund, 2016). Luckily, there are possibilities of a regional niche-market with such carbon-credit system. With the German concept of MoorFutures® it can be possible to finance a substantial part of the onset and management of peat-rewetting projects. The emission reduction when transitioning towards cattail cultivation could potentially result in an, on average, onetime gain of €14,000/ha (Riet et al., 2014). This value is based on the emission-reduction of Reed cultivation and a gain of €35 per ton of prevented emission (similar to MoorFutures®) over 30 years.

Table 1. Average yields on different harvest times and different sites (retrieved from Wichtmann et al., 2016).

| **Species** | **Yield (t DM /ha/year)** | **Harvest period** | **Site type** | **Country** | **References** |
|---|---|---|---|---|---|
| ***Typha spp.*** | ~15 | March-May | Gley and peat soil (salt marsh), natural vegetation | Canada | Grosshans et al., 2011 |
| ***T. angustifolia*** | 6.9 | September/October | Cutover fen peatland, 2-year cultivation | USA | Pratt et al., 1984 |
| | 11.5 | May-October | Natural vegetation | Canada | Boneville et al., 2008 |
| | 12.5 | September/October | Valley mire, 3 year cultivation | USA | Pratt et al., 1984 |
| | 6.5-14 | Winter | Rewetted fen peatland, cultivation | Germany | Heinz, 2011 |
| ***T. glauca*** | 8.1 | September/October | Valley mire, 2-year cultivation | USA | Pratt et al., 1984 |
| | 10.3 | August | Natural vegetation, fertilised | USA | Woo & Zedler, 2002 |
| ***T. latifolia*** | 4.6 | September/October | Cutover fen peatland, 2-year cultivation | USA | Pratt et al., 1984 |
| | 6.2 | September/October | Valley mire, 2-year cultivation | USA | Pratt et al., 1984 |
| | 7.8-12.1 | May-September | Rewetted fen peatland, succession | Germany | Steffenhagen et al., 2008<br>Schulz et al., 2011 |
| ***T. x glauca and T. angustifolia*** | 4.7 - 10.5 | September/October | Different peat soils, cultivation | USA | Pratt et al., 1988 |

For a transition from dairy farming to cattail cultivation, the estimated investment will be €7,300/ha. This is based on experience of setting up a 10 ha cultivation site for cattail in Ilperveld, North-Holland. These values are comparable to research conducted by Schätzl et al., 2006. The estimated management costs are compared to standard managing costs for 'swamps', which are €640/ha. Harvesting costs are compared to mowing reed with a track mower, which costs €2000. The estimated Interest and depreciation costs (following a running time of 30 years and interest rate of 3%) are calculated to be €530.

According Riet et al., the potential yields in cattail (and sphagnum) cultivation seem to be a sustainable alternative in peat meadow areas and can compete with revenues from dairy farming. Particularly, if the biomass is processed nearby the production sites, paludiculture may increase regional added value.

Another financial analysis has been performed by Duursen et al. (2016). The outcome from this analysis are in the same order as the analysis explained above. Whereas Riet et al. made a section with one-time investment costs, Duursen et al. calculated depreciation costs (of 10 years) and added these to their annual exploitation costs (Table 3). They estimate one plant is needed per m$^2$ as starting material. One hectare would require 10,000 plants, which cost ~ €0.30 each. Following a depreciation time of 10 years annual costs would be 300 euros. Other annual depreciation costs (e.g. farmland, agricultural tenancies, inventory, machinery) would be €700 per hectare. The total exploitation costs of €2,250 are less than the annual expected costs of 3,170 stated by Riet et al. This could be explained because Riet et al. proposed using a reed mower, which costs €2000 per hectare, instead of €800 per hectare. All in all, from these analyses it can be concluded that total exploitation costs per hectare are dependent on multiple factors (e.g. harvesting method, depreciation time), but will cost around 2,000-2,500 euros.

Table 2. Overview of estimated income when transitioning towards paludiculture (adapted from Riet et al., 2014).

| **Land usage** | **Dairy farming** | **Cattail cultivation** | **Sphagnum cultivation** |
|---|---|---|---|
| **Water level** | **-60 cm relative to surface level** | **-10 cm/+25 cm relative to surface level** | **0 cm relative to surface level** |
| **Investments (€/ha)** | | | |
| One-time investment costs | n/a | 7,300.00 | 23,300.00 |
| **Funding** | | | |
| CO2 credits (€/ha/30 years) | n/a | 14,000.00 | 14,000.00 |
| | | | |
| **Costs and profits (€/ha)** | | | |
| Annual potential profits | 4,600.00 | 4,800.00 | 8,800.00 |
| Annual subsidies and grants | 400.00 | 0.00 | 0.00 |
| | | | |
| Annual other costs | 1,710.00 | 2,640.00 | 4,000.00 |
| Annual depreciation costs | 2,325.00 | 530.00 | 1,175.00 |
| | | | |
| **Net income (€/ha/year)** | 965.00 | 1,630.00 | 2,625.00 |

Duursen et al. (2016) made a difference in revenue for blow-in insulation and insulation boards. For the financial gains of blow-in insulation, Duursen et al. use a revenue of €150 per ton DW raw material. This is low, considering the range of €100-200 (raw material) and €300-500 (processed) that Riet et al. use. The yields that are reported are, in turn, higher than previously reported (15-20 ton/ha vs 5-15 ton/ha). All in all, it can be concluded that the total gains for blow-in insulation will depend on the yield/hectare and the financial returns for the raw and/or processed material.

For insulation/construction boards, the expected returns are higher. A yield of 15 ton DW per hectare would be enough for 150 $m^3$ of construction- insulation material. Processing industry is willing to pay €50-100 per $m^3$, so this could result in returns of €7,500-15,000 per hectare (Duursen et al., 2016). A revenue of €7,500-15,000 per hectare seems very promising. However, one should be cautious with using these estimations. The expected yield of 15-20 ton DW/ha is very high. Furthermore, it is stated that not every part of the plant is used when processing for construction- insulation material. This could reduce the revenue per hectare. On the other hand, revenues can be gained from using the waste streams as bio-energy or fodder. All in all, the application of using cattail for construction-insulation material seems to have higher returns, but it is still dependent on the yield per hectare and the revenue per ton DW.

Table 3: Annual exploitation costs of cattail cultivation per hectare in large scale (5-10 ha) production.

| **Expenses** | **Costs for blow-in insulation (in €)** | **Costs for construction-insulation (in €)** |
|---|---|---|
| Depreciation plant material | 300 | 300 |
| Other annual depreciation costs | 700 | 700 |
| Cultivation costs | 100 | 100 |
| Harvesting costs | 800 | 1,100 |
| Overhead costs | 150 | 150 |
| Transport costs | 200 | 200 |
| **Total exploitation costs per ha** | **2,250** | **2,550** |

# 3. Cultivation

Since cattail is a marsh plant, harvest is more difficult compared to conventional crops and different aspects have to be taken into account for a good harvest. To get a better understanding of the difficulties in growing and harvesting cattail, this chapter will discuss several aspects of cultivating cattail. Starting with different methods of sowing cattail. Secondly, the growing specifications of cattail (i.e. growing density, fertilization, and artificial growing beds) will be discussed. Lastly, the current harvesting methods will be reviewed for their efficiency in handling the crop and possible new developments will be mentioned. After discussing these points, more insight should be gained about what the optimal cultivation methods are for the production of insulation or bio-adhesives, and how these methods can be applied to improve the quality of the final products.

## 3.1 Sowing methods

Different sowing methods can be applied to sow cattail. Three different methods of sowing have been proposed, namely sowing the seeds, planting parts of rhizomes, and relocating seedlings (Dubbe et al., 1988). Each method comes with their advantages and disadvantages, but all are quite time-consuming since sowing on wetlands is generally rather difficult and is often performed manually (Postma, personal communication, 2017). Using seeds to sow is relatively cheap, as seeds are not difficult to come across. However, cattail growing from seeds will not have an optimal yield in the first year, compared to hibernating rhizomes. Using partial rhizomes, requires first to have ample supply of mature cattail that can be harvested and used to create a new growing field. After sowing the partial rhizomes, they perform better than the seeds in the first year as they require less development time. Transplanting seedlings perform similarly to partial rhizomes, but seedlings do require a controlled environment for early development. In the end using seeds seems like the most logical choice for sowing, however this is assuming 100% germination. Germination of cattail seeds is very tightly controlled and often shows only around 50% germination in natural conditions (Dubbe et al., 1988). This leads to assume the best method of planting cattail is by transplanting partial rhizomes.

## 3.2 Growing specifications

After sowing the material, the growing conditions have a very big influence on the production of the plant. Poor growing conditions result in a poor harvest. Here some examples will be discussed that can be optimized to have an as high as possible yield. More specifically, the yield of usable products needs to be increased. The effect of growing density, use of fertilizer and general management of growing fields will be discussed.

### 3.2.1 Growing density

The growing density of the crop very often determines the ratio of plant parts, as plants in a high density need to compete for nutrients and sunlight. This is not necessarily a negative thing, since an increase in growth of one plant part might be beneficial for the production of certain compounds. For instance, if plant stems are harvested and due to a high growing density the plants compete to capture solar radiation, stems will be elongated which is good for the harvest. Therefore, it is important to know what the effects of growing density are on the development of cattail.

In nature the growing density varies per cattail species and also per region, and has been found to go up to densities of 140 plants/m$^2$ for *T. domingensis* in the northern parts of Mexico (Glenn et al., 1995). This may have negative effects if the plant is to be used for insulation material. For insulation material the stems and mainly the leaves will be used. To increase the ratio of usable part per not usable parts the best growing density must be determined. A study on the physiology of *T. angustifolia* in different growing densities has been performed (Corrêa et al., 2015). In this study they took plants from natural water bodies with different growing densities. Plants from high density population (>50% of the colonized by cattail) and low density (<50% colonized) were harvested and grown in a controlled environment in the density of their source. After 60 days plants were assessed for growth and certain characteristics, including aerenchyma proportion. They showed that plants in a high density show an increased relative growth rate, but also an increased root/shoot ratio. An increased root/shoot ratio is not wanted as this means less biomass will be present in harvested material. In a low density, plants showed a significant increase in palisade parenchyma thickness with an increased aerenchyma proportion. As discussed earlier, aerenchyma tissues are one of the major reasons cattail serves well for insulation material, and the amount of this is a goal to acquire good insulation material.

This research showed the effect that different growing densities can have on the proportions of plant parts. It also showed that low growing density looks to be a better method of growing cattail for the purpose of good quality insulation material. However, since the relative growth is higher in high density an assessment needs to be performed if the total harvestable product is actually lower or not. It also needs to be assessed if the increase in aerenchyma tissue is really necessary or insulation is adequate without the increased aerenchyma levels. In the end, more research will need to be performed to make definite statements on what is the best growing density for cattail.

### 3.2.2 Fertilization

Little studies have been performed on the effect of different fertilization methods of cattail. This is because cattail generally grows in nutrient-rich environments and growing fields experience a lot of nutrient drainage from surrounding agricultural fields (Postma, personal communication, 2017). For the production of insulation material the amount of aboveground biomass needs to be brought as high as possible, since the leaves and stems serve as the best source for insulation.

A study covering a 4 year time span on the effect of nitrogen (N) and phosphate (P) on plant communities in the Everglades National Park was performed (Chiang et al., 2000). They applied 22.4 g/m$^2$/year N and 4.8 g/m$^2$/year P on the soil and harvested various plant species each year to determine their biomass and Leaf Area Index (LAI, leaf area per ground area). An increase in total biomass was found of the entire plant population when increased levels of P were applied, but no increase in biomass was found by only applying N. However, only looking at the aboveground biomass of cattail revealed no significant differences compared to the control where no additional N or P were applied. Even though no increase in total biomass was found in the population a mean increase in LAI across years was found in cattail, suggesting an increase in biomass per ground area. The photosynthesis of cattail showed almost no significant increase between treatments, but since LAI was significantly increased, the photosynthesis per ground area showed an increase in fields with additional P. Table 4 provides an overview of the differences in LAI and photosynthesis between the various test plots.

Table 4. Leaf Area Index and photosynthesis of cattail treated with various fertilizers (Chiang et al., 2000).

| Treatment | Leaf Area Index | Photosynthesis (leaf area) | Photosynthesis (ground area) |
|---|---|---|---|
| **Control** | 0.19 | 16 | 3 |
| **High N** | 0.18 | 17.5 | 3.2 |
| **High P** | 1.56 | 17 | 26.5 |
| **High N and P** | 1.65 | 18.1 | 29.9 |

In conclusion, the most efficient use of space to produce the most biomass was acquired by applying high levels of N and P. However it should be taken into account that quantities do not exceed the legal limits for nutrients in water bodies (art. 10.4. Meststoffenwet; art. 11.1. Meststoffenwet, 2016). In the future it could be considered to cultivate cattail in controlled environments, since then there is little risk of drainage to nearby fields, this is however something that cannot be discussed extensively this early.

### 3.2.3 Artificial growing fields

Achieving maximum yield is sometimes difficult on natural fields, therefore ACT (2015) have proposed the creation of artificial growing fields. They discussed the advantages of usage of such fields for the cultivation of cattail. The first being adjustable water levels, harvesting of cattail is rather difficult in non-controllable environments, as is discussed below. Being able to adjust water levels in a growing field allows for the harvest using boats without having a big ecological impact. Another major advantage is the accessibility for management and harvesting. Natural fields sometimes suffer from poor weed management, as controlling this is very time-consuming. They also often lack a good landing shore which makes harvest more difficult. The last major advantage is the use of separated blocks. Natural waterflow causes an accumulation of nutrients in the south-west corners of fields (as cited in ACT, 2015). Separated blocks would partially solve this problem. A suggested growing field is depicted in Figure 6.

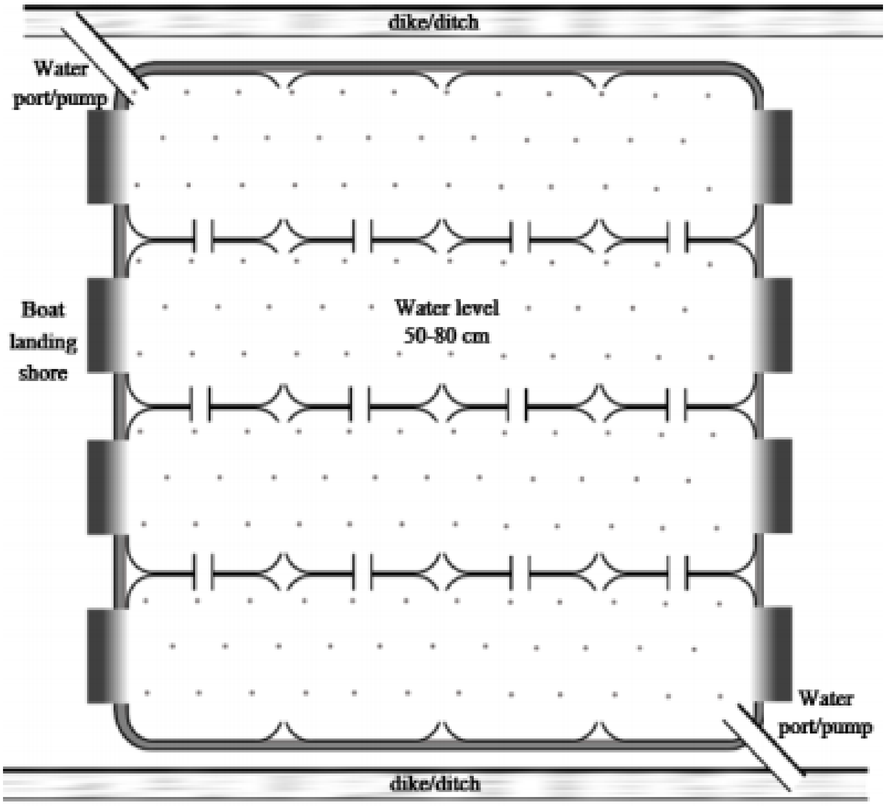


Figure 6. Suggested depiction of an artificial growing field. The water is adjustable with water pumps between up to 80cm to accommodate for harvesting equipment. The field is separated into four different lanes connected via tubes (ACT, 2015).

## 3.3 Harvesting

Harvest of cattail usually happens after it has fully matured, as for most plants with rhizomes nutrients are transported downwards during the fall to be able to survive through the winter (Toet et al., 2005). During winter the aboveground parts die off or can be harvested and the plant is able to grow back next season (Dubbe et al., 1988). However a problem with harvesting any marsh plant is the issue with the wetlands and the difficulty of minimizing the ecological impact during harvest. To not have a big ecological impact harvest could be performed by hand, however this is nowhere near economically feasible. Therefore, specialized machinery has been developed to be able to harvest marsh plants. However, specialized machines also have special requirements to be able to perform optimally (Grosshans, 2014; ACT, 2015). Different harvesting techniques have been previously discussed, and each have their advantages and disadvantages (ACT, 2015).

Since cattail can be harvested during winter and is not very restricted to being harvested right after maturing, an option is to wait with harvesting until the water is frozen. An advantage of a frozen growing field is that conventional machines are able to be used for harvest. Another advantage is that after a period of frost the cattail plants will be as dry as they can get, which saves drying costs (Geurts, personal communication, 2017). However, since it is not guaranteed to freeze strongly enough for the growing fields to be completely frozen the other option is to harvest by boat or completely draining the growing field (ACT, 2015). For harvesting by boat, companies such as Conver have developed specialized mowing boats that can be used to harvest cattail. A disadvantage to these boats is that the harvest is generally really slow and the boats need a rather high water level, which is not optimal for the production of certain species of cattail (Grace & Wetzel, 1982). Another issue that arises in harvesting by boat is that the plants usually are cut under the water level. If cattail is cut under water level it will die as a result of anoxic conditions (Sale & Wetzel, 1983), however cattail is known to survive for at least one week under these conditions (as cited in ACT, 2015). A solution for this would be to lower the water levels after harvesting so the plants are able to survive, but lowering the water level right after harvest is generally only possible in artificial growing fields. The option of draining the entire growing field before harvest also faces this issue. When it is possible to drain the growing field this could be a very good way of harvesting. This option however does often cause major ecological damage, solutions for this problem have been proposed. Companies have been starting to develop machines fitted with large balloon tires that navigate the wetland terrain without sinking and have a minimal impact on the environment (as cited in Grosshans, 2014). However, this again does have an impact on the harvesting speed.

Some pilots have been experimenting with harvesting twice a year, the first time during summer when the plants are starting to develop their seedheads, and the second time during winter (Geurts, personal communication, 2017). During the first harvest the stems and leaves are full of nutrients, which could be used for feed, or quality products, such as bio-adhesives. The second harvest is more directed towards insulating material as the material has already dried a lot during winter, which reduces the drying costs. The average percent dry weight of cattail is very heterogeneous, values that are found generally range from 12.2% to 22% (Lorenzen et al., 2001; Leo, 2008). Also, in winter many of the nutrients are stored in the rhizomes, this improves the growing of the plant in the next year. After harvest during summer the plants are able to grow back at a rate of 2.5 cm per day (Postma, personal communication, 2017). If harvesting twice a year has an impact on the yield of the following year will need to be studied. However, this could be an important point in harvesting of cattail in the future.

In summary, many different aspects have to be considered for the optimal cultivation of cattail. Starting with the sowing methods, as this heavily influences the harvest during the first year. Different forms of sowing were discussed and the most promising for the production of insulation seems to be transplanting of rhizomes, as the other methods are either very unreliable, or very laborious and time consuming. Also, the growing specifications after sowing can potentially influence the yield or quality of the final products. Density of growing influences the amount of aerenchyma tissue within the plants, where lower densities acquire higher amount of aerenchyma. However, as the density decreases the overall yield generally decreases as well. Adding to this, it is not known if this increased aerenchyma content actually has an effect on insulation properties. Therefore it is recommended to first study the effect of aerenchyma on insulation properties before deciding on the growing density. As for harvesting methods, the recommended method is harvesting by boat. However, harvesting by boat does require the growing fields to be designed for the harvest by boat. Therefore it is also recommended to create artificial growing fields in which the water levels can be controlled, and the amount nutrients can controlled, as this is hard to do in a natural environment. In the end a lot is still not known about cultivation of cattail, but companies are eager to start working with it.

# 4. Insulation

Insulation materials are intended to comply with basic functional requirements, which are minimizing energy losses (thermal insulation) and/or reducing sound transmission (acoustic insulation). They may also help preventing condensation of water on the surface. Safety requirements have to be considered as well as environmentally-friendly options (Stoerkmann, 2012). However, developing or enhancing an insulation material usually involves compromising on different properties. For instance, improving fire resistance by adding flame retardants may decrease the insulation properties of the material. In the same way, enhancing thermal insulation may increase water vapour transmission and, consequently, the risk of mould growth (Stoerkmann, 2012).

There are many types of insulation materials that are being used nowadays. Blow-in insulation material, also referred to as loose-fill material, is any material with insulation properties (thermal and/or acoustic) that is pumped or injected into walls, roofs, ceilings, or floors (Department of Energy USA, n.f.). Another type of insulation material is biocomposite, defined as a material formed by a resin matrix and a reinforcement of natural fibres, generally plant fibres or cellulose (Fowler, 2006). Cattail can be used as a bioresource to produce both blow-in and biocomposite materials. As of now, approximately 1900 patents are registered for manufacturing cattail-based insulation materials (Schwemmer, 2010). Examples of relevant patents are PCT/EP2013/003148 (Load-bearing and heat-insulating structural element made of *Typha* leaf mass), US3063125 A (Method of making heat insulating material from cattail fibres), and DE201110016562 A1 (Insulation material based on cattail leaf fibres).

This chapter addresses the required characteristics and properties of insulation materials in terms of insulation standards and gives input on the possibilities of producing cattail-based insulation materials compliant with those requirements. Apart from performing a literature research, an experiment on the thermal conductivity and compression tendency of shredded dry cattail material is reported. The results of this experiment give insights in the possibility of a cattail-based blow-in material complying with the required standards. Bouwgroep Dijkstra Draisma is the most interested in the outcome of this experiment. If the behaviour and results of the cattail test do not deviate from the parameters of the regularly used blow-in materials (e.g. Easycell®, Isofloc®), the company could confirm that the new material is likely suitable for use and further development steps may be taken.

## 4.1 General insulation properties

The insulation of a material can be defined as the material's property to reduce or stop the passage of electricity, heat or sound. Regarding blow-in materials or biocomposites, two types of insulation can be found, thermal and acoustic. Thermal insulation refers to the reduction of heat transfer between objects in thermal contact. Acoustic insulation refers to reducing the intensity of sound by any means with respect to a particular source and receptor (Diamant, 2012).

In order to measure the insulation quality of a material, different properties are assessed. Some of these properties are thermal conductivity and resistance, moisture absorption, fire and microbiological resistances, elasticity, rupture, and ecological quality (CIUR, n.f.).

For the case of thermal insulation, thermal conductivity is one of the most relevant parameters. Thermal conductivity can be easily measured with the use of heat flow meters according to different standards such as EN 12667:2001 (See Appendix I for more information on standards). Fire resistance is also an important property to measure for cellulosic-based insulation, as these materials are not fire-resistant themselves and usually flame retardants have to be added (Kymäläinen & Sjöberg, 2008). Some of the most important parameters in the development of insulation materials are described below.

Thermal resistance

Thermal resistance refers to the resistance a material possesses to heat flow, as a result of suppressing radiation, convection and conduction (Al-Homoud, 2005). This resistance is due to the microscopic dead air-cells that are present within the material, which suppress convective heat transfer. Its measurement, the R-value, is a function of the thickness, density and thermal conductivity of the material, and thus it is expressed in $W/m^2K$. A high R-value for a material means it possesses good thermal insulation properties.

According to the Dutch law "Bouwbesluit 2012", that still applies only with a few revisions, it is stated that when the R-value of the insulation material is 2.5 $W/m^2K$, it is only allowed to use this insulation in a caravan. For the walls of any other kind of building should be 4.5 $W/m^2K$ for all inner walls the outer walls and the insulation in the floor are allowed to have an R-value of 3.5 $W/m^2K$, but the roof and the floor of the first floor should have an R-value of 6 $W/m^2K$, this is in compliance with NEN 1068 (Ministerie van binnenlandse zaken en koninkrijksrelaties, 2012).

Related to this are the terms thermal conductance (C-value) and thermal transmittance (U-value). The first refers to the heat rate that flows through a unit of surface area of a component with a temperature difference between surfaces of one unit between surfaces of the two sides of the component and it is expressed in $W/m^2K$ (Al-Homoud, 2005). The second, often called "Overall heat transfer coefficient", is also a measure of the heat passing through the building shell elements and is expressed in the same units as R-value and C-value. In the Netherlands, this U-value is required to be at least 0.37 $W/m^2K$ (EURIMA, 2011).

There is a variety of standard protocols that describe how to measure the thermal transmittance. Three examples are the ASTM C1363-05, GOST 26602.1-99 and EN ISO 8990. Both the ASTM C1363-05 and EN ISO 8990 have the same principle for measuring the thermal resistance. There is a cold chamber and a hot chamber and in between those chambers the insulation that has to be tested is placed, the power that is needed to keep the hot room at a constant temperature is measured to calculate the thermal resistance. The GOST 26602.1-99 has two versions, one version is similar to the ISO and ATMS while in the other version the thermal resistance is measured by measuring the heat flow and temperature difference between the hot and the cold room for different homogeneous areas of the test subject. In Figure 7 it is shown how the placement of sensors should be on the to-be-tested product, which in this case is a window for the deviant GOST method. This products should be placed in the a guarded hotbox, as can be seen in Figure 8.

The total heat transmittance is calculated using the following equation:

$$U_{ST} = \left( \frac{1}{h_{ST,i}} + \frac{A_S}{\sum_{p=1}^{m} A_p q_p / (T_{p,s,e} - T_{p,s,i})} + \frac{1}{h_{ST,e}} \right)^{-1} \qquad \text{(Eq. 1)}$$

Where:

$h_{st,i}$ = the standardized internal heat exchange surface coefficient 8.0 ($W/m^2K$).
$h_{st,e}$ = the standardized external heat exchange surface coefficient 23.0 ($W/m^2K$).
$A_s$ = area specimen (test subject ) ($m^2$).
$A_p$ = area of a homogeneous zone ($m^2$).
$q_p$ = specific heat flow per area of a homogeneous zone ($W/m^2$).
$T_{p,s,e}$ = external surface temperature of a homogeneous zone (K).
$T_{p,s,i}$ = internal surface temperature of a homogeneous zone (K).
$\Sigma_p^m$ = the sum of the properties mentioned above of all homogeneous zones.

The ISO and ASTM use a calibrated hotbox as shown in Figure 9.

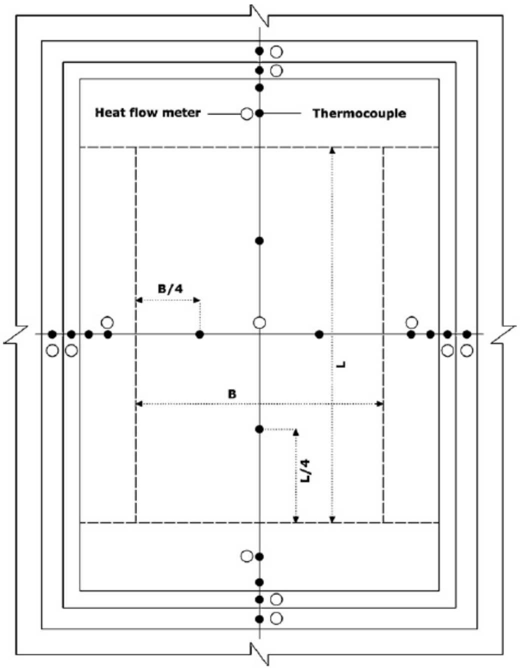


Figure 7. Heat flow meter and Thermocouple placement in accordance with the GOST 26602.1-99 protocol.

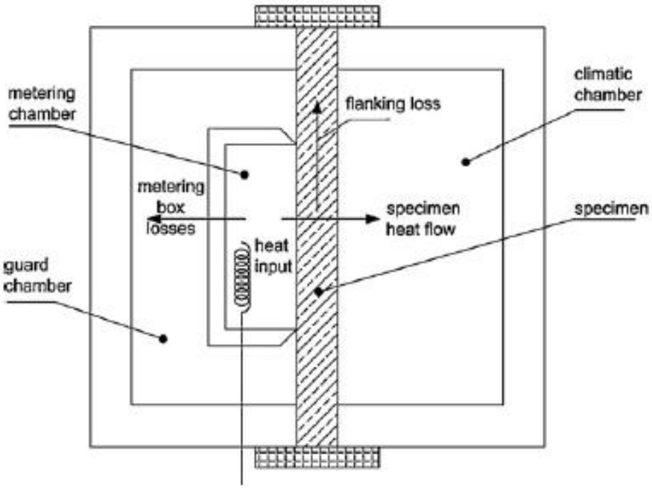


Figure 8. Guarded hotbox as used in the GOST 26602.1-99 protocol.

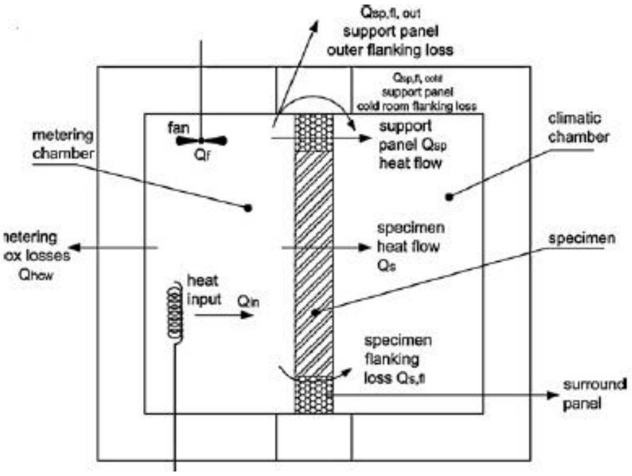


Figure 9. Calibrated hotbox as used in the EN ISO 8990 and ASTM C1363-05 protocols.

A heat balance should be made taking into account all the heat sources and losses, this balance will be as followed:

$$Q_S = Q_{in} + Q_f - Q_{hcw} - Q_{sp} - Q_{sp,fl,cold} - Q_{sp,fl,out} - Q_{S,fl} \qquad \text{(Eq. 2)}$$

Where:

$Q_S$ = the heat flow through the test subject.

$Q_{in}$ = the heat produced by the heating source.

$Q_f$ = the heat released by the fan.

$Q_{hcw}$ = the heat that exits the hotbox through the outer walls.

$Q_{sp}$ = the heat flow from the hot chamber to the cold chamber through the support panel.

$Q_{sp,fl,cold}$ = flanking heat loss from the hot chamber to the cold chamber through the support panel.

$Q_{sp,fl,out}$ = flanking heat loss from the hot chamber to the environment through the support panel.

$Q_{S,\ f}$= flanking heat loss of the test subject.

The ISO standard does not describe how to measure the heat lost to the environment ($Q_{hcw}$), while the ASTM has an analytical method for this, which is described in its annex. Analytical measures for $Q_{S,fl}$ and $Q_{sp,fl,out}$ are described in the annexes as well, while the ISO standard gives tables with standard values based on the geometric properties of the test subject.

The ASTM method measures the heat exchange through the support frame ($Q_{sp}$ and $Q_{sp,fl,cold}$) by placing surface heat sensors both on the cold and the hot side of the test subject while the ISO method uses a test subject with known thermal properties to measure these heat flows. The hot chamber should be 20°C for all three standards, but the temperature for the cold chamber varies. For the ISO standard the cold chamber should have a temperature of 0 °C while the ASTM requires a the temperature to be -17°C and GOST -20°C. The GOST standard has the lowest uncertainty with 2.12% deviation of the expected values, the second most accurate standard is the ASTM with a deviation of 2.15% and the standard with the most uncertainty is the ISO standard with a deviation of 2.19% (Asdrubali et al., 2011).

Moisture absorption

Water inside the insulation will cause the material not to reach its optimal insulating properties. As water is a very good conductor, heat can travel more easily through the insulation, thus reducing its R-value. Water also promotes the growth of moulds, increasing deterioration of the product. Increasing moisture content may also alter dimensions and chemical composition of the insulation material by removing constituents (Kymäläinen, 2004). Permeability, or how easily the insulation material can absorb moisture, is therefore an important quality that should be assessed. The material can be tested for water absorption by submerging it in water and determining the weight gained due to the increase in water content in the insulation. A moisture content of 2% by volume has to be reached to be in compliance with NEN-EN 12087 (Ministerie van binnenlandse zaken en koninkrijksrelaties, 2013), although moisture values from 4% to 13% are also allowed according to the TIS 876-2547 standard (Luamkanchanapam et al., 2012). Equilibrium moisture content absorption can also be measured when exposing the material to different relative humidity values by determining the changes in sample weight (Kymäläinen, 2004).

To control moisture level of the insulation material, different approaches can be followed (Al-homoud et al., 2005). The moisture source and/or transportation mechanisms can be avoided through careful design and building assemblies to avoid leaks, openings and cracks in the building envelop. The climate and different moisture sources should be investigated in order to choose the best option for each case. Storage of the material outdoors may pose a risk if the relative humidity is high (Kymäläinen, 2004). The susceptibility of the material to moisture damage may also be reduced by using additives (Kymäläinen, 2004).

Cattail has proven to have lower water absorption values compared to wheat straw when used for particle boards (Bajwa et al., 2015), meaning less additives may be needed for cattail-based insulation materials than for other bio-based insulations. In a research of the Estonian University of Tartu, Institute of Ecology and Earth Sciences, the moisture absorption of pure clay-sand plaster is compared to the moisture absorption of clay-sand plaster mixed with a variable amount of fluffy material and shredded cattail. These results show that a mix of clay-sand with fluffy material and shredded material with the ratio of 2:1 has better water resistant properties than when it is not mixed, absorbing 11.0 g/m$^2$ of moisture, This was the only mix of those tested that has better water resistance properties than pure clay-sand, which had 11.3 g/m$^2$ (Maddison, 2008).

Fire resistance

Fire safety is very important for insulation material, as materials should not easily catch fire. For this reason many requirements have to be met before a new insulation material can be brought onto the market. To measure fire safety many guidelines exist (Table 5), each one specifying a different aspect of fire safety. Based on the results of the tests specified in these guidelines the material is given a classification as specified in NEN-EN 13501 (Ministerie van binnenlandse zaken en koninkrijksrelaties, 2012), where A1 is the most fire safe and F the least. Untested material is also given classification F. Depending on the use of the insulation different classifications are required. In order to use the material for insulation in normal housing classification D has to be achieved, which means the material can withstand 100 kW/m$^2$ for up to 2 minutes before catching fire.

Another point that is important in assessing fire safety is the amount of smoke produced. When using the material in a normal housing situation, the material is allowed to reach up to a smoke-density of 10 m$^2$ under fire, as is specified in NEN 6066 (Ministerie van binnenlandse zaken en koninkrijksrelaties, 2012).

Table 5. Guidelines specifying different aspects of fire safety.

| Guideline | Description |
|---|---|
| **NEN 6063** | Test method for external fire exposure to roofs |
| **NEN 6064** | Determination of the non-combustibility of a building product |
| **NEN 6065** | Determination of the contribution to fire propagation of building products |
| **NEN 6066** | Determination of the smoke production during fire of building products |
| **NEN 6068** | Determination of the resistance to fire movement between spaces |
| **NEN 6069** | Testing and classification of resistance to fire of building products and building elements |
| **NEN 6090** | Determination of fire load |
| **NPR 6091** | Resistance against external fire spread |

Mechanical properties

Tensile strength (expressed in MPa) can be measured according to the EN 12089 standard (Sassoni et al., 2014). In this test, the ends of the material sample are glued to two metallic plates and is then subjected to a settled crosshead speed. The stress produced in the material until breaking is measured using a tensometer. The same standard is also applied for testing impact strength (expressed in J/m), in which the sample are fractured using an impact testing machine to measure the energy absorbed and the width of the sample. For compression resistance (expressed in MPa), a mechanical may be used to apply a settled force to the sample material and thus measure the maximum stress the material can bear before breaking. The outcome of compression test should comply with the EN 826 standard (Sassoni et al., 2014).

Other important parameters are Modulus of Elasticity (MOE) and Modulus of Rupture (MOR), which can be measured by means of a bending test and the values should comply with the BS EN 310 standard (Vidil et al., 2016). Mechanical properties may also be measured following the guidelines in ASTM D1037 (ASTM, 2012) or TIS 876-2547 standards.

Ecological quality

In the Netherlands the Energy Performance Norm (EPN) regulation is applied, which consists of an index, a non-dimensional figure showing the efficiency in terms of energy of new constructions (PRC, 2011). This index had a value of 0.8 in 2010, and is being decreased in order to reach a value of 0 (energy neutral construction) by 2020. How to reach the index value is not stipulated in the EPN regulation, thus building companies have the freedom to choose measures to meet this requirement. It is left to municipal building authorities how to enforce the regulation regarding sustainable construction.

Microbiological resistance

Mould is a colloquial term for a variety of micro fungi from different categories. Some of the commonly occurring species of fungi growing on building materials are *Aspergillus versicolor, Eurotium herbariorum, Aureobasidium pullulans, Penicillium chrysogenum, Stachybotrys chartarum* and *Cladosporium sphaerospermum*. Nutrient availability, pH, moisture and temperature are critical conditions for mould growth (Johansson et al., 2012).

The mould resistance of a building material can be evaluated through a set protocol for the assessment of all the conditions for the material leading to mould growth (ie. temperature, relative humidity, and time). Cattail-based insulation materials fall into the category of 'Insulation materials and their facings' of standards such as the ASTM C1338-00. Thus, these materials are subjected to comply with this testing standard. According to this standard, the mould resistance should be assessed in at least 3 specimens, with 5 types of fungi species inoculated by spraying. The temperature of this protocol is 30±2ºC and a relative humidity (RH) of 95±4% for a minimum of 28 days (ASTM, 2000).

Another standard for testing cattail-based biocomposites may be the BS 1982:Part 3:1990, concerning the category of 'Panel products made of or containing materials of organic origin'. According to this standard, the mould resistance should be assessed in at least 3 specimens, with 7 types of fungi species inoculated by spraying. The temperature of this protocol is 24±1ºC and a relative humidity (RH) of 95±4% for 4 weeks (BSI, 1990).

For both standards, the mould resistance is validated in five different categories, ranging from 0 to 4. With 0 being no mould growth; 1, initial growth, one or a few hyphae and no conidiophores; 2, sparse but clearly established growth, often conidiophores are beginning to develop; 3, patchy, heavy growth with many well-developed conidiophores, and; 5, heavy growth over more or less the entire surface (Johansson, 2014).

It is important to consider that for materials with high content of organic compounds such as the present in fibres of cattail leaves, or in wood or paper materials, the water requirement for mould growth is lower and the biodiversity of fungi may be higher than in those materials with lower content of organic compounds (Pietarinen, 2008). Cattail is able to withstand swamp climate due to its polyphenols such as tannins. This protection may make cattail a good bioresource for building applications, probably making the addition of anti-composting chemical additives unnecessary (Krus et al., 2014). However, during the processing of cattail its composition may change.

Some manufacturers of bio-based insulation materials use additives (i.e. sodium borate) to impregnate the fibres and decrease the critical moisture levels for mould growth (Adams, 2011). Decreasing the availability of nutrients by means of a digestion pretreatment may be another solution (van Dam, personal communication, 2017).

In summary, different standards have been developed for the testing of properties of insulation material. In this section, several have been discussed and more information about testing standards can be found in Appendix I. When it is needed to obtain certification standards for the cattail-based insulation material, this section could provide guidance to what standards should be met for each insulation property, as well as where to find the protocols needed to measure them. However, some of the standards are periodically updated, meaning the information contained in this section may become outdated in the following years.

## 4.2 BREEAM certification

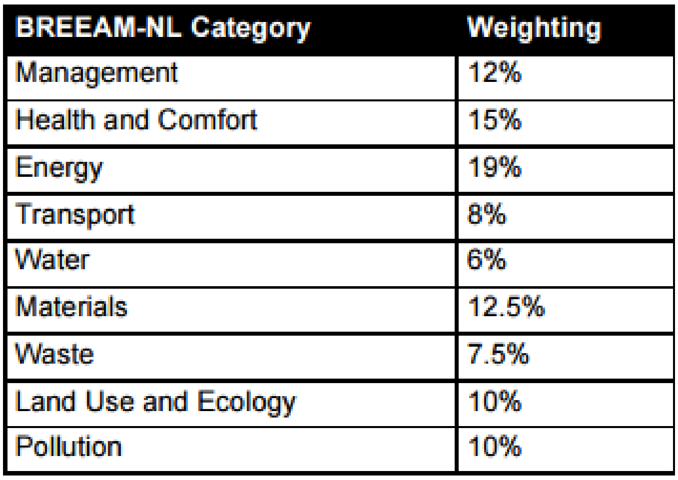
One of the most important certification standards for the sustainability of buildings and projects is the BREEAM standard. BREEAM is the acronym for Building Research Establishment Environmental Assessment Method. Within this certification, a building is assessed in different categories, including energy, health and wellbeing, management, transportation, waste, pollution, water, land use and ecology, innovation, and material (Park et al., 2017). Therefore, only buildings and projects can get a certification, and not construction and insulation materials alone.

In the Netherlands, BREEAM-NL is managed by the Dutch Green Building Council (DGBC), under the license of BRE Global Ltd. BREEAM-NL is the Dutch adaptation of the international BREEAM. Among the aims of BREEAM-NL are to provide market recognition for low environmental impact buildings, to stimulate the demand for sustainable buildings, and to provide a credible environmental label for buildings. The compliance with the BREEAM-NL certification is organized in a three-party certification system. This system consists of:

1) The project (e.g. work, area, building): provides proof to comply with the intended score.
2) An independent assessor: evaluation of the completeness of the assessment and determining the rating of the project.
3) The Dutch Green Building Council: Supervision of the work of the assessor.

The total BREEAM-NL score for a project is determined by adding the scores of all the categories assessed. These scores are multiplied by a percentage that applies to each category, in the case of the Netherlands, the BREEAM international weighting percentages are maintained as seen in the Table 6 (BREEAM-NL, 2014).

Table 6. Weighting percentages for BREEAM-NL certification in a building (BREEAM-NL, 2014).



| BREEAM-NL Category | Weighting |
|---|---|
| Management | 12% |
| Health and Comfort | 15% |
| Energy | 19% |
| Transport | 8% |
| Water | 6% |
| Materials | 12.5% |
| Waste | 7.5% |
| Land Use and Ecology | 10% |
| Pollution | 10% |

Each of those categories is subdivided into different issues. Each of those issues has targets, for which points can be earned. For the assessment process, a building or project is checked against those targets and target-specific points are awarded by an independent assessor. After the whole assessment of the building, depending on the total number of credits awarded, a final performance rating is achieved. There are three categories in which credits may be granted regarding cattail-based insulation products: Health, Energy, and Materials (BREEAM-NL, 2014). These issues are:

| | | |
|---|---|---|
| HEA 13 | Acoustic Performance | (1 point maximum) |
| ENE 26 | Assurance of thermal quality of building shell | (2 points maximum) |
| MAT 1 | Materials specification | (8 points maximum) |
| MAT 5 | Responsible sourcing of materials | (4 points maximum) |

HEA 13 Acoustic performance belongs to the Health category of BREEAM-NL. A maximum of 1 point is granted when within all areas of the assessed building there is sufficient noise insulation and soundproofing measures have been applied. Other specific characteristics should be met in accordance to BS EN 12354 and BS 5077 (see Appendix II, Table 1).

ENE 26 Assurance of thermal quality belongs to the Energy category of BREEAM-NL. A maximum of 2 points can be awarded when in the building assessed a thermographic survey is performed and it meets the requirements set in BS EN 13187 (Thermal performance of buildings - Qualitative detection of thermal irregularities in building fabric - Infrared method). In general, these requirements are met when there are no significant thermal leaks present, no significant air infiltration occurs, and no excessive thermal bridges occur.

The category Materials in BREEAM-NL may be the most relevant for the cattail-based insulation materials usage in a building, as the highest quantity of points can be awarded in this category. Two issues in the Materials section are mentioned, MAT 1 and MAT 5. For MAT 1 Materials Specification, a maximum of 8 points can be assigned. The credit criteria of MAT 1 is depicted in Table 7. The MAT 1 qualification is based on using materials that have a low environmental impact throughout the lifecycle of the building. The environmental impact is assessed by calculation of a shadow price (€/m$^2$ of Gross Floor Area (GFA)). The shadow price is the sum of the environmental impact of all individual materials, based on their Life Cycle Assessments. For the assessment, the shadow price of a building is compared to a reference value (Table 7). The reference value of the shadow price can change over time, but a value was used of 0.8 €/m$^2$ GFA (BREEAM-NL, 2010).

Table 7. Targets and corresponding points that can be achieved in the MAT 1 category (BREEAM-NL, 2010; BREEAM-NL, 2014).

| **Points** | **Target** |
|---|---|
| 1 point | At least three materials options are considered which have a significant impact on the shadow price. |
| 2 points | The environmental impact of the materials used is below 0.8 €/m$^2$ GFA (reference value) |
| 3 points | The environmental impact of the materials used is at least 10% lower than 0.8 €/m$^2$ GFA (reference value) |
| 4 points | The environmental impact of the materials used is at least 20% lower than 0.8 €/m$^2$ GFA (reference value) |
| 5 points | The environmental impact of the materials used is at least 30% lower than 0.8 €/m$^2$ GFA (reference value) |
| 6 points | The environmental impact of the materials used is at least 40% lower than 0.8 €/m$^2$ GFA (reference value) |
| 7 points | The environmental impact of the materials used is at least 50% lower than 0.8 €/m$^2$ GFA (reference value) |
| 8 points | The environmental impact of the materials used is at least 60% lower than 0.8 €/m$^2$ GFA (reference value) |

In order to promote cattail-based insulation material for usage in BREEAM certified buildings, its contribution to the shadow price should be low. For actual BREEAM projects, calculations of the shadow price should be performed by an independent assessor. However, the BREEAM website addresses indications of how the shadow price can be calculated, using a calculator that utilizes the National Environmental Database (http://www.milieudatabase.nl/viewNMD/index.php), for example the MRPI Freetool (http://www.mrpi-mpg.nl/). Using this tool, calculations were made to get insight into the contribution of insulation materials to the total shadow price. Unfortunately, cattail-based insulation is not included in the National Environmental Database and therefore it could not be compared with competing insulation materials. For the competing materials, a shadow price per 100 $m^2$ insulation material was calculated, based on a residential building with a life expectancy of 75 years and a Gross Floor Area of 130 $m^2$. In this way, the data gives a rough indication of an insulation material's shadow price in an average insulation project (100 $m^2$ is indication for the whole cavity wall (isolatie-weetjes.nl, 2017); 130 $m^2$ GFA is indication for a typical row house (Voss & Musal, 2013).

The values of the shadow price range from €0.005 for Flexible Wood Fibre Insulation, to €0.015 for EPS or to €0.565 for Sheep Wool (More materials in: Appendix 2, Table 2). Although these values are not calculated by professionals, they indicate that the type of insulation material that is used can have a major impact on the shadow price. It also indicates that, in order to have a lower shadow price than the reference value of €0.8/$m^2$ GFA, a sustainable material should be chosen. A Life Cycle Assessment of cattail-based insulation materials will be needed to calculate their shadow price. After that, a comparison with other insulation materials can be made and, potentially, the shadow price of cattail insulation will be lower than competing insulation materials. Then, the usage of Cattail insulation and its added value for BREEAM certified projects can be shown and/or recommended.

For MAT-5 Responsible sourcing of materials, a maximum of 4 points can be granted. The first point is given when at least 80% of the insulation materials used have a legal and proven origin. This, and extra points can be awarded according to the sustainability of the resources determined by the MAT-5 calculator. This is a calculation tool developed by BRE and uses the sustainability tier a material is placed in (i.e. Tier level 1-4). In order to promote cattail-based insulation material to use in BREEAM certified buildings, the material should have a high tier. Proof required for the highest tiers is based on a BES 6001:2008 certificate level (i.e. 'excellent' or 'very good' for tier 1; 'good' or 'pass' for tier 2) (Appendix 2, Table 3; BES 6001, 2008).

In conclusion, cattail-based insulation materials could be promoted to be used in the construction of BREEAM certified houses if certain conditions are met. Among these conditions are compliance of the acoustic performance results with the required parameters, no thermal leakage when using the material in the building, a life cycle assessment of the material with low impact in the overall shadow price, and having a BES 6001 certificate for the insulation material. However, one should take in mind that complying to these requirements only has an added value if the material will be used in BREEAM certified buildings/projects. This requires a lot of (administrative) work, and although it is growing it is currently still a niche market. Therefore construction companies usually prefer to work with NEN-norms, which are product specific (Verboom, personal communication, 2017).

## 4.3 Types of insulation

Cattail can be used for the production of different insulation materials. These includes mainly foams, blow-in material, and particle boards. The potential use of cattail for the production of these types of insulation will be described in this section, considering the optimum cattail parts for each type. The processes available for the production of each insulation material will also be assessed.

### 4.3.1 Spray foam

Sprayed foam insulation is used to prevent air leakage and keep the energy from flowing out. Sprayed foam quickly expands itself many times its initial volume in the liquid phase and then solidifies, sealing the air holes which cause the energy losses from inside the building. This also prevents harmful particles and aerosols from outside coming through the leak routes in walls and roofs. There are two types of sprayed foam regarding its composition: open-cell and close-cell. Open-cell foams have low density, flexibility, softness, sponge-like textures and are used for interior applications. Compared to open-cell, close-cell foams have higher density, tensile, bond strength and R-value. According to Energsmart Foam Insulation company, they can reject bulk water so it is normally used for exterior applications. Sprayed foam has the highest R-value, compared to other insulation materials (see appendix III).

A large portion of sprayed foams is derived from petroleum. One of the widely used sprayed foams is polyurethane foam, which production process contains two main components: isocyanate and polyol, as can be seen in Figure 10 (Kapps & Buschkamp, 2004). Bio-based polyol, which is extracted from plants, shares the same properties and can replace the polyester polyol in processes of polyurethane production. Therefore, these sprayed foam products made from bio-based renewable sources can be considered as an alternative way. They reduce the energy consumption for manufacturing insulation industry, thus lowering the carbon footprints (Meyer, 2011). Vegetal fibres have also been proposed as an enhancement of foams (Banik & Sain, 2007; Silva et al., 2010), but little research has been performed so far in this area, as well as for the use of oil extracted from cattail seeds to replace the polyol. This will be explained in further detail in section 4.4.2.

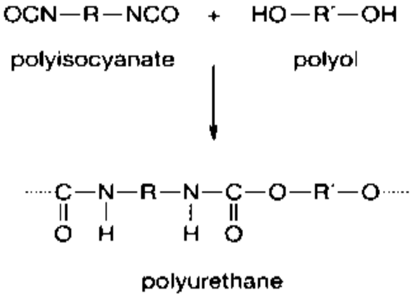


Figure 10. Polyurethane production (adapted from Kapps & Buschkamp, 2004).

### 4.3.2 Rigid, flexible foam

Polyurethane foam also has application in both rigid and flexible foam boards. In fact, the sprayed polyurethane foam is the result of mixing the two main components mentioned above at the time they come out of the spray gun at normal atmosphere conditions. Compared to sprayed foam, these types of foam show higher mechanical strength because of the difference in density. Rigid insulation material is often used for the external or internal walls and the roof while flexible board foam is more used to install internal walls for sound attenuation. Rigid polyurethane foam has large variety of densities and it adheres to numerous facings without the use of adhesives. Furthermore, rigid polyurethane foam’s application can cover the irregular shapes and seal gaps. Flexible foam is more used as furniture cushioning and packaging material than as wall insulation. This is because the flexible foam has low density and contains many open-cells, meaning that air can permeate through its structure.

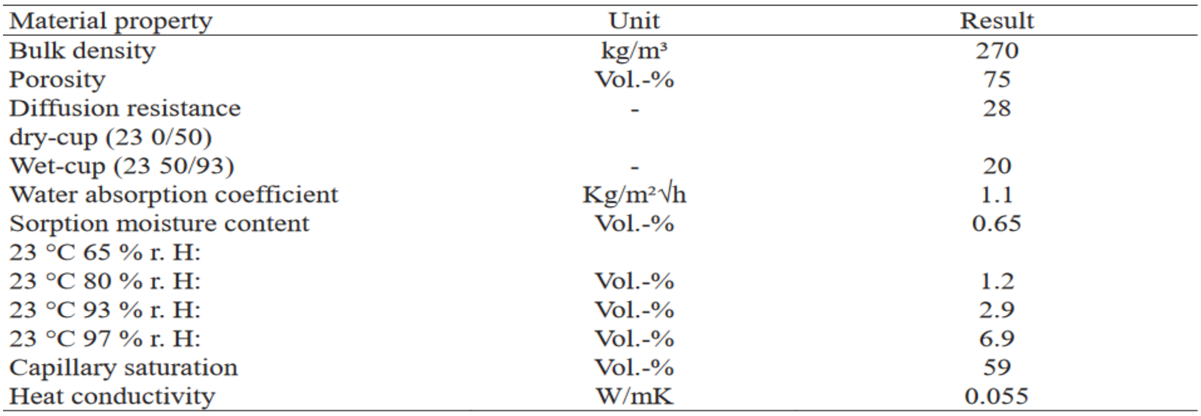
### 4.3.3 Particle boards

Particle board is the most popular insulation material used, because of its advantage in a wide range of input material regarding waste paper, plants containing high amount of cellulose, simple manufacturing processes and cheap production price. This type of insulation is often used for insulating walls and roofs. First, the fresh woody biomass needs to be dried before continuing with the shredding step and then move to the grinder, where all the materials are turned into smaller particles. At this step, the material is mixed with the binder, for example gypsum, cement or glue, to stick the particles together. Then, the mixture will be transferred to a mould and pressed under high pressure and high temperature to form up the particle panel product. The materials used for this thermal insulation type include a wide variety from wood, plywood, wood chip to small stem like hemp, cattail and even finest particle as fibreboard.

Cattail suitability for producing this type of insulation has been already assessed (Luamkanchanaphan, 2012), and the conclusion reached was that insulation boards made with narrow-leaved cattail fibres possess good mechanical and physical properties, and showed thermal conductivity (λ) values of 0.0438-0.0606 W/mK, which comply with the TIS. 876-2547 standard. However, the λ-values mentioned belong to a tested wall of 10 mm. According to the Dutch governance, as a guide line the R-value should be a least 2.5 W/m$^2$K (Ministerie van binnenlandse zaken en koninkrijksrelaties, 2013). This 10 mm thick test wall has in the best case scenario, when the wall has a density of 200 kg/m$^2$, a λ-value of 0.0438 W/mK, and an R-value of 0.228 W/m$^2$K. This means that in order to comply with the Dutch law any insulation wall should be at least 10 cm in order to be useful. In order to be usable as an outer wall of buildings it should be at least 15 cm thick. For inner walls a thickness of 19 cm is needed and for roofs a thickness 26 cm. According to these calculations, values indicate that according to Dutch law insulation material should have at least a thickness of 10 cm. Although companies such as Typha Technik mention their boards are 4-12 cm (Typha Technik, 2017), a minimum thickness of 10 cm is very high. One point that should be addressed on which the Governmental website is not clear, is the meaning of the R-value of 2.5 W/m$^2$K. They indicate that 'vertical separating constructions' should have that insulation value, but it is not specified if the wall itself also is part of the R-value of 2.5 W/m$^2$K. If so, this would indicate the minimal thickness of the cattail-based insulation will be lower to comply to the law. Nevertheless, these calculations give an indication that cattail-based insulation boards and their typical λ-value (i.e. 0.044 W/mK) should be of sufficient thickness to comply to Dutch guidelines.

Other important properties are moisture absorbance and mechanical properties (modulus of rupture and modulus of elasticity). The modulus of rupture is the measurement of how much stress is required to rupture the material. The modulus of elasticity is the measurement of how much stress is needed to temporarily deform a certain material. In Table 8 the moisture absorption coefficient and the water content in the cattail-based insulation board at different relative humidity levels at 23 ℃ are shown and the porosity and capillary saturation as well. It also shows that the λ-value differs if the density changes.

Table 8. Properties of cattail particle board (Krus, 2014).



| Material property | Unit | Result |
|---|---|---|
| Bulk density | kg/m³ | 270 |
| Porosity | Vol.-% | 75 |
| Diffusion resistance dry-cup (23 0/50) | - | 28 |
| Wet-cup (23 50/93) | - | 20 |
| Water absorption coefficient | Kg/m²√h | 1.1 |
| Sorption moisture content 23 °C 65 % r. H: | Vol.-% | 0.65 |
| 23 °C 80 % r. H: | Vol.-% | 1.2 |
| 23 °C 93 % r. H: | Vol.-% | 2.9 |
| 23 °C 97 % r. H: | Vol.-% | 6.9 |
| Capillary saturation | Vol.-% | 59 |
| Heat conductivity | W/mK | 0.055 |

According to the Dutch law, insulation material is allowed to have 2 Vol.-% of moisture. So the cattail fibre insulation complies with the Dutch law as long as the relative humidity of the air is lower than 86.5% (Figure 11). Since the average annual relative humidity between 1981 and 2010 ranges from 80% to 85% during winter (Koninklijk Nederlands Meteorologisch Instituut, 2010), moisture levels of cattail insulation will likely comply with the law.

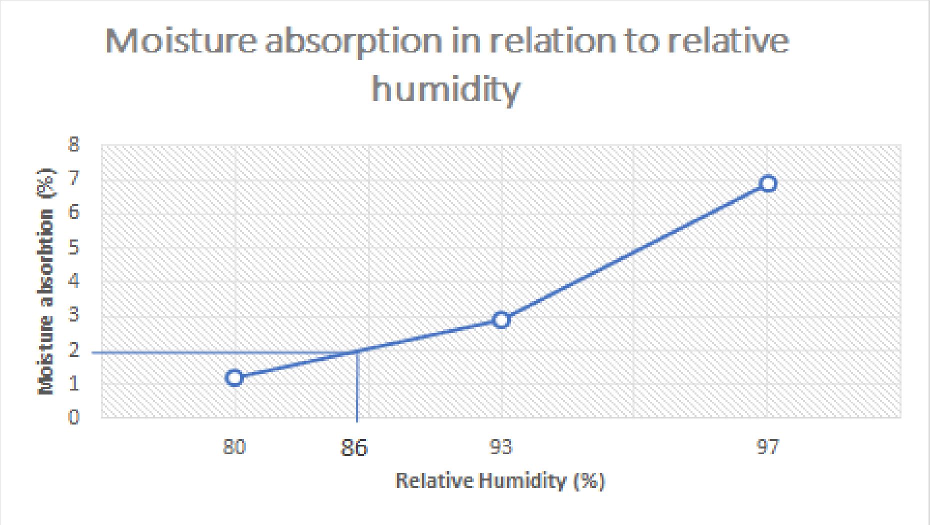


Figure 11. Moisture absorption in relation to relative humidity. Based on data from Krus, 2014.

The MOR and MOE are also assessed by Luamkanchanaphan (2012). The results are that for material with the density range from 200 to 400 kg/m$^3$ the MOR-values range from 7.73 bar to 36.12 bar. According to the standards used (those reported in the guide published by Hoadley, 2005), the range of MOR-values should be 13.79-55.16 bar. For MOE, the range of values obtained by Luamkanchanaphan is 0.77-3.27 bar, while the standards range 1.72-8.62 bar. Compared to this standard the cattail insulation with density of 300 kg/m$^3$ and 400 kg/m$^3$ comply but the the insulation with the density of 200 kg/m$^3$ does not.

While the insulation material has better thermal resistance properties at lower densities, there are problems with the other properties if the insulation wall has a density of 200 kg/m$^3$. But in table 7 it can be seen that with a density of 270 g/m$^3$ the cattail insulations complies with the moisture sorption standard and could comply with the mechanical properties. There is information about densities 200 and 300 kg/m$^3$,200 does not comply with the standard while 300 does, so further research is needed. Furthermore will the thickness needed to comply with the required R-value change slightly,from the calculations made before, ranging from 13.75 to 33 cm. A normal insulation of a outer wall can be 18 cm thick and the minimum thickness for roof insulation, which is the highest end of the range, is normally 22 cm, so this range is still achievable (Lambda.be, Minimale isolatiewaarde anno 2016 voor EPB, 2016). These findings confirms that cattail is potentially suitable for insulation board production, which can be used against noise, cold, and hot weather. This new insulation material can then be applied in flat roofs, roofs with air circulation, roof frames, walls and other cavities.

### 4.3.4 Blow-in material

Heat insulation properties of cattail-based blow-in material were assessed by performing an experiment in collaboration with Bouwgroep Dijkstra Draisma. The purpose of this experiment was to evaluate the λ of a cattail-based blow-in material in order to compare it to those of currently used insulation materials (e.g. Easycell® or Isofloc®) and to check if the λ-values obtained could be ≤ 0.035 W/mK (Reference λ of Isofloc®). Another point that is important to assess regarding blown-in insulation material is presence/absence of the tendency to compress in the material. Both aspects will be tested and compared to a reference material (Isofloc®).

The tested material consisted of a mix of cattail leaves and fluffy material. Leaf material with an initial (wet) weight of 8.17 kg was left to dry at room temperature for six days. After the drying treatment, the material showed a reduction in weight of 80%. The dried material was then shredded using an Eliet® neo electric garden shredder until an average particle size of approx. 2 cm was acquired. Fluffy material from dry cattail seedheads from a previous harvest (October 2016) were mixed with the shredded leaf material in approx. half-and-half on volume base. Afterwards, a sampling mould (0.45x0.5x0.0875 m) was filled with approximately 2 kg of the cattail mixture, reaching a density of 91.5 kg/m$^3$.

The thermal conductivity was then determined by applying a heat flow of 1000-2000W from a heat source (Munters LOR 2 FE, electrical PTC Fan Heater) to one side of the sampling mould at a distance of around 15 cm. Temperatures on both sides of the sampling mould were measured over time for up to 45 minutes. Thermal conductivity was calculated using the following equation:

$$\text{Thermal conductivity } (\lambda, \text{W/mK}) = QL/A\Delta T \qquad \text{(Eq. 3)}$$

Where:

Q = Heat flow in W (J/s).

L = Length/thickness of the mould in m (0.0875 m).

A = Area in m$^2$ (0.225 m$^2$).

ΔT = Difference in temperature between each side of the mould.

The material was also tested for compression tendency. The mould filled with cattail material was left for one week and reduction in the filled volume was assessed afterwards. The volume occupied by cattail material was indeed slightly reduced after a week, as some empty spaces appeared in the upper corners of the mould. This means the material has a small tendency to compress.

In order to calculate the heat flow (Q), a graph was made for both the cattail and the reference material plotting the temperature vs the time. The linear regression equation was then calculated, which shows the average temperature increase of the mould per second. It was shown that the reference material required in average 18.3 seconds to increase its temperature in one unit ℃. The specific heat capacity of the reference material is known, 2150 J/kgK, so the heat flow can be calculated using the following equation:

$$\text{Heat capacity } (Cp, \text{J/kgK}) = q/m\Delta T \qquad \text{(Eq. 4)}$$

Where:

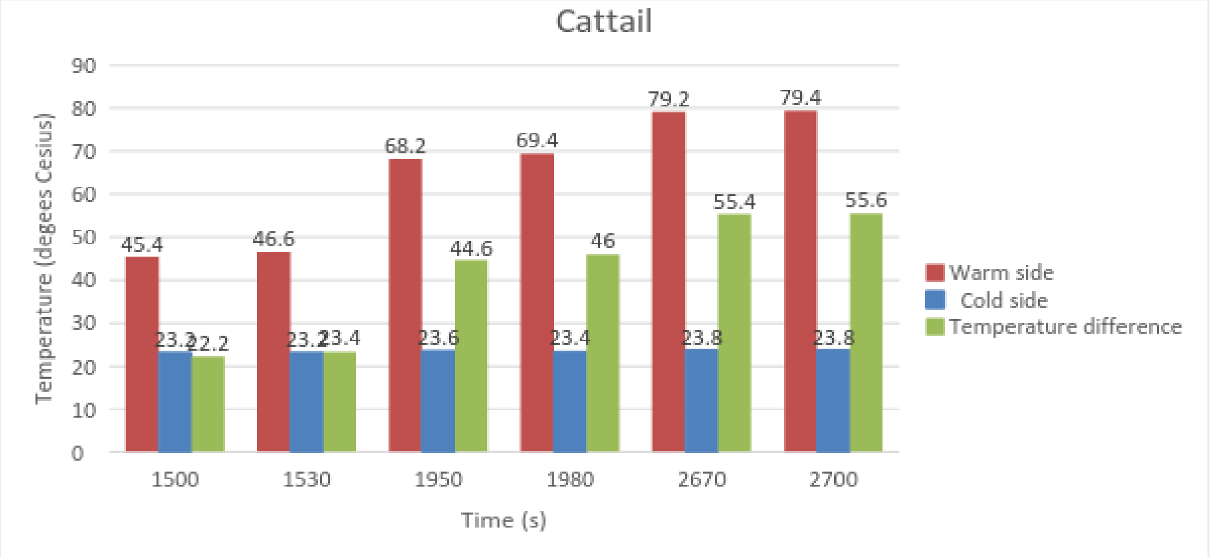
q = heat content of the material in J, which can be also expressed as the steady heat flow (J/s) times the increase in time (s).

m = mass of the sample in kg (1 kg Isofloc®, 1,8 kg cattail).

ΔT = increase in the average temperature of the material.

Since 1 kg of the reference material needs 2150 J to increase its temperature in one temperature unit, knowing that it required 18.3 s to do so means that the actual heat flow applied to the material was Cp/(18.3*1*1)= 2150/18.3= 117.49 J/s. The heat capacity of the cattail material was then calculated using the same approach: in average, cattail material required 21 s to increase its temperature in one unit when a heat flow of approx. 58.7 J/s is applied, therefore Cp= (58.7*21)/(1.8*1) = 684,83 J/kgK.

The thermal conductivity was then calculated using the obtained temperature data (Appendix IV) and the calculated heat flows with the thermal conductivity equation (Eq. 3). As can be seen in Figure 12, the tested cattail material has insulation properties close to those of the Isofloc® material under similar conditions. It should be noticed that the cattail material was warmed for a longer period of time, but from the 1500 second mark onwards, in the cattail measurements the heat source capacity was increased from 1000W to 2000 W, which was also the capacity used during the Isofloc® testing. It can be seen that, whereas the hot side is warmer for the Isofloc®, the cold side is more or less the same for both. The temperature difference between the cold and warm chamber was bigger during the Isofloc® test than during the cattail test, but the differences are small (44.5 ℃ and 53.8 ℃, 46 ℃ and 54.6 ℃, 55.4 ℃ and 56 ℃, 55.6 ℃ and 56.6 ℃). This also shows that at high temperatures the performance of both insulation materials becomes more similar.



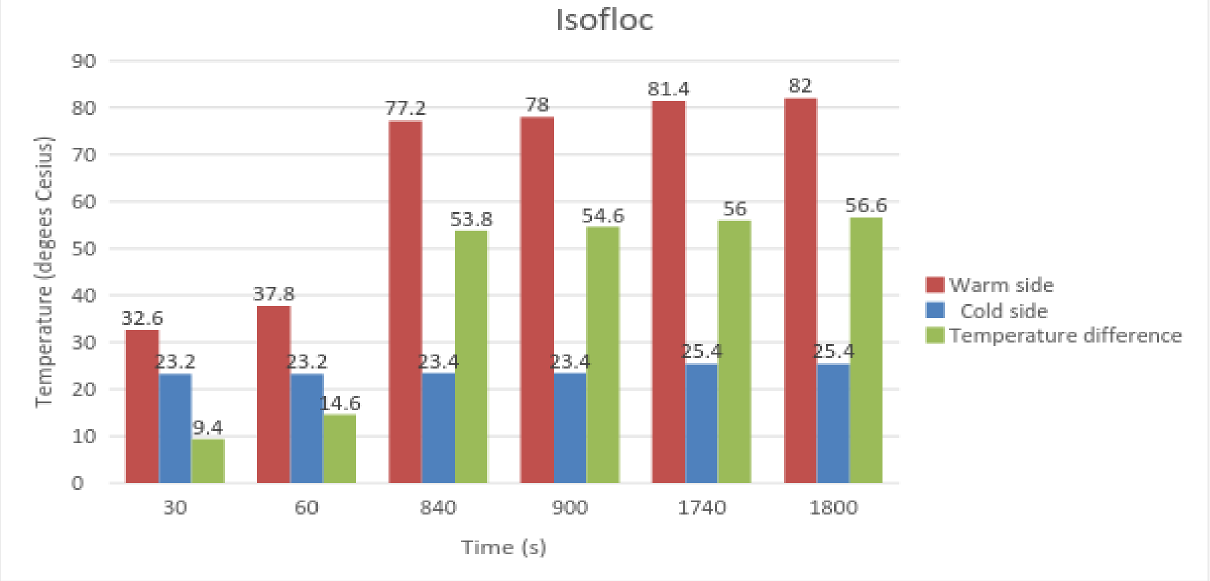


Figure 12. Graphical representation of the temperatures measured at different time.

When calculating the thermal conductivity, the cattail insulation moulds reached an average λ-value of 1.53 W/mK, while the reference material showed an average λ-value of 1.43 W/mK. These values are very high compared to what it has been reported in the literature, both for the reference material and cattail insulation. This is likely due to the experimental set up not complying with the standard testing procedures. The particle boards made of cattail leaves that were tested by Luamkanchanaphan (2012) had densities ranging from 200 to 400 kg/m$^3$, showing thermal conductivities among 0.0438-0.0606 W/mK. The author also proved that an increase in the material density leads to an increase in the thermal conductivity. Similar statements were also claimed by Dieye et al. experiment (2017). This means that the λ-values obtained in the experiment for cattail blow-in material should have been lower than those reported by Luamkanchanaphan, as the density of the tested material was 91.5 kg/m$^3$. In the same way, λ-value for the reference material should have been of about 0.038 W/mK, as specified in the product specifications (Spanotech, 2013). This high values may be a result of the high heat flow rates used, as well as the narrow width of the moulds (0.0875 m). It should be also noted that the moisture level of the cattail material was probably higher than desired, which could have increased its thermal conductivity, and that the temperatures and duration of the measurements were not equal for cattail and reference materials.

Further attention should be paid to the density needed for the cattail material to fully fill the box. This value was found to almost doubled the desired density of 50 kg/m$^3$ acquired by the reference material, meaning that cattail insulation may be heavier than previously expected. This high value could be partly due to the moisture content of the cattail material, as it could not be properly estimated and maybe was still too high. The difficulties found for the shredding and mixing of the material may also have affected the density obtained. Regarding the shredding, cattail leaves had to be shredded three times to obtain an acceptable particle size, and even after that large fragments could still be found. This was most likely due to the shredding machine used, which may not be appropriate for achieving the required particle size. As for the mixing, the fluffy material tend to clump together, thus hampered greatly its proper mix with leaf material. These issues were also reflected in the difficulties encountered for filling the upper corners of the mould.

Insects were previously reported to be present in cattail seed material (Postma & Verboom, personal communication, 2017). However, none was found during this experiment. This is likely due to the long storage time of the material (about 6 months). Nevertheless, it may be recommended to subject cattail material to a cold (-20°C) or heat pretreatment to avoid pests and diseases outbreaks, which would reduce the quantity and quality of the insulation (Verboom, personal communication, 2017). Additionally, it should be checked if these pretreatments can be applied to cattail material without having a significant impact in its insulation properties.

As a conclusion, even though the density and λ-value obtained for the tested cattail insulation material were higher than expected, the λ-value of the reference material was also higher than reported in the literature. This means the experimental setup was not suitable for achieving a good estimation with an adequate accuracy. Moreover, better drying, shredding and mixing may be sufficient to solve the main issues found. Finally, it should be highlighted that, even though no statistical significance can be calculated using these data, this material seemed to perform comparably to the reference material without the need of additives, which seems promising and so more research should be performed to finally assess the properties and requirements for this kind of insulation.

### 4.3.5 Insulation properties comparison

Table 9 displays a summary of different bio-based insulation materials, whose properties can be comparable to those reported for cattail-based insulation materials. One of the most relevant properties is thermal conductivity, which for both biocomposites and blow-in materials ranges among 0.04 and 0.035 W/mK. For the case of blow-in materials except the cattail-based insulation material assessed in the experiment, the thermal conductivity is among 0.035 and 0.250 (W/mK). The thermal conductivity reported for the cattail fibres in the test performed was found to be too high, but this could be due to many other factors affecting the results such as the moisture content and the bad mixing of the material. More research is then needed to further conclude about the feasibility of cattail as a blow-in material. Density and moisture level are also important parameters to consider, as they have large impact in the thermal insulation properties and the final weight of the building structure. The density found in the experiment was very high compared to other blow-in materials, but it may be reduced with a better control of the moisture content and processing methods, as explained in the previous section.

In summary, there are several types of insulation materials that can be produced with cattail material: blow-in, particle boards and spray foam. Spray foam forms when polyurethane and polyol react with each other when they are sprayed on the wall and form polyurethane  There is ridged and flexible spray foam, the rigid spray foam is mostly used  for outer walls and the flexible spray foam for the inner walls if it is used for walls at all. The flexible foam is mostly used for packaging and cushions for furniture. The spray foams often are petroleum based  due the use of polyol, there is bio-based polyol which could be an alternative, but there is not much research done about it. Particle boards are made from cellulose rich biomass, which will first be dried, then shredded and grinded; during the grinding it a binding resin will be added that will function like a glue to keep everything together after the process is done. the last step is transferring the material into a mould where it will be pressed under high temperature and pressure. Cattail particles boards comply with the Dutch law for the insulation materials when the density is 270 kg/m$^3$.

In order to get information about the properties of cattail based blow-in insulation, an experiment was carried out to measure the thermal conductivity and compression tendency of shredded, dried cattail material, and to compare it to a reference material currently used (Isofloc®). The density of the cattail was almost twice as high as the density of the Isofloc® and the thermal conductivity measured for both cattail and Isofloc® were much higher than expected. Despite the limitations of the experiment, the results showed that the cattail material is comparable to Isofloc® and that the higher the temperature the smaller the difference between the two insulation materials. There were some issues during the experiment that should be considered when further assessing cattail blow-in material: the moisture level should be measured to confirm the material is dry enough, pretreatments should be considered to reduce the risk of pests during drying, better shredding machines should be tested in order to overcome the problems related to shredding and mixing, and experimental set-ups complying with the standard protocols should be used.

When the conductivity and density of cattail insulation is compared to other bio-based insulation, it can be seen that it is most comparable to cork and to a lesser degree to kenaf and wheat straw. Furthermore it can be seen that cattail has better properties than: shells, cotton stalk fibre and a mix of durian peel and coconut coir.

Table 9. Insulation parameters of various bio-based materials.

| **Material** | **Type** | **Density** (kg/m$^3$) | **Thermal conductivity** (W/mK) | **Thickness to obtain an R-value of 2.5** (cm) | **R-value (conductivity /thickness)** | **Moisture diffusion coefficient** | **Source** |
|---|---|---|---|---|---|---|---|
| Cattail fibres | Blow-in | 91 | 1.53 | n/d | n/d | n/d | Present study |
| Hemp | Blow-in | 20-45 | 0.04-0.06 | n/d | n/d | n/d | CMA, 2002 |
| Narrow-leaved cattail fibre (hot-pressed) | Biocomposite | 200-400 | 0.0438-0.0606 | n/d | n/d | 11-15 % moisture content | Luamkanchanaphan et al., 2012 |
| Wheat straw board | Biocomposite | 150-250 | 0.0481-0.0521 | n/d | n/d | n/d | Zhou et al., 2010 |
| Cotton stalk fibre | Biocomposite | 150-450 | 0.0585-0.0815 | n/d | n/d | n/d | Zhou et al., 2010 |
| Durian peel and coconut coir | Biocomposite | 311-611 | 0.0728-0.1117 | n/d | n/d | n/d | Khedari et al., 2004 |
| Kenaf | Biocomposite | 100-250 | 0.040-0.065 | n/d | n/d | n/d | Xu et al., 2006 |
| Expanded perlite | Blow-in | 78-224 | 0.0477-0.0616 | n/d | n/d | n/d | Zhou et al., 2010 |
| Vermiculite | Blow-in | 80-200 | 0.047-0.07 | n/d | n/d | n/d | Zhou et al., 2010 |
| Reed | Biocomposite | n/d | 0.06 | 15 | 2.5 | n/d | Dam & Oever, 2012 |
| Coconut latex bound | Biocomposite | n/d | 0.045 | 11 | 2.5 | n/d | Dam & Oever, 2012 |
| Flax | Blow-in | 50 | 0.04-0.055 | 14 | 2.5 | n/d | Dam & Oever, 2012 |
| Sheep wool | Blow-in | n/d | 0.035-0.04 | 10 | 2.5 | n/d | Dam & Oever, 2012 |
| Shells | Blow-in | n/d | 0.106-0.250 | 63 | 2.5 | n/d | Dam & Oever, 2012 |
| Cork | Biocomposite | 200 | 0.45 | 11 | 2.5 | n/d | Dam & Oever, 2012 |
| Cellulose | Biocomposite | 30-70 | 0.04 | 10 | 2.5 | 1.5 | Dam & Oever, 2012 |

## 4.4 Vegetal fibre for insulation

Fibres, consisting mainly of cellulose, can be extracted from plant material for their application as insulation. The structures and properties of this compound will be described in this section, as well as the methods that can be used for fibre extraction and processing for insulation. The feasibility of using cattail plants for fibre extraction will then be assessed and the optimum extraction and processing method will be discussed.

### 4.4.1 Cellulose properties

Cellulose is the most common organic polymer and one of the main components of plant fibres (Klemm et al., 2005). It is located primarily in the plant cell walls, surrounded by other two components, hemicellulose and lignin. This carbohydrate polymer consists of repeated β-D-glucopyranose units linked covalently, which provides linear structures as shown in Figure 13.

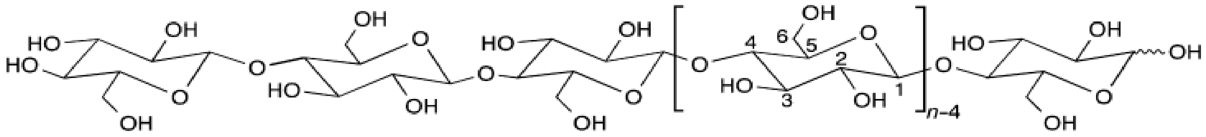


Figure 13. Cellulose structure (Klemm et al., 2005).

Cellulose is a fibrous and water-insoluble polymer with strong inter- and intramolecular hydrogen-bonding. However, the mechanical properties of cellulose depend on the type of cellulose present (I, II, III$_1$, III$_2$, IV$_1$ and/or IV$_2$) and the state in which it is present (solid or in alkali-based solvents solution (Kihlman et al 2013). In nature, cellulose is only found in type I polymorph, which has the best mechanical properties but it is less thermodynamically stable, while cellulose type II is considered the most relevant stable structure (Morán et al., 2008). Cellulose type II can be made by two different treatments of cellulose type I, mercerization or precipitation/regeneration which lead to the formation of fibre and film. Cellulose in solid state is represented by its crystalline structure which consists of two parallel cellulose chains (O'sullivan, 1997). The structure of cellulose in solution depends on the type of cellulose, the polymer concentration, the chain length distribution and the type of solvent used as shown by Klemm et al. (2005) (Figure 14). Due to its gel-forming particles, cellulose in solution is considered to have a high potential in the packaging industry.

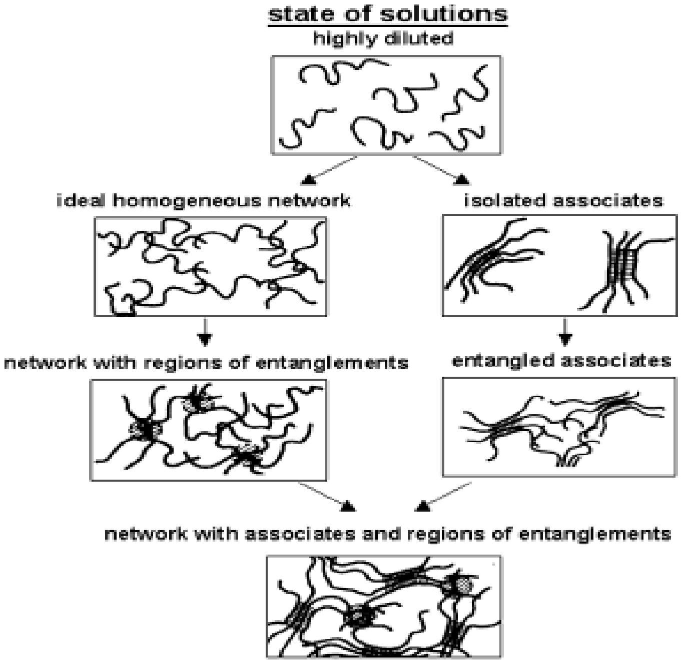


Figure 14. Cellulose structures formed in solution (Klemm et al., 2005).

Cattail has been reported by Al-Hakkak & Bar-booti (1989) to have a total cellulose content (%DW) of 41%. However, more recently it has been found by Küçük et al. (2005) that cattail can have a total cellulose content of up to 47%DW. These percentages also change for lignin content, as previously it had been reported to be 24%DW but in the most recent study it was shown to be 21.9%DW. However Küçük et al. (2005) research did not specify which species of cattail was used for their analysis. Cellulose microfibrils in cattail leaves are positioned parallel to the long axis of the fibre, which allow for strong bonding with lignin and hemicellulose. Hemicellulose is located between the cellulose microfibrils. Cellulose is bound to hemicellulose and lignin via hydrogen bonds. Hydrogen bonds must be broken in order to access the cellulose contained in the lignocellulosic material, and this can be done through multiple processes, which are covered in the following section.

### 4.4.2 Fibre properties

Plant fibres are long and multiple-celled or short and single-celled, composed mainly of cellulose, but also of hemicellulose, moisture, lignin, pectins and ashes which bind the fibres together. The long, multi-celled fibres can be divided into hard and soft according to the level of stiffness and how thin the fibres are. The biological content determines the strength and durability of the fibre. A higher content of cellulose leads to stronger fibres while high contents of lignin leads to lower tensile strength. Therefore, the fibres should be processed in order to reduce the amount of lignin in the fibre without reducing the cellulose content of the fibre.

Fibre can be obtained from the seedheads, the leaves, and also from the stem of cattail plant. The research of Cao et al. (2016), showed that cattail fibre length ranges from 3 to 11 mm while the fineness was found at range of 10-17,5 μm. There are two options by which fibre from cattail can be used for insulation material. The first option is using the combination of seedheads fibre and the leaf fibre as blow-in insulation material. The second option is enhancing the performance in terms of density and thermal stability of both spray foam and normal foam regarding polyurethane foam by reinforcing the cells of foam with the fibre. Nevertheless, there is very little literature on the feasibility of using fibre and polyol derived from cattail in order to improve the performance of polyurethane foam. Banik & Sain (2007) prepared the mixture of cellulose fibre as aqueous suspension with the foam and stirred for different periods of times. Their results showed that the density of the foam increased significantly along with higher mixing time, while another study showed the thermal conductivity witnessed a small drop in the same conditions (Silva et al., 2010). Long fibre with higher ratio aspect contributes to complex structure and act as chain extender, therefore have better enhancement of the foam cells than short fibre. With the addition of fibre, it also helps to delay the thermal degradation, increases the compressive strength of foam (Khazabi, 2011).

### 4.4.3 Extraction methods

There are multiple methods by which cellulose and plant fibres, including cellulose can be extracted from cattail. These has been researched due to the high content of both in cattail, which has made it an attractive bioresource for the production of 2nd generation bioethanol. The majority of these processes focus on pretreating the lignocellulosic material in order to make cellulose more accessible or to increasing fibre properties by removing lignin, as seen in Figure 15. The treatments vary on style since they can be mechanical, chemical, enzymatic or a combination of both mechanical and chemical as outlined in Figure 16.

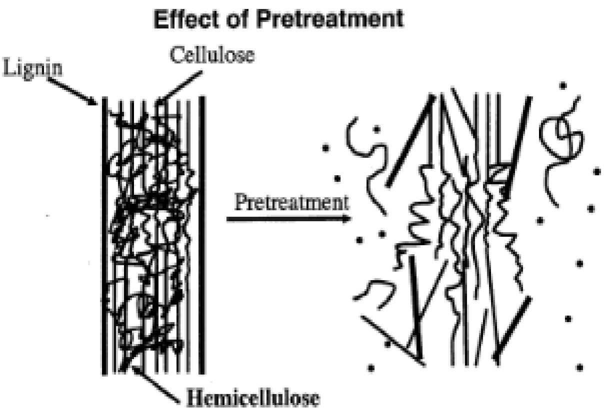


Figure 15.Effect of pretreatment on lignocellulosic material (adapted from Harmsen et al., 2010).

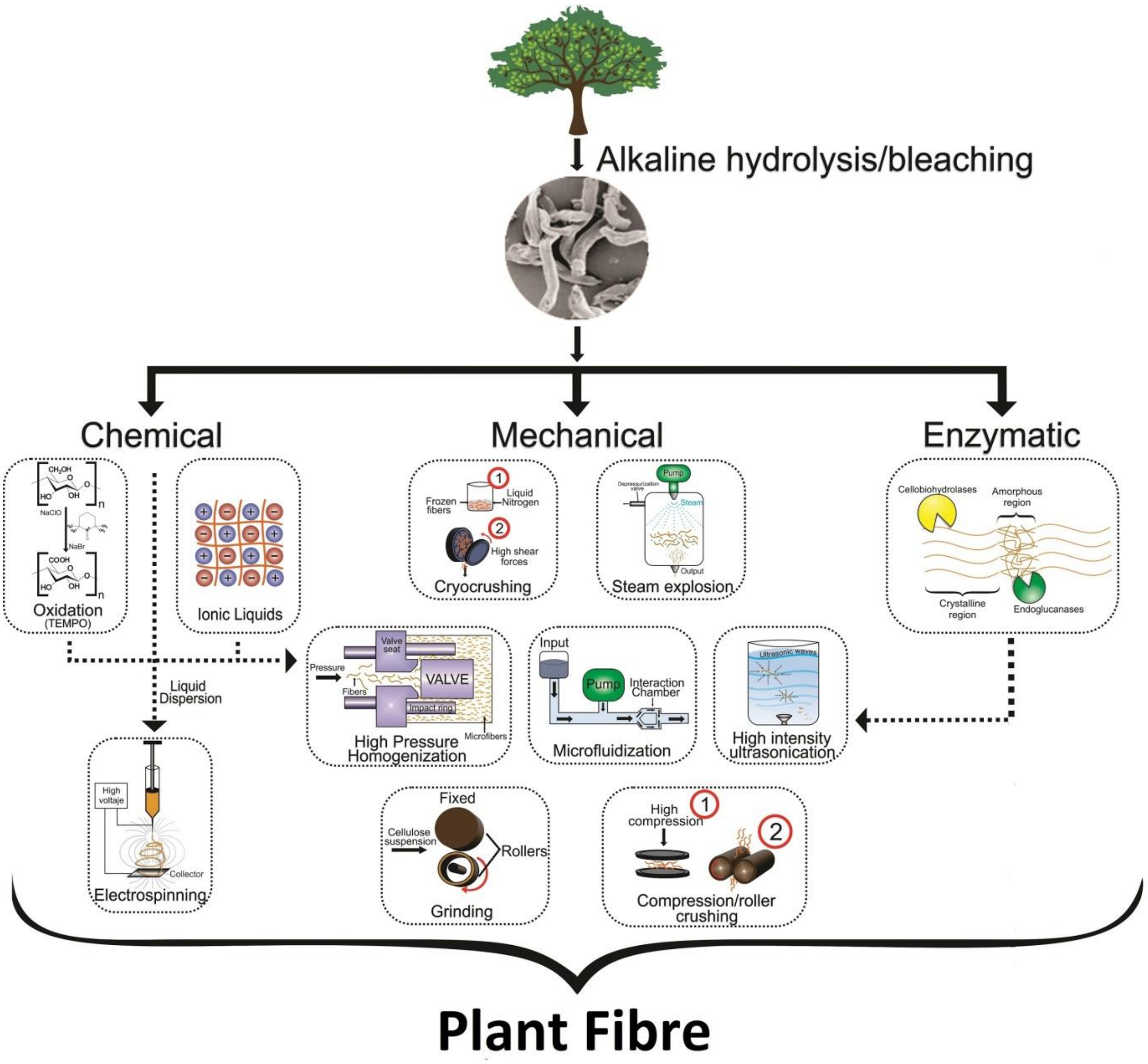


Figure 16. Fibre extraction methods (adapted from Rojas et al, 2015).

The main mechanical pretreatment process for the extraction of plant fibres is milling, which consists of the chipping or grinding the lignocellulosic material in order to increase the surface to volume ratio and ease the handling of the material.

There are multiple chemical pretreatment options, however the most economical ones are the liquid hot water pretreatment and the chemical retting using alkali or acidic solutions (Kumar & Murthy, 2011). The liquid hot water pretreatment involves the use of hot water and pressure in order to break the hydrogen bonds formed between hemicellulose, lignin and cellulose. The recommended treatment for obtaining the highest amount of cellulose through this method according to Zhang et al. (2010) is heating the material at a rate of 25°C/min until reaching 190°C and maintaining that temperature for 15 minutes. The chemical retting process, on the other hand, is a cheap process used to dissolve non-cellulosic material. The process consists on placing biomass in a heated reaction vessel containing alkali or acidic solutions and chelating agents in order to dissolve the non-cellulosic components. Long incubation times at high temperature lead to increased availability of cellulose and the decrease of lignin and hemicellulose as seen by Moghaddam et al. (2016) research. The experiment conducted made use of *T. australis* leaves. The leaves were first  chipped into small pieces and then retted in the container with an alkaline solutions containing NaOH, KOH, sodium tripolyphosphate, and EDTA. The ratio between the liquor and solution was 50:1 and the retting was performed at a temperature of 60°C for 6 hours, resulting in a fibre extraction efficiency of roughly 32%. Moghaddam et al. (2016) showed that by increasing the temperature from 60°C to 80°C and maintaining the temperature for 8 hours, the lignin to cellulose ratio decreases. As for the combined pretreatments methods, sulfur dioxide ($SO_2$) steam explosion is considered by some as most cost-effective pretreatment process with the maximum conversion efficiency (Zhang & Abolghasem, 2011). Steam explosion is a thermomechanical process (200-270°C) that exposes the cellulose exposure by using steam at high pressure around 14 and 16 bars (Rojas et al., 2015). To be more specific, this process penetrates through the biomass by diffusion in short periods of time followed by a sudden decompression (explosion), which will create shear force. Once the explosion takes place, the solid which exploded by steam, is separated by filtration, then rinsed with pure water. After that the solution is being centrifuged to eliminate the fluid, following by drying step, and ended up as cellulose pulp (Phinichka, 2017). However, $SO_2$ which is used in the most cost effective type of steam explosion is extremely toxic and may be hazardous for the environment. These treatments can be used both for the acquisition of cellulose and plant fibres by either increasing the temperature to obtain cellulose or lowering the temperature in order to obtain a higher lignin content in the fibres. Once obtained, both materials can be further processed for use in multiple applications.

Out of the three chemical processes for the extraction of fibres with increased cellulose mentioned, the most recommended process is hot water pretreatment. This is due to the properties of fibre extracted through chemical retting being poor compared to those obtained by other methods. The costs involved in hot water pretreatment are lower than those for steam explosion (Kumar & Murthy, 2011). These costs consider the amount of energy required to process the material, the chemicals used, purchasing, installation, piping, design work and buildings required.

### 4.4.4 Processing

For the first approach, the seedheads and the leaves are harvested and dried. The experiment at the Bouwgroep Dijkstra Draisma used a combination of fluffy material and shredded leaves. After being dried, both leaves and fluffy material are shredded into small pieces and mixed together. This mixture may be used directly as a blow-in insulation, incorporating the required additives. Otherwise, it can also be used for production of particle boards by adding a binder, such as natural rubber latex (Tangjuank & Kumfu, 2011), and placing the mixture into square panel mould for pressing it. The pressing temperature can then be performed at 140 °C during 3 minutes, and the pressure force at approxi. 40 bars (Luamkanchanaphan, 2012). Both blow-in and particle boards have to be tested for fire resistance and other parameters to check their quality.

The second approach involves using natural fibre to enhance the foam. For this approach there is no protocol available related to cattail fibre, but it is possible to develop a process based on studies using similar materials as the wood fibre reinforced soy-based polyurethane foam (Khazabi, 2011).

The pulp fibre, after being derived from the cattail plant, goes through a length measurement. The different amount of pulp fibre, for example 10, 20, 30 parts per hundred grams of polyol, are mixed with 100 parts of polyol for 20 minutes. After that, the combination will be added to the neat polyurethane foam, using isocyanate as a binder, together with additives regarding diamine as catalyst, polysiloxane as surfactant and distilled water as blowing agent. The mixture will be mixed for 5 minutes under ambient temperature, then be transferred into a mould for expansion and drying. Finally, a process of stirring under ambient temperature will be performed.

In general, the raw fibre in normal size can be used both for blow-in material by mixing with the binder or it can be pressed into particle panels. Hot water pretreatment is considered as the most recommended process for the extraction of microfibre due to its simplicity and cost. Literature reviews have shown the feasibility of reinforced foam cells using fibres extracted from cattail as an enhancement factor increasing the of polyurethane. However, it is unclear that the effect of cattail fibre length and the other parameter regarding ratio between length and diameter, fineness on structure as well as to the tensile strength of foam. Yet, in order to design the complete process of using cattail fibre for insulation purposes, it is necessary to conduct more research based on the process of other kind of plant.

In summary, fibres (including cellulose) can be extracted from cattail for its application as insulation materials. There are mainly three types of insulation in which these compounds can be used: blow-in, particle boards and foam enhancement, and four extraction methods were analysed for its suitability to be used in cattail biomass: milling, hot water pretreatment, chemical retting and steam explosion. For particle boards and blow-in insulation, the preferred pretreatment method is milling due to the requirements specified by the insulation method. However for particle board, hot water pretreatment can be used to increase the cellulosic surface area thus allowing for easier binding when starch-based adhesives are applied. As for the enhancement of foam, it can be treated either by steam explosion or hot water pretreatment while chemical retting is not recommended due to the poor fibre properties obtained from the process. However, since little literature is known, using cattail in foam enhancements is only a theoretical option, and should not be considered a serious application yet. The protocols for the mentioned extraction methods have yet to be optimized for cattail since they are mainly used as a pretreatment step in the production of ethanol from high cellulose content plants such as corn stover and tall fescue.

# 5. Bio-adhesives

Currently, most glues employed in everyday life are synthetically produced from petroleum and natural gas due to their durability, effectiveness and price. The most common synthetic adhesives in the packaging industry are made from vinyl acetate polymers and latex (Clark, 1992; Wool & Sun, 2011). However, the need to move towards a production system that is less dependent on non-renewable resources has led to research focusing on the use of renewable material as the source for everyday products, in this case glue. The majority of bio-based glues obtained from plants are produced from plant oil, starch, proteins and agricultural fibres containing lignin and/or cellulose. The development of bio-based products from these components can be separated into 5 major units: plant science, production, bioprocessing, utilization, and product design (Wool & Sun, 2011). Plants can be used to obtain biochemical components suitable for producing bio-adhesives. Some crops that are commonly used due to their composition and availability are oilseed crops for polyols, cereals (grains) for starch, woody plants for lignocellulosic material and legumes for proteins. However, cattail shows to be a promising substitute due to its biochemical composition, outlined in Table 10. In this chapter, information will be provided on the adhesive properties of cattail's biochemical components, the steps involved in the biorefinery process for each compound and the feasibility of using each compound for production of bio-adhesives.

Table 10. Composition of cattail biomass (Al-Hakkak & Bar-Booti, 1989).

| **Parameter** | **Cattail (% DM)** |
|---|---|
| Cellulose | 41 |
| Hemicellulose | 30 |
| Lignin | 24 |
| Ash and minerals | 5 |
| Acid-Detergents-Fibre (ADF) | 64 |
| Neutral-Detergents-Fibre (NDF) | 74.5 |
| Acid-Detergents-Lignin (ADL) | 16.1 |

## 5.1 Methylcellulose

Cellulose can be chemically modified in order to generate new biomaterials with different physical and chemical properties. Methylcellulose (MC) is one of the most important cellulose-based modified polymers due to its many industrial applications. MC is synthesized from purified dissolving cellulose through the etherification of cellulose leading to the substitution of the hydroxyls at C-2,C-3 and/or C-6 by methyl groups as seen in Figure 17. MC is usually synthesized through a heterogeneous route in a four-step process, which will be covered in this section.

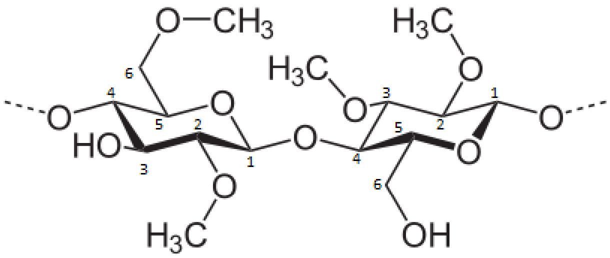
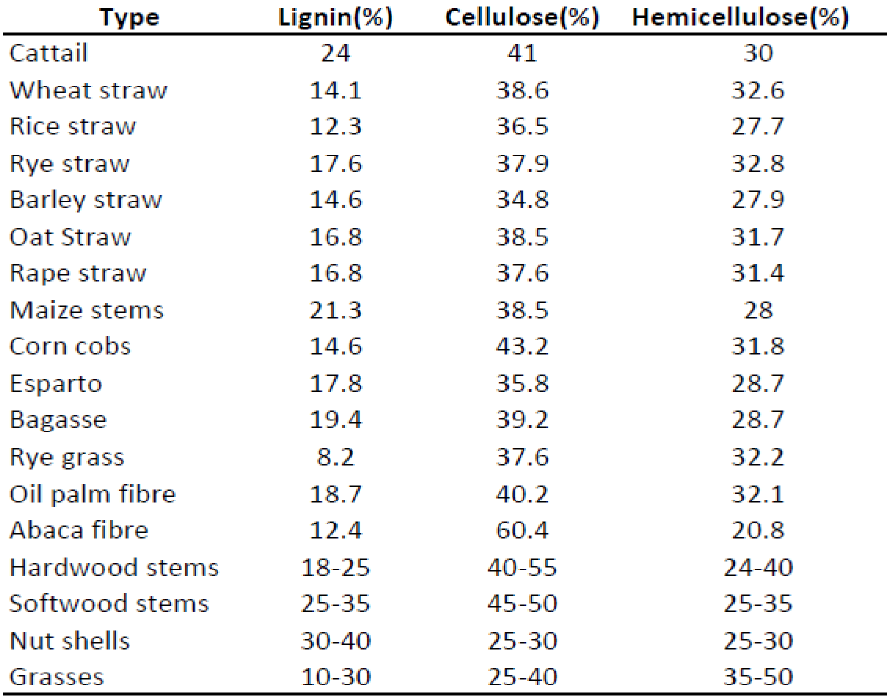


Figure 17. Methylcellulose structure (adapted from wikimedia commons).

MC is provided as white powder which can dissolve in cold water to form a clear viscous solution. MC is soluble in water, mixed solvents and organic solvents. MC can mix with other polymers such as polyvinyl alcohol and salt. Aqueous solutions of MC allow the preparation of films that prevent oil absorption. MC also acts as a binder for pigments, cellulosic fibres, pharmaceutical products and ceramics due its amphiphilic properties. Other properties include enzyme resistant, non-toxicity, and non-allergenicity. As for its adhesive properties, MC is a weak adhesive, used mainly in bookbinding paper, wallpaper pastes and sizing paper and fabrics. MC can also be used as a weak glue that can be rinsed away with water. It is not affected by heat or freezing (Nasatto et al., 2015).

Currently, the most common source for cellulose is paper pulp, which is obtained from wood fibres (Ververis et al., 2011). Research on cattail's lignocellulose composition has shown a similar composition to softwood and hardwood which are the most common wood fibres, as can be seen in table 11. This comparison shows the potential of cattail as a source for cellulose and a substitute for the currently used material.

Table 11. Composition of lignocellulose in several sources from dry matter (adapted from Sun & Cheng, 2002; Ghaffar, & Fan, 2014).



| Type | Lignin(%) | Cellulose(%) | Hemicellulose(%) |
|---|---|---|---|
| Cattail | 24 | 41 | 30 |
| Wheat straw | 14.1 | 38.6 | 32.6 |
| Rice straw | 12.3 | 36.5 | 27.7 |
| Rye straw | 17.6 | 37.9 | 32.8 |
| Barley straw | 14.6 | 34.8 | 27.9 |
| Oat Straw | 16.8 | 38.5 | 31.7 |
| Rape straw | 16.8 | 37.6 | 31.4 |
| Maize stems | 21.3 | 38.5 | 28 |
| Corn cobs | 14.6 | 43.2 | 31.8 |
| Esparto | 17.8 | 35.8 | 28.7 |
| Bagasse | 19.4 | 39.2 | 28.7 |
| Rye grass | 8.2 | 37.6 | 32.2 |
| Oil palm fibre | 18.7 | 40.2 | 32.1 |
| Abaca fibre | 12.4 | 60.4 | 20.8 |
| Hardwood stems | 18-25 | 40-55 | 24-40 |
| Softwood stems | 25-35 | 45-50 | 25-35 |
| Nut shells | 30-40 | 25-30 | 25-30 |
| Grasses | 10-30 | 25-40 | 35-50 |

Cellulose is usually processed to MC in heterogeneous conditions since it is insoluble in the most common solvents. This process is done in four steps:

1. Swell the cellulosic fibres via an alkaline medium such as NaOH in order to obtain alkaline cellulose.
2. Reaction of alkaline cellulose with an etherifying agent.
3. Purification and removal of by-products through a hot water wash.
4. Drying and pulverization of methylcellulose.

However, cellulose can also be processed in homogeneous conditions by substituting the first step with solubilization of the cellulosic fibres in quaternary ammonium hydroxides, a mixture of dimethylacetamide and lithium chloride, or NaOH/urea in aqueous solution. However a heterogeneous process is preferred since it has a higher degree of substitution of hydroxyl groups. A higher degree of substitution increase the viscosity of the methylcellulose since the methoxyl groups added lead to hydrophobic interactions (Nasatto et al., 2015).

The amphiphilic properties of MC make it a good cellulosic binder for packaging, in some cases it has even been considered a more efficient adhesive than starch (Nasatto et al., 2015). However, MC's adhesives properties are overshadowed by its multiple applications in other areas such as viscosity control in food, foam stability in cold drinks, thickening in personal care products, treating dry eyes and stool softener in pharmaceuticals, paint stabilizer in construction materials, and binding pesticides and nutrients to seeds in agriculture, among others. Therefore, while the production of MC from cattail should be considered, the purpose should not be focused only on the production of bio-adhesive.

## 5.2 Lignin and epoxy resin

Lignin is a complex naturally occurring polymer found in plant cell walls, providing rigidity by acting as permanent binder between cells in the stem, protection from microorganisms and controlling water transport through the cell wall. Lignin is derived from three hydroxycinnamyl alcohols: p-coumaryl alcohol, coniferyl alcohol, and sinapyl alcohol (Ghaffar & Fan, 2014). It is always associated to hemicellulose physically and chemically through covalent bonds. In herbaceous crops, lignin forms complexes with hemicellulose through ester bonds formed by ester-linked ferulic acid. Lignin is usually a waste product of the processing of wood pulp for the extraction of cellulose which is either burned or disposed of in the waste stream. Due to being a highly abundant organic resource, having a low cost of production, and being biodegradable, it has become a material of interest in recent years. Lignin in herbaceous plants, such as cattail, is different in composition from that of woody lignin, since herbaceous lignin consists of H, G and S subunits while woody lignin only contains G and S lignin as seen Figure 18.

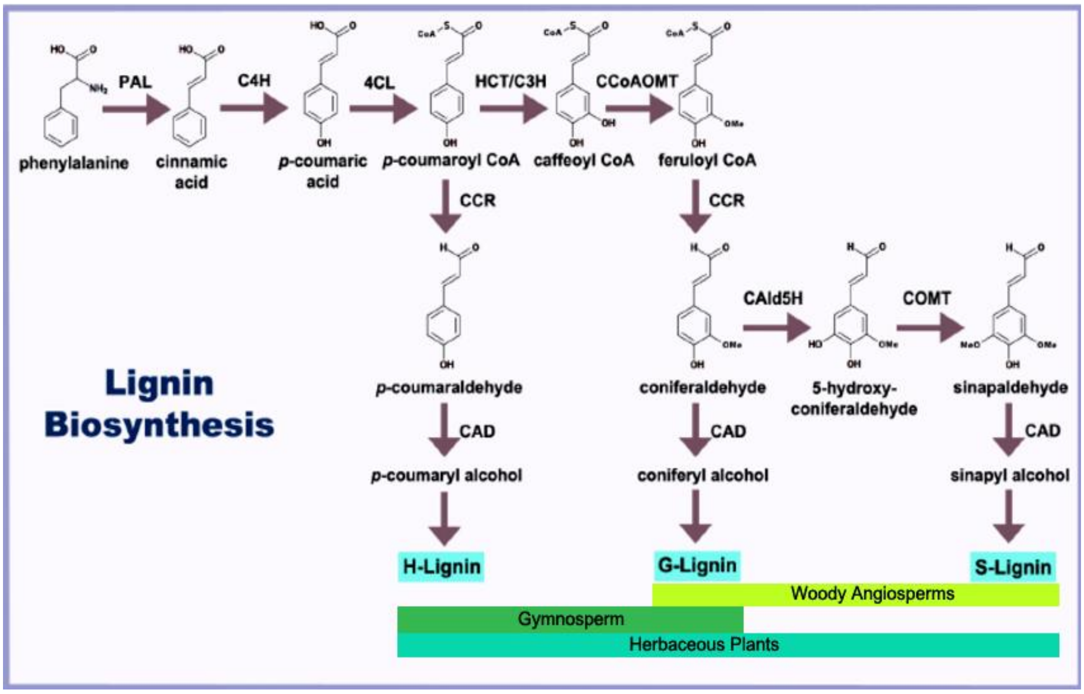


Figure 18. Lignin biosynthesis in Woody angiosperms, Gymnosperms and Herbaceous plants (adapted from Castellanos-Hernández et al., 2011).

Due to the binding capabilities of lignin to carbohydrates, they have been considered as potential substitutes for currently used wood adhesives such as phenol-formaldehyde (PF) resins. One of the most common application of lignin as glue is its use as a binder in fibreboard. The main reason for using lignin in the production of bio-based resins is the phenolic nature of lignin itself, which can be used to replace phenol in PF resins. Lignin can be treated to produce lignin derivatives such as lignosulfonates, a by-product from sodium, calcium, and ammonium-based sulphite spent liquors (Ghaffar & Fan, 2014) which can be used directly with resins in small proportions for the development of wood adhesives (Pizzi, 2006). Also, lignin-phenol-formaldehyde has been researched using lignin obtained from bagasse which has led to an optimum replacement of 50% of phenol by lignin while still maintaining a similar bonding strength comparable to commercial PF adhesives (Khan et al., 2004). While the research done on the use of lignin as a bio-adhesive may sound promising, it is not very applicable in the industry due to impracticalities coming from the use of lignin-phenol-formaldehyde resins. The lignin molecules in the lignin-phenol-formaldehyde resins have a large molecular size which make it hard to penetrate the surface of the wood to get good adhesion, and it also prevents any significant condensation with phenol. Therefore, as the ratio of lignin in the resin increases, the adhesive properties decrease.

Lignin has also been used in the production of epoxy resins through three different mechanisms with each method providing different physical and chemical properties which can be used for distinct application: the blending of lignin extracted from paper pulp with epoxy resins, modification of lignin by epoxides and modification of lignin to increase the reactivity before the reaction with epoxides (Ghaffar & Fan, 2014).

Based on Table 11, bagasse has a lignin content of 19.4%DW while cattail has a lignin content of 24%DW. Since both are products from herbaceous plants, they must have similar compositions and therefore cattail can also become a suitable replacement in PF adhesives and epoxy resins.

In herbaceous plants, lignin and hemicellulose are attached through ester and ether bonds formed by p-coumaric and ferulic acids in order to form a lignin/phenolics–carbohydrate complex. Due to this bridges between lignin and hemicellulose, it is very hard to extract lignins in pure form (Buranov & Mazza, 2008). Lignin also forms multiple types of covalent bonds as seen in Figure 19 which add to the complexity of the polymer.

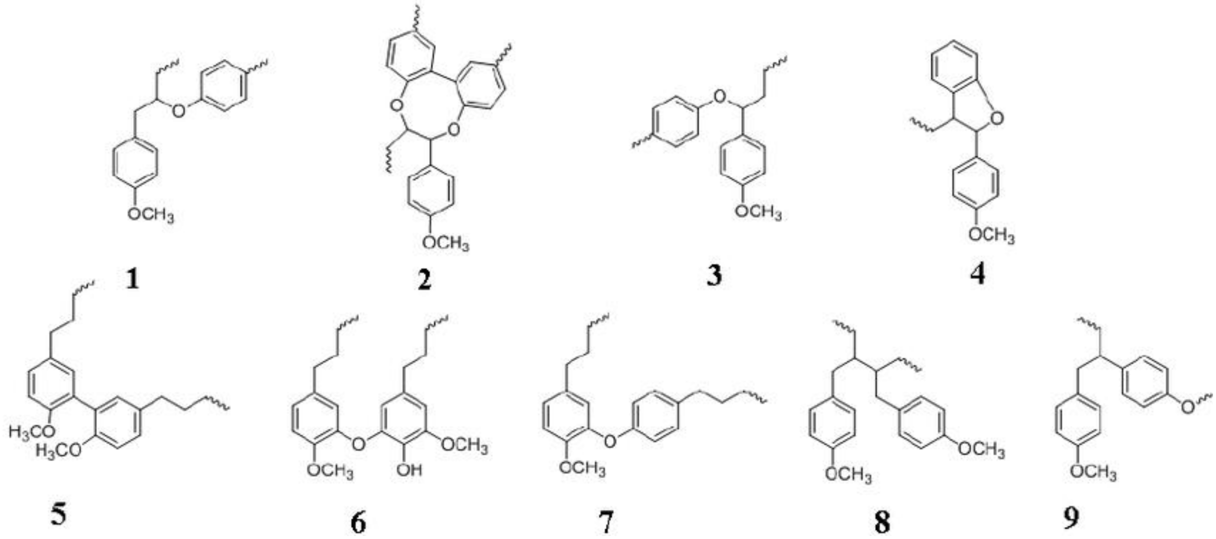


Figure 19. Lignin Covalent Bonds. 1. β-O-4 linkage 2. 5-5 and α-O-4 linkage 3. α-O-4 4. β-5 linkage 5. 5-5 linkage 6. 5-O-4 linkage 7. 4-O-5 linkage 8. β-β linkage 9. β-1 linkage (Adapted from Achyuthan, et al. 2010).

The quality of lignin depends on the method used to process lignocellulosic material. Pretreatments involving diluted acid or hot water lead to most the lignin being left as a solid, while processes involving high pH conditions may remove lignin and hemicellulose from the lignocellulosic material or just make the biomass more available for enzymes. Lignin extraction through alkaline pretreatments involves fragmentation and solubilization of lignin after which lignin can be recovered in later stages. Lignin extraction through organosolv lead to the precipitation and recovery from the concentrated liquid. Lignin obtained through this process is sulfur-free, rich in phenolics groups and low on carbohydrates contamination.

Once lignin has been extracted, it has to be treated in order to increase its adhesive properties since it makes a poor binder for wood composites compared to PF resins which is represented by a slow press rate. Multiple strategies have arised to increase the adhesive capabilities of lignin, which were reviewed by Ghaffar & Fan (2014). These methods are phenolation, ultrafiltration, biological pretreatments, and the improvement of lignin reactivity towards formaldehyde.

Phenolation is done in order to improve the reactivity position of acid-insoluble lignin after hydrolysis through the addition of phenolic groups. The process involves lignin interacting with phenols and sulphuric acid at different concentrations leading to the substitution of aliphatic hydroxyl groups by phenols in different positions, as seen in Figure 20. This process leads to increased adhesive properties of lignin thanks to the increased covalent interactions between lignin and resin provided by the added phenolic groups.

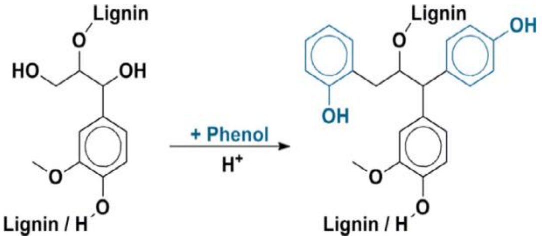


Figure 20. Phenolation of lignin (adapted from Podschun et al., 2014).

Another process for obtaining high quality lignin with increased adhesive properties involves the separation of lignin based on molecular weight. This process is known as ultrafiltration and it was found that low molecular weight lignin has better adhesive properties than high molecular weight lignin. These properties were influenced by the composition of reducing sugars and lignin (Shen et al., 1980). However, both ultrafiltration and phenolation, might not be accepted commercially due to environmental concerns raised by the use of chemicals to modify lignin.

For biological pretreatments, two approaches can be taken: enzymatic activation of lignin and laccasse assisted adhesion. The enzymatic activation of lignin improves self-bonding properties through oxidation of the surface lignin, while laccasse assisted adhesion relies on treating fibres with laccasse which allow for surface cross-linkage as fibres are pressed into boards (Ghaffar & Fan, 2014). These methods are used in binder-less wood boards which leads to less pollution due to reduced use of PF resins.

Lignin has been intensely research for bio-adhesive purposes and been successfully incorporated into PF resins for its use in plywood mills. However, formaldehyde is still used in the resins and this chemical is considered an environmental pollutant. Therefore in order to produce an environmentally friendly bio-adhesive, a pure lignin resin would have to be developed but no pure lignin resins have been able to succeed commercially at an industrial level due to not meeting relevant standards. Further research should be done in which the focus should be shifted towards the development of pure lignin resins instead of using lignin as a phenol substitute in PF.

## 5.3 Starch

Starch is a carbohydrate polymer usually derived from roots but can also be found in seeds and leaves. The most common source of starch are cereals but they are also found in roots and tubers. Starch is composed by two major groups, amylose and amylopectin, which can be distinguished by their structure. Amylose is composed of long linear chains of α-1,4 linked glucose units with few α-1,6 branches, while amylopectin consist of multiple short α-1,6 linked glucose branches and few α-1,4 linked glucose as seen in Figure 21 (Burrell, 2003). These two molecules are used to build starch granules of different sizes. Starch and maltodextrin, a starch derivative, are mainly used in the food industry. However, they are also known to be used in adhesives.

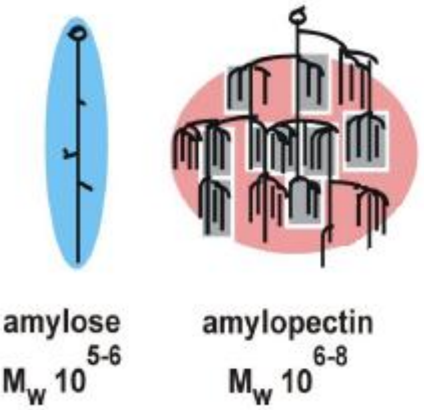


Figure 21. Amylose and Amylopectin structural representation (adapted from Light, 1990).

Due to its high availability, low cost and its versatility for chemical modifications, starch makes for an attractive substitute material for synthetic polymers. The adhesive properties of starch involve the affinity to polar materials such as cellulose. The starch-based adhesive wets the polar surface, penetrating crevices and pores, forming strong adhesive bonds through van der Waals forces and mechanical interlocking (Imam et al., 1999).

The starch content in cattail is mainly located in the rhizome which consist of 60-70%DW starch in winter but has a slightly lower content in the summer. The rest of the plant may consist of 10-15%DW starch (Kurzawska et al., 2014). In the same study it was shown that cattail starch composition consisted of 32% amylose however the distribution of amylopectin could not be determined. When compared to starch crops such as cereals, rice, wheat, and corn with a starch content of 75%DW, 64-70%DW, and 67%DW respectively (Kurzawska et al., 2014), cattail seems like a potential substitute for the source of starch due to cattail not being a staple crop.

The usual steps for isolating starch from plants involve the disintegration of the cell wall, through physical and chemical methods, followed by collection and purification of the starch granules through rinsing and centrifugation. However, the disintegration of the cell wall in cattail has been proven difficult as determined by Kurzawska et al. (2014). Regular chemical methods of disintegration lead to large losses of starch during the process. However, a time consuming method involving sonication followed by repeated washing with water and separating through centrifugation can be used, as this process lead to no large losses of starch.

Once the starch has been isolated, starch is processed by heating in water until gelation temperature is reached (57-72°C) in order to break up the starch granules. This is done through the swelling of the starch granules after exposure to hot water, followed by the addition of either salts or caustic soda in order to lower the gelation temperature. The adhesive is created by controlled use of the temperature and amount of time stirring (Petrie, 2004). If caustic soda was added the product has to be neutralized with acids. The level of viscosity is determined by the amylose/amylopectin, an increased ratio gives an increased viscosity.

As confirmed by Tjeerd Veenhoven, CEO at Studio Tjeerd Veenhoven and CSO at HuisVeendam, processing cattail for starch is too labour intensive and troublesome due to the acquisition of the rhizomes and the disintegration of the cell wall of the rhizome are very cumbersome. Therefore, while the starch content might lead to considering the usage of cattail for production of glue, the problems that arise during the processing of the plant make it an unreliable source for starch for adhesives.

## 5.4 Oil and waxes

Plant triglycerides (i.e. type of oils) and polyols (i.e. alcohols with multiple -OH groups) can be used to synthesize pressure sensitive adhesives (PSAs) together with polysaccharide-derived lactides and lactones (Maassen et al., 2016). This type of adhesives has the characteristic of allowing instantaneous adhesion when a low contact pressure is applied to them. The main materials used for its production are natural or nitrile rubber, petroleum-based styrene-butadiene-styrene, polyurethanes, polyisobutylene and polyacrylates. They usually perform well in polar surfaces like aluminium or glass.

Many examples of bio-based PSAs have been reported in the literature recently. They aim to replace petroleum-based adhesive, as well as obtaining adhesives with improved performance (as cited by Maassen et al., 2016). Li et al. (2015) synthesized polymer networks for PSA application by copolymerization of epoxidized soybean oil and lactic acid oligomers with 260-674 g/mol molecular weights. They found that PSAs produced with lactic acids of low molecular weight showed maximal peel adhesion strength, tack adhesion and shear adhesion resistance. Ahn et al. (2011) also used soybean oil to synthesize PSAs with high thermal and chemical resistance, peel strength, and transparency. Bunker & Wool (2002) produced acrylated monomers from methyl oleate by epoxydation and further modification with acrylic acid. This monomers were then able to react in a free-radical polymerization reaction and form polymers with high molecular weight ($10^6$ g/mol). Klapperich et al. (2009) produced PSA with potential for medical application by copolymerization of acrylated oleic methyl ester with methyl methacrylate and ethylene glycol dimethacrylate.

PSA synthesis is usually done by emulsion polymerization, although water based emulsion systems can also be considered to avoid the use of solvents (Bunker et al., 2003). As monomers derived from plant oils are highly insoluble in water, miniemulsion polymerization may be used, which has been proven to increase the physical properties of the polymers formed, as well as significantly reduce the amount of surfactant and time required for the reaction compared to the conventional emulsion method.

Little research has been done regarding the properties of cattail oils. Nevertheless, the oil content of cattail plants was found to be of about 4% of the total dry matter (Korkut et al., 2016). This content was measured using the Soxhlet method, which has poor extraction of polar lipids, meaning the total oil content may be higher. The highest oil content is about 20%DW in the seeds (Clopton & Korff, 1945), while cattail fibres has been reported to contain about 10%DW of wax (Dong et al., 2015).

Overall, the extraction and processing of oils to produce PSAs has been well studied and has recently become a good market opportunity. However the low content of oils in cattail likely make it unsuitable for this application. Using only cattail seeds may be an option as the oil content may be improved by means of plant breeding, thus more research should be done in this regard. While Naporo has stated that they have produced a bio-adhesive named Natglue using oils and waxes from cattail (Schwemmer, 2012), there is conflicting information on the production of Natglue since it is also stated in a different source (see section 2.1) that the glue is produced from protein adhesive. Since there is no detailed information available on the product nor is there a product on the market, Natglue should not be considered as a reliable source for the application of cattail wax and oil or protein as a bio-adhesive.

## 5.5 Proteins

Adhesives based on proteins are also widely used and can be obtained not only from animal proteins like casein, but also from vegetables like gluten or zein (reviewed in Santoni & Pizzo, 2013). Soybean proteins were also used in the 1920s for bio-adhesive production, but petroleum-based glues replaced them due to their higher bonding strength and water resistance (Li et al., 2009). Nowadays its use has been resumed as recent research has shown that the adhesive properties of these proteins can be improved by means of modifications that break internal bonds. This breakage leads to the unfolding of the proteins, thus exposes hydrophobic and/or reactive groups which can then react with other external molecules (Li et al., 2009). Methods that can be used for improving adhesive properties of proteins includes heat treatments, etherification by ethanol and HCl solution and the addition of denaturation agents, being guanidine chloride and urea the most commonly used (Li et al., 2009; Khosravi et al., 2010; Santoni & Pizzo, 2013). Moisture has also been shown to promote adhesion behaviour of soybean proteins (Li et al., 2009). Addition of cross-linkers such as melamine/epichlorohydrin prepolymeral can further enhance the adhesive properties of proteins (Luo et al., 2016). However, more research is still needed to assess the production costs of the different methods.

Adhesives made from soybean proteins can be used for wood board preparation, while zein and gluten from maize, pea proteins and wheat gluten has been suggested for its application as wood adhesives (Khosravi et al., 2010; Santoni & Pizzo, 2013). For this applications, the press temperature and time may influence the adhesive properties (Li et al., 2009, Santoni & Pizzo, 2013). The best results has been obtained using protein dispersions instead of dry protein powders, and with a press time longer than 5 minutes at a temperature higher than 90 $^{o}$C (Khosravi et al., 2012; Nordqvist et al., 2012).

For a plant species to be suitable as a protein source, its protein content and/or its abundance should be high enough. For instance, cereals have a low protein content of about 10-12%DW, but they are used as a protein source due to the large amounts of cereals that are globally produced. This makes the total amount of proteins that can be extracted from cereals comparable to that obtained from oilseeds, which are produced in lower amounts but contains a higher protein content (Sari et al., 2015). Protein content in cattail has been estimated to be 9.5%DW (Korkut et al., 2016), while in leaves seems to be a bit higher (7-12%DW) (Duke, 1983) and in the derived flour is between 6-8%DW (Mitich, 2000). These low values, together with the currently low availability of this plant for the industry make it a poor candidate for protein extraction for the time being.

As a final summary, it is possible to use cattail to produce bio-adhesives. Several methods of production were explained and discussed. Cellulose, lignin and starch, are all possible opportunities for bio-adhesives, while production from proteins, oils and waxes is not currently reliable due to lack of product. The cellulose in the leaves can be modified to make methylcellulose, which can be used as a weak glue. Lignin can be used as a substitute in phenol-formaldehyde resins by modifying lignin through phenolation. However, the leaves are currently mainly used for insulation, so they are not viable products in the biorefinery process. Starch could also be used for a bio-adhesives, as it is able to form strong bonds to cellulosic materials, such as wood. This usage of cattail again has its drawbacks, as the starch is mainly concentrated in the rhizomes, which are generally not harvested. Adding to the processing of cattail rhizomes for obtaining starch is not optimized. In the end it is possible to create bio-adhesives from cattail, but the limitations cause it to be a not very viable option.

# 6. Market conditions

In 2016 a market examination was conducted by Duursen et al. in which the potential of several paludiculture crops was evaluated. The authors concluded that cattail has a potential in the sustainable insulation market. They address that parties already on the market, Naporo, and Typha Technik, already saw this chance and have invested in processing- and production technology. Both companies now have the knowledge and ability to produce cattail insulation. According to Robert Schwemmer and Werner Theuerkorn (resp. Naporo and Typha Technik), both companies are in lack of the raw material (Duursen et al., 2016). Furthermore, this research gave insight in the interested companies and organizations and gave several boundary conditions and recommendations. In the long term, three boundary conditions should be met:

1. Scale: The insulation market is a bulk market, in which prices are important. Since a higher volume will decrease the costs, the market requires the product to have a (consistent) high volume (cultivation on 5-10 hectare) with reasonable costs.
2. Product specifications: the market requires the product that has a consistent quality
3. Product chain: Improvement of growing- and harvesting techniques will be needed. Furthermore, in the Netherlands there is no capacity to process the material. Therefore, in the long term, a processing facility should be realised.

All these boundary conditions should be met to make cattail production in Dutch peat lands feasible. However, in short term, the researchers recommend to start on a small scale. The market has recommended to start establishing a basis and have knowledge/control about the exact properties of the material, the available volumes, the costs, the legislation, etc. Market parties indicate this knowledge is a prerequisite for them to commit and invest in Cattail as a product. Although there were several pre-requisites from the market, there was also a lot of interest. Duursen et al. were able to identify at least six companies/organizations that had a concrete interest to collaborate: Naporo, Typha Technik, Kingspan Insulation, Unipro, EcoScala, and Huis Veendam. Two of these parties, Naporo and EcoScala, already returned a signed Declaration of Intent (Duursen et al., 2016).

Aside from the market conditions it is also important to understand the green, sustainable building market and its expected growth. Heuvels et al. (2013) concluded that the building market is a rigid market. It is difficult to change construction practices and often construction professionals are not readily willing to change. This is due to the fact that they fear that their product will become less reliable and that this will have juridical consequences (Heuvels et al., 2013). A survey study by the World Green Building Trends in 2016 identified the top 4 challenges the European Green Building Market is facing. These are, in no particular order, noted below. After each problem a percentage is given about the percentage of German firms that selected it as top barrier to Green Building.

| | |
|---|---|
| Higher Perceived First Costs | 52% |
| Affordability/only for high-end projects | 30% |
| Lack of public awareness | 6% |
| Inability to prove business case | 21% |

Contrary to this fact that the building market can be rigid, the survey study by the World Green Building Trends showed a major increase in sustainable building. The amount of companies that expects to have more than 60% of their projects certified green will double from 18% in 2015, to 37% in 2018, and is expected to continue to double every three years (World Green Building Trends, 2016). Another source that reports a major increase in sustainable building is the Dutch Green Building Council, which administers the BREEAM-NL sustainability label. In 2012, 37 sustainability certificates were awarded, whereas in 2015 already 100 certificates were awarded. Currently, already 70% of the large building projects are built with a BREEAM-NL certificate (Dutch Green Building Council, 2016).

# 7. Conclusion

The problems the region of North-East Friesland is facing are part of a broader global problem in peat soils. Performing paludiculture on re-wetted peatlands could be a vital solution in the future. The agricultural system of peatlands can change from high $CO_2$-eq. emission towards sustainable, environmental-friendly farming. In the search for linking this wet cultivation strategy with regional economic development, cattail has been recognized for its high potential to fulfill this role. This marsh plant has a high nutrient removal ability and produces up to 15 tons of DW per hectare every year. Therefore it could be a perfect first stage in the transition from dairy farming towards paludiculture. The most promising application of cattail is usage for insulation (either blow-in or construction boards). Austrian and German companies (resp. Naporo and Typha Technik) have recognized this potential and invested in knowledge and abilities to produce cattail insulation material. In the Netherlands, the interest in cultivating cattail is growing and several research projects have been performed. At least six companies and organizations have stated their concrete interest in the usage of the cattail material that could be produced. Although financial analyses differ from each other, overall conclusion is that the cattail cultivation will be financially possible. Major factors that influence the net gain are the harvest costs, the total yield/ha and the gain per ton DW.

Cultivation of cattail is dependent on many factors that can influence the yield. Starting with different types of sowing methods that influence the yield in the first year. Different forms of sowing each have their advantages and disadvantages, some are very cheap, but unreliable, while others are more reliable, but very laborious. Secondly, the specifications during growing also have a big impact on the yield and quality of the product. The points that were mainly discussed showed that there is still a huge lack of knowledge on the effects of different growing specifications on the production of cattail. For example, the effect of growing density on the quality of the product, studies showed that the aerenchyma content increased when growing in low density. If this has any effect on the actual insulation qualities has yet to be determined. Lastly the harvesting methods were discussed. It showed that companies are experimenting with creating good methods of harvesting cattail by creating specialized harvesting equipment. However, again a lot is still not known about the harvest of cattail and much more should be studied before cattail can really become a competitive crop.

The literature research and the experiment performed indicate a potential use of cattail to make bio-based insulation materials. There are three approaches for using cattail (blow-in and particle boards, fibre extraction for foam reinforcement and oil extraction for polyol production), but only the production of blow-in and particle boards has been proven to be actually feasible. The mixture of shredded leaves and the seedheads from cattail plants can first be treated as raw material and used as blow-in material or particle thermal insulation board. The experiment revealed some issues that should be considered when further studying the suitability of cattail for blow-in insulation, mainly the high density that was required, the pests risks in the raw material and the shredding and mixing processes.

Cattail particle boards comply with standards moisture standard NEN-EN 12087 and the modulus of rupture and modulus of elasticity might comply with the guide published by Hoadley, 2005 cited by (Luamkanchanaphan, 2012) at a density of 270 kg/m$^3$. Further study is needed, since only information about densities of 200 kg/m$^3$ and 300 kg/m$^3$ are found, and because 300 kg/m$^3$ complied and 200 did not. At the density of 270 kg/m$^3$ the thermal conductivity is 0.05 which means that it is an insulation material according to the international standard ASTM C518. But, in order to comply with the Dutch guidelines of "het Bouwbesluit" the insulation walls with the density of 270 kg/m$^3$ need to have a thickness in the range of 13.75- 33 cm, depending on the use. Also, it is advisable to perform a moisture measurement to gain insight in the properties of absorption of the cattail fibres as raw material for the cattail-based insulation materials.

On the other hand, cellulosic fibres extracted from cattail have a broader application than the previous one. Regarding the extraction methods discussed, using hot-water would be the cheapest method in terms of production scale, infrastructure investment, and waste disposal. Extraction of cattail fibres can theoretically be feasible as they can be used as a reinforcement to increase the quality of current foam material. In the same way, the oil extracted from cattails' seeds matches the characteristics required to replace the petroleum-based polyol component in polyurethane foam process, but the amount of seeds harvested from a specific area of cattail is limited and the oil has to be chemically modified to introduce hydroxyl groups into its structure. Therefore, these two applications are mostly theoretical, thus for practical means they should not be currently considered.

Regarding the BREEAM certification, if the cattail-based insulation material wants to be inserted in the market of BREEAM-certified buildings, it should meet the requirements specific to the respective BREEAM categories and issues. For the case of HEA 13 Acoustic Performance, the acoustic parameters of the cattail insulation material should comply with the parameters specific to the type of building. For the ENE 26 Assurance thermal quality, no thermal leakage should exist when using this insulation material in the building. For MAT 1 Materials specification, the life cycle assessment of the cattail-based insulation material should have a low impact in the overall shadow price of the building in order to be as much as or more sustainable than other related insulation products. For the case of MAT 5 Responsible sourcing of materials, the cattail-based insulation materials should have a BES 6001 certificate. Finally, after making sure that the majority of these requirements are met for the insulation material, this product can have an added value on the achievement of credits for a building/project with a BREEAM-certification.

Regarding bioadhesives, cattails' lignocellulosic components has been shown to certainly possess good adhesive properties. Cellulose can be modified to make methylcellulose, which can be used as a weak non-toxic glue applicable as a bookbinding adhesive and thus being of interest to the paper industry. Lignin can be used as phenol substitute in phenol-formaldehyde resins by modifying lignin through phenolation in order to increase reactivity of lignin before incorporating into formaldehyde resins. However, both lignin and cellulose are obtained from the leaves and stem of the plant which are required for the blow-in insulation material so they are not viable products in the biorefinery process. Starch has a high affinity to polar surfaces, forming strong bonds to materials such as wood. At first glance, the high availability of starch in the rhizomes of cattail make it an attractive component for the synthesis of bioadhesives. However, as stated in Chapter 5, the harvesting of the rhizomes is too troublesome and the processing of cattails rhizomes for obtaining starch is not optimized, so cattail is not recommended as a starch source either. As for the proteins, oils and waxes, their levels *in planta* are too low to be considered for bioadhesive production at this initial stage.

# 8. Advice

Agronomy and harvesting

Increasing the yield and quality of the product starts with the cultivation of the crop. In chapter 3 different aspects of cultivation were discussed and showed in what way they could be altered to possibly increase yield and/or quality. Now the best combination of the different aspects will be discussed in order to reach an as high as possible yield and/or quality of the product. It should be noted that since there is little research performed on the production of cattail, these recommendations should be taken cautiously.

Firstly the method of sowing, different methods were discussed, namely: using seeds, using seedlings, and transplanting parts of rhizomes. Studies show that using seeds for cultivation, be it very cheap, is also very unreliable, as only around 50% germination is achieved under natural conditions. Adding to this is the poor yield that will be achieved in the first year's harvest, as the plants have not had enough time to fully mature. The second possibility would be using seedlings produced in a nursery, this is a more reliable method. However, for the germination and early development phases of the plant a lot of care has to be taken, which is laborious. The last method looks to be the most promising, transplanting parts of rhizomes. This method allows for a good first year's harvest, while not being very labour demanding. The actual planting of the plants is equally as time-consuming compared to using seedlings. Therefore, transplanting rhizomes is the best method of sowing cattail.

Secondly the density at which the plants should be sown to achieve the highest yield and quality was discussed. The density of cattail can be very high (up to 140 plants per $m^2$, Glenn et al., 1995). However, the quality of the product will be less with an increased density, as plants that grow in a low density were shown to have an increased amount of aerenchyma tissue, this is important in the insulation properties of cattail. Since the density of growth will be lowered the yield per $m^2$ will also be lowered. To see if the lowered density and increased aerenchyma tissue improves the quality of the insulation material has yet to be studied. If it has no effect it will be better to try to achieve a density as high as possible, as this usually also increases the yield.

Lastly, the different harvesting methods were discussed. It showed that there is still is a lot to be studied about harvesting techniques, but companies are eager to start exploring the possibilities. It was also shown that different harvesting periods have an influence on the quality and the amount of processing that needs to be performed postharvest. The method that seems to have the highest potential is harvest by boat in a semi-controlled environment. First the plants will be harvested and afterwards the water level will be controlled so the plants will not die due to anaerobic activity. Another point that can be taken into account is harvesting twice a year, once in summer, and once in winter. In the summer the leaves can be harvested which are at that point full on nutrients that could be used for cattle feed, and during the winter the material can be used for insulation.

Most of these points are hard to control in a natural environment, therefore it is recommended to create artificial growing fields for an easier cultivation. Also in these controlled environment it will be possible to control the nutrient levels, such as nitrogen and phosphate, in the water, which is hard to do in natural environment.

Economic feasibility

Cattail cultivation and its usage for insulation material has proven to be successful in multiple studies and in multiple companies in multiple countries abroad. For the short term, it is recommended to contact market parties that have a concrete interest in the product. It is advised to start with small scale production, in order to be on top of the requirements specified by potential partners (i.e. knowledge/control about the exact properties of the material, the available volumes, the costs). For the beginning stages, we advise to sell unprocessed plant material to the partners, which has returns of €100-200 per ton DW. In a later stage, it could be more rewarding to sell processed material (i.e. market value €300-500) but more research is needed to explore the options of processing the material before selling. Also, for later stages it is advised to upscale the cultivation to at least 5-10 ha since higher volumes will decrease the costs. It is also advised to stay updated about the possibility of selling Carbon Credits on voluntary offset markets. It could possibly be an extra income per hectare, but more research and contact with other (Dutch) cattail pilots is needed to get complete insight into this.

### Development of cattail-based insulation materials

In order to improve the technical feasibility of using cattail as insulation material, more research on the technical aspects is required, which should comply with the respective laws and standards, as discussed in this report. For the blow-in material, it is necessary to assess how different leaves: seedheads volume ratios will impact the insulation properties of the final insulation product, to find out what the best combination is. Moisture level for both the insulation material and the environment should be considered to ensure the measurements will correlate with the actual properties of the material in its final application. Technical aspects of the processing should also be further studied to confirm the issues found with the shredding and mixing can be solved. Moreover, the stems may also be used as blow-in material, thus it has to be studied is suitability in terms of using the stems alone or in combination with other part of cattail plants. Finally, the use of pretreatments may also be considered, mainly cold or heat pretreatment to reduce risk of pests outbreaks and hot water pretreatment to increase cellulose content. Although it has been showed the later has advantages due to its simplicity, cost, and effectiveness, it may not be recommended since applying only a milling process will likely be sufficient for blow-in insulation.

For the production of particle boards, hot water pretreatment may be recommended as it will imply reducing the needs of adding binders to the mixture. This option, although it has been tried already, still needs to be further studied to confirm the properties of the final product will adjust to the requirements of respective Dutch standards.

For the fibre reinforcement of polyurethane foam, it is currently advised to not consider this application. If in the future more cattail biomass is available and this application is further developed, it will then be advised to measure the fibre length and diameter after the extraction, since these parameters contribute directly to the quality of the final product. Moreover, the input quantities of foam, fibre, and chemical additions have to be further tested to see the effects these components have on the final reinforced foam. For fire and mould resistances, a proper assessment is still needed and, in case they result to be too low, chemical additives such as sodium borate can be used to impregnate the cattail fibres and thus improve both properties at the same time. Besides, along with the extraction processes, the chemical cost from this process and waste products treatment should be taken into account.

It should also be noted that this report has focused mainly in the use of cattail as thermal insulation, whereas the fluffy material of this plant can also be used for acoustic insulation. This application needs still to be assessed.

### BREEAM Certification

As already explained in section 4.2, a building, but not a product/material, can be BREEAM-certified. Though, a material complying with certain requirements can be promoted to use in the construction of BREEAM certified buildings. It is advised to first discuss with potential market partners (e.g. Bouwgroep Dijkstra Draisma, or the potential market partners addressed in chapter 6) if they want to use the material in BREEAM certified projects and/or if the requirements should be met. If not, the material should only meet the technical standards addressed in section 4.1. In case the market wants the requirements to be met, tests should be performed to check if the material meets the acoustic and thermal requirements. Furthermore, a Life Cycle Assessment should be performed and a BES 6001 certificate should be obtained.

### Development of cattail-based bio-adhesives

Due to the necessity of using the lignocellulosic material of cattail for insulation, biorefinery is not an option and thus it is not recommended to use cattail for bio-adhesives. However, protein, oils and waxes may be extracted from cattail for this purpose, but this should only be considered when enough biomass amounts are available in the market, due to the low contents of this compounds *in planta*. As for the production of bio-adhesives from starch material, the picking and the processing of the rhizomes should be optimized in order to produce marketable product since the current methods of processing rhizomes are too tedious.

# 9. References

Abel, S., et al. (2013). The database of potential paludiculture plants (DPPP) and results for western pomerania. Plant Diversity and Evolution, 130(3-4): 219-228.

Academic Consultancy Training project proposal 1482 (2015). Cattail Production Chain Development in Northeast Friesland. Wageningen University and research Centre, Wageningen.

Achyuthan, K. E. , et al. (2010). Supramolecular self-assembled chaos: polyphenolic lignin's barrier to cost-effective lignocellulosic biofuels. *Molecules,* 15(12): 8641-8688.

Adams, D. (2011). Fire-resistant and insulating additives for building materials, their methods of production and uses thereof. U.S. Patent No. 8,066,807.

Ahn, K. B. , et al. (2011). Thermally stable, transparent, pressure-sensitive adhesives from epoxidized and dihydroxyl soybean oil. Biomacromolecules, 12(5): 1839-1843.

Al-Homoud, M. S. (2005). Performance characteristics and practical applications of common building thermal insulation materials. Building and environment, 40(3): 353-366.

ASTM (2000). ASTM C1338-00 Standard Test Method for Determining Fungi Resistance of Insulation Materials and Facings.

ASTM (2001). 518-98,"Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus". 2001 Annual Book of ASTM Standards, 4: 174-185.

Asdrubali, F. et al. (2015). A review of unconventional sustainable building insulation materials." Sustainable Materials and Technologies, 4: 1-17.

Asdrubali, F. & Baldinelli, G. (2011). Thermal transmittance measurements with the hot box method: Calibration, experimental procedures, and uncertainty analyses of three different approaches.

Banik, I. & Sain, M. (2007). Structure of glycerol and cellulose fibre modified water blown soy polyol based polyurethane foams. J. Reinf. Plast. Compos., 27: 1745-1758.

Batzer, D.P. & Sharitz, R.R. (2014). Ecology of freshwater and estuarine wetlands. Univ of California Press.

BES 6001: ISSUE 3.1. Downloaded on June 2017 from:
http://www.greenbooklive.com/filelibrary/responsible_sourcing/BES-6001--Issue-3.1.pdf Accessed on June 2017.

BREEAM-NL (2010). Label for Sustainable Real Estate. Assessor manual new buildings. Version 2.0, September 2010. Downloaded on June 2017 from:
https://www.breeam.nl/sites/breeam.nl/files/bijlagen/20100929_BRL_2010-v2.0_BREEAM-NL-EN_0.pdf

BREEAM-NL (2014). Label for Sustainable Real Estate. Assessor manual New Construction and Refurbishment. Version1.01, September 2014. Certification based on English Version of Manual. Not available. Downloaded on June 2017 from:
https://www.breeam.nl/sites/breeam.nl/files/bijlagen/BRL%202014%20v1,01%2020140711%20-%20ENG.pdf

British Standards Institution (1990). BS 1982:Part 3 Fungal resistance of panel product made of or containing materials of organic origin. Methods for determination of resistance to mould and mildew.

Bruce Hoadley R. (2005) Understanding Wood : A Craftmann's Guide to Wood Technology.

Bunker, S.P. & Wool, R.P. (2002). Synthesis and characterization of monomers and polymers for adhesives from methyl oleate. Journal of Polymer Science Part A: Polymer Chemistry 40(4): 451-

458.

Bunker, S. et al. (2003). Miniemulsion polymerization of acrylated methyl oleate for pressure sensitive adhesives. International journal of adhesion and adhesives, 23(1): 29-38.

Buranov, A.U. & Mazza, G. (2008). Lignin in straw of herbaceous crops. Industrial crops and products, 28(3): 237-259.

Burrell, M.M. (2003). Starch: the need for improved quality or quantity—an overview. Journal of Experimental Botany, 54(382): 451-456.

Cao, Shengbin, et al. (2016). Study on structure and wetting characteristic of cattail fibres as natural materials for oil sorption. Environmental technology, 37(24): 3193-3199.

Castellanos-Hernández, O.A. et al. (2011). Genetic transformation of forest trees. INTECH Open Access Publisher. Chapter 10.

Chiang, C. et al. (2000). Effects of 4 years of nitrogen and phosphorus additions on Everglades plant communities. Aquatic Botany, 68(1), 61-78.

Chirayil, C.J. et al. (2014). Review of recent research in nano cellulose preparation from different lignocellulosic fibres. Rev. Adv. Mater. Sci., 37: 20-28.

CIUR a.s. (2016). Comparison of Thermal Insulation Systems. Available on: http://www.ciur.cz/soubor/zobrazit/srovnani-tepelnych-izolaci Accessed on June 2017.

Clark, N.L. (1992). Environmental Developments In Aqueous Vinyl Dispersion Adhesives. Adhesives In Packaging Symposium: 3-5.

Clopton, J.R. & Von Korff, R.W. (1945). Typha (Cattail) seed oil. Journal of the American Oil Chemists' Society, 22(12): 330-331.

Corrêa, F. F. et al. (2015). Anatomy and physiology of Cattail as related to different population densities. Planta Daninha, 33(1): 01-12.

Dam, J.E.G. & Oever, M.J.A. (2012). Catalogus biobased bouwmaterialen: het groene bouwen. Wageningen UR, Food & Biobased Research.

Department of Energy USA. Types of Insulation. Web. Energy.gov, 2017: https://energy.gov/energysaver/types-insulation Accessed on June 2017.

Diamant, R.M.E. (2014) Thermal and acoustic insulation. Butterworth-Heinemann.

Dong, T. et al. (2015). Oil spill cleanup by structured natural sorbents made from cattail fibres. Industrial Crops and Products, 76: 25-33.

Dubbe, D.R. et al. (1988). Production of cattail *(Typha* spp.) biomass in Minnesota, USA. Biomass, 17(2), 79-104.

Duke, J.A. (1983). Handbook of energy crops. Available on:
https://www.hort.purdue.edu/newcrop/duke_energy/Typha.html Accessed on June 2017.

Dutch Green Building Council (2016). Explosieve groeiverwachting voor groen bouwen: mondiale markt verdubbelt iedere drie jaar. Web-article. Available on:
https://www.dgbc.nl/actueel/nieuwsarchief/explosieve-groeiverwachting-groen-bouwen-mondiale-markt-verdubbelt-iedere-drie Accessed on June 2017.

Duursen, J. et al. (2016). Rapport: Marktverkenning Paludicultuur: Kansen voor de landbouw in veenweidegebieden met behoud van veen.

Energysmart (2017). Energsmart Foam Insulation Open vs. Closed Cell Foam. Available on: http://www.energsmart.com/spray-foam-insulation/open-vs-closed-cell-foam.html Accessed on June 2017.

EURIMA (2011). U-values in Europe. Web. EURIMA, 2011. Available on: http://www.eurima.org/resource-centre/facts-figures/u-values-in-europe.html Accessed on June 2017.

Fair Climate Fund. Web article. Available on: http://www.fairclimatefund.nl/en/english-what-is-the-difference-between-voluntary-emission-rights-vers-and-compliance-emission-rights-cers/ Accessed on June 2017.

Fowler, P. et al. (206). Biocomposites: technology, environmental credentials and market forces. Journal of the Science of Food and Agriculture, 86(12): 1781-1789.

Fraunhofer-Gesellschaft (2017). Building Material Made of Cattail (*Typha*). Ibp.Fraunhofer. Available on: https://www.ibp.fraunhofer.de/en/Product_Developments/buidling-material-cattail.html Accessed on June 2017.

Fritz, C. et al. (2016). Natte teelten en paludicultuur: van ecosysteemdiensten naar duurzaam waterbeheer. CoP XXL, Zwolle.

Fritz, C. et al. (2014). Paludicultuur–kansen voor natuurontwikkeling en landschappelijke bufferzones op natte gronden.

Gâştescu, P. et al. (2014) 2nd International conference - Water resources and wetlands. Tulcea (Romania). Available on: http://www.limnology.ro/water2014/proceedings/40_Krus.pdf Accessed on June 2017.

Gerwen, R. et al. (2017) Het innovatie programma veen in Noord-Holland.

Gerwen, R. (2016). Vernatten van veengebieden. Stadswerk magazine.

Geurts, J. Radboud University Nijmegen. Personal communication. June 2017. E-mail.

Ghaffar, S.H. & Fan, M. (2014). Lignin in straw and its applications as an adhesive. International Journal of Adhesion and Adhesives, 48: 92-101.

Glenn, E. et al. (1995). Effects of salinity on growth and evapotranspiration of Typha domingensis Pers. Aquatic Botany, 52(1), 75-91.

Grace, J. B., & Wetzel, R. G. (1982). Niche differentiation between two rhizomatous plant species: *Typha latifolia* and *Typha angustifolia*. Canadian Journal of Botany, 60(1), 46-57.

Grosshans, R. E. (2014). Cattail (*Typha* spp.) biomass harvesting for nutrient capture and sustainable bioenergy for integrated watershed management. (Doctoral dissertation, University of Manitoba).

Harmsen, P.F.H. et al. (2010) *Literature review of physical and chemical pretreatment processes for lignocellulosic biomass*. No. 1184. Wageningen UR Food & Biobased Research.

Heuvels, S. & Sauveur, R. (2013). Transitioning towards a biobased and sustainable construction industry. Erasmus Universiteit.

Hoadley, R.B. (2005). Understanding Wood : A Craftmann's Guide to Wood Technology. Taunton press, 2000.

Hubbe, M.A. et al. (2017) Nanocellulose in Thin Films, Coatings, and Plies for Packaging Applications: A Review. BioResources, 12(1): 2143-2233.

IFAS, Center for Aquatic Plants University of Florida (1990). *Typha* Cattail. Greenville. Available on: https://plants.ifas.ufl.edu/wp-content/uploads/images/typspe/typha2.jpg. Accessed on June 2017.

Imam, Syed H., et al. (1999). Wood adhesive from crosslinked poly (vinyl alcohol) and partially gelatinized starch: preparation and properties. STARCH-STUTTGART-51: 225-229.

Isolatie-weetjes. Website:

https://www.isolatie-weetjes.nl/spouwmuurisolatie/kosten-spouwmuurisolatie/ Accessed on June 2017.

Johansson, P. (2014). Determination of the critical moisture level for mould growth on building materials. Vol. 1020. Byggnadsfysik LTH, Lunds Tekniska Högskola.

Johansson, P. et al. (2012). Laboratory study to determine the critical moisture level for mould growth on building materials. International Biodeterioration & Biodegradation, 73: 23-32.

Kapps, M. & Buschkamp, S. (2004). The production of rigid polyurethane foam. Bayer Materials Science, 20: 3-12.

Keddy, P. A. (2010). Wetland ecology: principles and conservation. Cambridge University Press.

Khan, M.A. et al. (2004). Development and characterization of a wood adhesive using bagasse lignin. International Journal of Adhesion and Adhesives, 24(6): 485-493.

Khazabi M. et al. (2011). Fibre reinforced soy-based polyurethane spray foam insulation. Part 2, BioResources, 6: 3757-3790.

Khedari J. et al. (2004). New low cost insulation particleboards from mixture of durian peel and coconut coir. Building and Environment, 39:59-65.

Khosravi, S. et al. (2010). Protein-based adhesives for particleboards. Industrial crops and products, 32(3): 275-283.

Kihlman, M. et al. (2013). Cellulose dissolution in an alkali based solvent: influence of additives and pretreatments. Journal of the Brazilian Chemical Society, 24(2): 295-303.

Kim, J.-H. et al. (2015). Review of nanocellulose for sustainable future materials. International Journal of Precision Engineering and Manufacturing-Green Technology, 2(2): 197-213.

Klapperich, C.M. et al. (2009). A novel biocompatible adhesive incorporating plant-derived monomers. Journal of Biomedical Materials Research Part A, 91(2): 378-384.

Klemm, D. et al. (2005). Cellulose: fascinating biopolymer and sustainable raw material. Angewandte Chemie International Edition, 44(22): 3358-3393.

Koninklijk. Nederlands Meteorologisch Instituut, Ministerie van Infrastructuur en Milieu, Klimaat Atlas 2010.

Korkut, A.Y. et al. (2016). Preliminary study for utilization of some invasive aquatic plants as raw material for aquaculture feeds. FEB-FRESENIUS ENVIRONMENTAL BULLETIN: 4915.

Krus, M. (2013). Fraunhofer Institute for Building Physics. Available on: https://www.ibp.fraunhofer.de/en/Press/Research_in_focus/Archives/May2013_cattail.html Accessed on June 2017.

Krus, M. et al. (2014). New sustainable and insulating building material made of cattail. Full papers NSB.

Krus, M., Theuerkorn, W. &, Grosskinsky, T. (2014). *Typha* cultivation in agriculture. 2$^{nd}$ International Conference - Water resources and wetlands, Romania. Available on: http://www.limnology.ro/water2014/proceedings/40_Krus.pdf Accessed on June 2017.

Küçük, M.M. et al. (2005). Supercritical fluid extraction of reed (Thypa). Energy sources, 27(5): 445-450.

Kumar, D., et al.. (2011). Impact of pretreatment and downstream processing technologies on economics and energy in cellulosic ethanol production. *Biotechnology for biofuels*, *4*(1), 27.

Kurzawska, A. et al. (2014) The molecular and supermolecular structure of common cattail *(Typha latifolia*) starch. Starch-Stärke, 66(9-10): 849-856.

Kymäläinen, H.-R. et al. (2008). Flax and hemp fibres as raw materials for thermal insulations. Building and environment, 43(7): 1261-1269.

Lambda, Minimale isolatiewaarde vanaf 2016 EPB available at:
https://www.lambda.be/nl/energietips/minimale-isolatiewaarde-anno-2016 Accessed June 2017

Leo, T. (2008) Uptake and Release Kinetics of Sulfolane by Cattail Plants (2008). Utah State University, Utah. MSc Thesis. Paper 47.

Li, Y. et al. (2015). Copolymers from epoxidized soybean oil and lactic acid oligomers for pressure-sensitive adhesives. RSC Advances, 5(35): 27256-27265.

Li, Xin, et al. (2009). Mechanical and water soaking properties of medium density fiberboard with wood fiber and soybean protein adhesive. Bioresource technology, 100(14): 3556-3562.

Light, J.M. (1990). Modified food starches: Why, where, and how. Cereal Foods World: 20.

Lorenzen B. et al. (2001). Growth, biomass allocation and nutrient use efficiency in Cladium jamaicense and Typha domingensis as affected by phosphorus and oxygen availability. Aquatic Botany, 70: 117–133.

Luamkanchanaphan, T. et al. (2012). A study of physical, mechanical and thermal properties for thermal insulation from narrow-leaved cattail fibres. APCBEE Procedia, 1: 46-52.

Luo, Jing, et al. (2016). A high performance soy protein-based bio-adhesive enhanced with a melamine/epichlorohydrin prepolymer and its application on plywood. RSC Advances, 6(72): 67669-67676.

Maassen, W. et al. (2016). Unique adhesive properties of pressure sensitive adhesives from plant oils. International Journal of Adhesion and Adhesives 64: 65-71.

Martin M. (2008). Dynamics of phytomass production and nutrient standing stock of cattail and its use for environment-friendly construction. (Doctoral dissertation, University of Tartu, Estonia).

Meststoffenwet (2016). Available on: http://wetten.overheid.nl/BWBR0004054 Accessed on June 2017.

Meyer, H-P. (2011). Sustainability and biotechnology. Organic Process Research & Development, 15(1): 180 - 188.

Mitich, L. M. (2000). Common cattail, *Typha latifolia* L. Weed technology, 14(2): 446-450.

Moghaddam, M.K. & Mortazavi, S.M. (2016) Physical and Chemical Properties of Natural Fibres Extracted from *Typha australis* Leaves. Journal of Natural Fibres, 13(3): 353-361.

Morán, Juan I., et al. (2008) Extraction of cellulose and preparation of nanocellulose from sisal fibres. Cellulose, 15.1: 149-159.

MRPI. MPG-software. Available on: http://www.mrpi-mpg.nl/Home/Home Accessed on June 2017.

Naporo (2017). Development of the production technology for cattail insulating materials. Basis study to the feasibility of a serial production. Available on:
https://nachhaltigwirtschaften.at/en/fdz/projects/insulation-material-made-of-cattail.php Accessed on June 2017.

Naporo (2012). Presentation at Ecosummit. Available on:
http://ecosummit.net/uploads/eco12_230312_1520_robertschwemmer_naporo.pdf Accessed on June 2017.

Naporo (2012). The world of Naporo *Typha*. PDF. Available on:
https://experimentpool.files.wordpress.com/2012/04/final_the_world_of_naporo_typha_small.pdf Accessed on June 2017.

Nasatto, P.L., et al. (2015). Methylcellulose, a cellulose derivative with original physical properties and extended applications. Polymers, 7(5): 777- 803.

National Environmental Database. Version 2.0. Available on:
https://www.milieudatabase.nl/viewNMD/index.php Accessed on June 2017.

Nordqvist, Petra, et al. (2013). Plant proteins as wood adhesives: Bonding performance at the macro-and nanoscale. Industrial crops and products, 44: 246-252.

Osinga, T. et al. (2014). Effecten van klimaatverandering op maaivelddaling en grondwaterstanden in Friesland.

O'sullivan, A.C. (1997). Cellulose: the structure slowly unravels. Cellulose, 4(3): 173-207.

Park, J. et al. (2017). Critical Review of the Material Criteria of Building Sustainability Assessment Tools. Sustainability, 9(2): 186.

Phinichka, N. & Kaenthong, S. (2017). Regenerated cellulose from high alpha cellulose pulp of steam-exploded sugarcane bagasse. Journal of Materials Research and Technology.

Pietarinen, V.-M., et al. (2008). Quantitative PCR analysis of fungi and bacteria in building materials and comparison to culture-based analysis. Journal of Environmental Monitoring, 10(5): 655-663.

Pizzi, A. (2006). Recent developments in eco-efficient bio-based adhesives for wood bonding: opportunities and issues. Journal of adhesion science and technology 20(8): 829-846.

Petrie, E. (2004). Starch and Dextrin Based Adhesives. Web. Available on: http://www.adhesivesmag.com/articles/84472-packaging-enduser-starch-and-dextrin-based-adhesive Accessed on june 2017.

Petrullo, M. et al. (2016). World Green Building Trends 2016: Developing Markets Accelerate Global Green Growth. Smart market report. Bedford: Dodge Data & Analytics.

Podschun, J. et al. (2015). Reactivity enhancement of organosolv lignin by phenolation for improved bio-based thermosets. European Polymer Journal, 67: 1-11.

Postma, S. (2017). Personal communication. E-mail.

Riet, B. et al. (2014). Vernatting voor veenbehoud, carbon credits en kansen voor paludicultuur en natte natuur in Noord- Holland. Landschap Noord-Holland, Heiloo.

Rojas, J. et al., (2015).Current trends in the production of cellulose nanoparticles and nanocomposites for biomedical applications. Cellulose–Fundamental Aspects and Current Trends. Intech: 193-228.

Sale, P.J.M., & Wetzel, R.G. (1983). Growth and metabolism of *Typha* species in relation to cutting treatments. Aquatic Botany, 15(4): 321-334.

Santoni, I., & Pizzo, B. (2013). Evaluation of alternative vegetable proteins as wood adhesives. Industrial crops and products, 45: 148-154.

Sari, Yessie W., et al. (2015). Towards plant protein refinery: review on protein extraction using alkali and potential enzymatic assistance. Biotechnology journal, 10(8): 1138-1157.

Schwemmer, R. (2010). Entwicklung der fertigungstechnologie für rohrkolben-dämmstoffe. Berichte aus Energie-und Umweltforschung, 69.

Schwemmer, R. (2012). Injection insulating material based on bulrush leaf fibres and a suitable production method therefor. Patent.

Schwemmer, R. (2012). NAPORO: Organic material of the year 2012. PowerPoint file.

Shen, K.C. & Calve, L. (1980). IMPROVING BY FRACTIONATION-AMMONIUM-BASED SPENT SULFITE LIQUOR FOR WAFERBOARD BINDER. Adhesives Age, 23(8): 25-29.

Silva, M.C. et al. (2010). Composites of rigid polyurethane foam and cellulose fibre residue. Journal of Applied Polymer. Science 117(6): 3665-3672.

Soortenbank web, accessed on June 2017:
http://www.soortenbank.nl/soorten.php?soortengroep=flora_nl_v2&id=454;
http://www.soortenbank.nl/soorten.php?soortengroep=flora_nl_v2&id=455

Stoerkmann, M. (2012). Technical insulation materials must meet many different requirements. Armacel. Armacell GmbH. Web. Accessed on June 2017.

Sun, Y. & Cheng, J. (2002). Hydrolysis of lignocellulosic materials for ethanol production: a review. Bioresource technology, 83(1): 1-11.

Tangjuank, S. & Kumfu, S. (2011). Particle Boards from Papyrus Fibres as Thermal Insulation. Journal of Applied Sciences, 11: 2640-2645.

The Netherlands. Ministerie van binnenlandse zaken en koninkrijksrelaties. Bouwbesluit Hoofdstuk 5. Technische bouwvoorschriften uit het oogpunt van energiezuinigheid en milieu, nieuwbouw 2012

Toet, S. et al. (2005). Nutrient removal through autumn harvest of *Phragmites australis* and *Typha latifolia* shoots in relation to nutrient loading in a wetland system used for polishing sewage treatment plant effluent. Journal of Environmental Science and Health, 40(6-7): 1133-1156.

Transmission Properties by Means of the Heat Flow Meter Apparatus (C 518) (2010). West Conshohocken, PA 19428-2959, United Stated: 152-166.

Typha Technik. Website: http://typhatechnik.com/pages/produkt.php Accessed on June 2017.

U-Values in Europe. Web Article. Available on:
http://www.eurima.org/resource-centre/facts-figures/u-values-in-europe.html Accessed June 2017.

Vèjelienè, Jolanta, et al. (2011). Evaluation of Structure Influence on Thermal Conductivity of Thermal Insulating Materials from Renewable Resources. Materials Science 17(2): 208-212.

Verboom, C. (2017). Personal communication. E-mail.

Ververis, C., et al. (2001). Cellulose, hemicelluloses, lignin and ash content of some organic materials and their suitability for use as paper pulp supplements. Bioresource Technology 98(2): 296-301.

Vidil, Lisa, et al. (2016). Thermal insulating particle boards reinforced with coconut leaf sheaths. Green Materials 4(1): 31-40.

Vincent, D. A. (1962). Method of making heat insulating material from cattail fibres. Patent.

Voss, Karsten, and Eike Musall (2013). Net zero energy buildings: international projects of carbon neutrality in buildings. Walter de Gruyter.

Wichtmann, W. et al. (2016). Paludiculture-productive use of wet peatlands: climate protection-biodiversity-regional economic benefits. Schweizerbart Science Publishers.

Wool, R. & Sun, X.S. (2011). Bio-based polymers and composites. Academic Press: 1-12.

Wuzellaa, G. et al. (2014). Novel, binder-free fibre reinforced composites based on a renewable resource from the reed-like plant *Typha* sp. Industrial Crops and Products, 33(3): 683-689.

Xu, J, et al. (2006). Development of binderless fibreboard from kenaf core. Journal of wood science 52(3): 236.

Zhang, B. & Shahbazi, A. (2011). Recent developments in pretreatment technologies for production of lignocellulosic biofuels. J Pet Environ Biotechnol, 2(2): 111.

Zhou X.Y. et al. (2010). An environmental-friendly thermal insulation material from cotton stalk fibres. Energy and Buildings, 42:1070-1074.

# Appendix I: Insulation standards

**Different standards and licensing procedures possibly applicable to cattail-based insulation materials are shown.**

| Standard | Type of standard | Legislation frame | Description |
|---|---|---|---|
| **ASTM C518** | Testing | USA | Standard Test Method for Steady-State Thermal Transmission Properties by means of the Heat Flow Meter Apparatus |
| **ASTM C1338-00** | Testing | USA | Standard Test Method for Determining Fungi Resistance of Insulation Materials and Facings |
| **ASTM C1363-05** | Testing | USA | Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus |
| **ASTM D1037 - 12** | Testing | USA | Standard Test Methods for Evaluating Properties of Wood-Based Fibre and Particle Panel Materials |
| **BS 1982:Part 3** | Testing | European | Fungal resistance of panel product made of or containing materials of organic origin. Methods for determination of resistance to mould and mildew. |
| **BS EN 1608:2013**<br>**Thermal insulating products for building applications** | Testing | European | Determination of tensile strength parallel to faces |
| **DIN EN 12667/12939** | Testing | European | European Standard for Measurements of Insulating Materials Using the Heat Flow Meter Method or the Guarded Hot Plate Technique |
| **EN 12667:2001**<br>**Thermal performance of building materials and products** | Testing | European | Determination of Thermal resistance according to the method using the hot plate and Heat flow meter apparatus_Products of high and medium thermal resistance |
| **EN 317:2005**<br>**Particle board/Fibreboard/Biocomposites** | Testing | European | Determination of swelling in thickness after immersion in water |
| **EN 319:2005**<br>**Particle board/Fibreboard/Biocomposites** | Testing | European | Determination of tensile strength perpendicular to faces |

| | | | |
|---|---|---|---|
| **EN ISO 8990:1996**<br>**Thermal Insulation** | Testing | European | Determination of steady-state thermal transmission properties - Calibrated and guarded hot box |
| **EN ISO 11925-2:2009**<br>**Reaction to fire tests of building materials** | Testing | European | Flammability of construction at direct impingement of flame |
| **EN ISO 11925-2:2009**<br>**Reaction to fire tests of building materials** | Testing | European | Flammability of construction at direct Impingement of flame |
| **NEN EN 12087:2013**<br>**Thermal insulating products for building applications.** | Testing | European | Determination of long term water absorption by immersion |
| **NEN 1068:2012** | Testing | European | Thermal insulation of buildings |
| **ISO 8301** | Testing | European | Thermal conductivity |

# Appendix II: BREEAM standard requirements

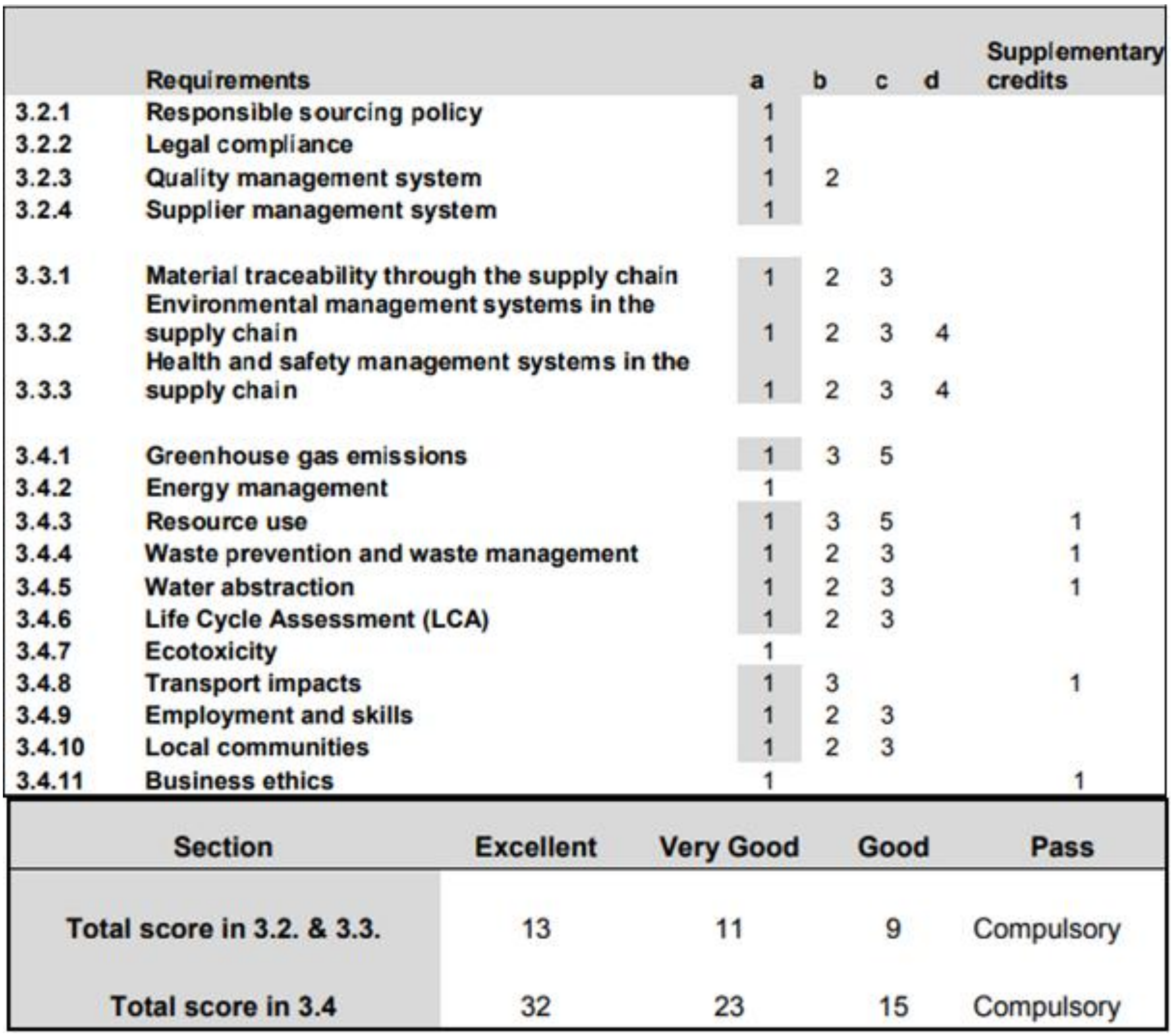
**Table 1. Limit values for characteristic soundproofing, characteristic airborne sound insulation, impact sound insulation and noise level of installations per distinguished building and / or room feature. Adapted from BREEAM-NL, 2014.**

| Use Function | Characteristic noise protection (G a,k ) | Characteristic airborne sound level difference (D nT, A, k) | Weighted sound level (L nT, A) | Typical installation sound level (L I, A, k) |
|---|---|---|---|---|
| **Office Function** | In accordance with Decree Requirements for homes, art. 3.2 t / m 3.4. | > 38 dB between all present within the building usable floor areas; except between usable floor areas available within the building with a wall with door for which > 33 dB applies. | <59 dB between all present within the building usable floor areas. | <35 dB (A) |
| **Education Function** | Conforms to standards required under art.3.2 t / 3.4 m of the Building. | > 38 dB between all present within the building usable floor areas; except between classrooms themselves, for which < 42 dB applies. | <59 dB between all present within the building usable floor areas. | <35 dB (A) |
| **Living Function** | 5 dB better than standards required under art. 3. 2 t / m 3.4 of the Building. | > 32 dB between all groups within a housing accommodation areas. | <59 dB between all groups within a housing accommodation areas. | <30 dB (A) |

**Table 2: Shadow price per 100 m$^2$ of different insulation materials, calculated using the following web tool: http://www.mrpi-mpg.nl/. Calculations are based on a residential building with a life expectancy of 75 years and a GFA of 130 m$^2$**

| Product | Shadow price (€/100m$^2$ insulation/m$^2$ GFA) |
|---|---|
| Flexible Wood Fibre Insulation (55 kg/m3) | **0.005** |
| Glass Wool Boards | **0.007** |
| ROCKWOOL Rockfit 433 BP | **0.009** |
| Foam insulation of biopolymers (BIO-EPS) | **0.012** |
| EPS | **0.015** |
| PUR | **0.021** |
| Phenolic Foam Insulation | **0.024** |
| Wood Fibre Board (115 kg/m3) | **0.047** |
| Sheep Wool | **0.565** |
| Expanded Insulation Corkboard | **8.471** |

**Table 3: Performance Ratings and threshold scores required to achieve a certain Overall Assessment Score, according to BES:6001, 2008.**



| | Requirements | a | b | c | d | Supplementary credits |
|---|---|---|---|---|---|---|
| 3.2.1 | Responsible sourcing policy | 1 | | | | |
| 3.2.2 | Legal compliance | 1 | | | | |
| 3.2.3 | Quality management system | 1 | 2 | | | |
| 3.2.4 | Supplier management system | 1 | | | | |
| 3.3.1 | Material traceability through the supply chain | 1 | 2 | 3 | | |
| 3.3.2 | Environmental management systems in the supply chain | 1 | 2 | 3 | 4 | |
| 3.3.3 | Health and safety management systems in the supply chain | 1 | 2 | 3 | 4 | |
| 3.4.1 | Greenhouse gas emissions | 1 | 3 | 5 | | |
| 3.4.2 | Energy management | 1 | | | | |
| 3.4.3 | Resource use | 1 | 3 | 5 | | 1 |
| 3.4.4 | Waste prevention and waste management | 1 | 2 | 3 | | 1 |
| 3.4.5 | Water abstraction | 1 | 2 | 3 | | 1 |
| 3.4.6 | Life Cycle Assessment (LCA) | 1 | 2 | 3 | | |
| 3.4.7 | Ecotoxicity | 1 | | | | |
| 3.4.8 | Transport impacts | 1 | 3 | | | 1 |
| 3.4.9 | Employment and skills | 1 | 2 | 3 | | |
| 3.4.10 | Local communities | 1 | 2 | 3 | | |
| 3.4.11 | Business ethics | 1 | | | | 1 |

| Section | Excellent | Very Good | Good | Pass |
|---|---|---|---|---|
| Total score in 3.2. & 3.3. | 13 | 11 | 9 | Compulsory |
| Total score in 3.4 | 32 | 23 | 15 | Compulsory |

According to BES:6001, 2008: "The Overall Assessment Score" depends on:

- The total score achieved in the requirements of sections 3.2 and 3.3 combined; and
- The total score achieved in section 3.4

And is given by the lowest score achieved in either the combined sections 3.2 and 3.3, or 3.4 as shown in Table 2 (e.g. if an organisation achieves a 'Very Good' in 3.2 & 3.3 but only achieves a 'Good' in 3.4, then it will receive an Overall Assessment Score of 'Good')."

# Appendix III: Insulation materials

**R-value and depths of different insulation materials (Adapted from greenstar.gov)**

| Material | R-value/in | 3 1/2" | 5 1/4" | 10" | 12" | 15" |
|---|---|---|---|---|---|---|
| Fibreglass (batt) | 3.1 - 3.4 | 10.8 - 11.9 | 16.3 - 17.8 | 31.0 - 34.0 | 37.2 - 40.8 | 46.5 - 51.0 |
| Fibreglass blown (attic) | 2.2 - 4.3 | 7.7 - 15.0 | 11.5 - 22.6 | 22.0 - 43.0 | 26.4 - 51.6 | 33.0 - 64.5 |
| Fibreglass blown (wall) | 3.7 - 4.3 | 12.9 - 15.0 | 19.4 - 22.6 | 37.0 - 43.0 | 44.4 - 51.6 | 55.5 - 64.5 |
| Mineral Wool (batt) | 3.1 - 3.4 | 10.8 - 11.9 | 16.3 - 17.8 | 31.0 - 34.0 | 37.2 - 40.8 | 46.5 - 51.0 |
| Mineral Wool blown (attic) | 3.1 - 4.0 | 10.8 - 14.0 | 16.3 - 21.0 | 31.0 - 40.0 | 37.2 - 48.0 | 46.5 - 60.0 |
| Mineral Wool blown (wall) | 3.1 - 4.0 | 10.8 - 14.0 | 16.3 - 21.0 | 31.0 - 40.0 | 37.2 - 48.0 | 46.5 - 60.0 |
| Cellulose blown (attic) | 3.2 - 3.7 | 11.2 - 12.9 | 16.8 - 15.0 | 32.0 - 37.0 | 38.4 - 44.4 | 48.0 - 55.5 |
| Cellulose blown (wall) | 3.8 - 3.9 | 13.3 - 13.6 | 19.9 - 20.8 | 38.0 - 39.0 | 45.6 - 46.8 | 57.0 - 58.5 |
| Polystrene Board | 3.8 - 5.0 | 13.3 - 17.5 | 19.9 - 26.2 | 38.0 - 50.0 | 45.6 - 60.0 | 57.0 - 75.0 |
| Polyurethane Board | 5.5 - 6.5 | 19.2 - 22.7 | 28.9 - 34.1 | 55.0 - 65.0 | 66.0 - 78.0 | 82.5 - 97.5 |
| Polyisocyanurate (foil-faced) | 5.6 - 8.0 | 18.2 - 28.0 | 29.4 - 42.0 | 56.0 - 80.0 | 67.2 - 96.0 | 84.0 - 120.0 |
| Open Cell Spray Foam | 3.5 - 3.6 | 12.2 - 12.6 | 18.4 - 18.9 | 35.0 - 36.0 | 42.0 - 43.2 | 52.5 - 54.0 |
| Closed Cell Spray Foam | 6.0 - 6.5 | 21.0 - 22.7 | 31.5 - 34.1 | 60.0 - 65.0 | 72.0 - 78.0 | 90.0 - 97.5 |

# Appendix IV: Experimental data

The outcome of the temperature measurements are recorded in tables 1, 2 and 3. During the experiments, some issues were found that should be considered in the development of cattail blow-in insulation material. The main problem was found to be shredding the material, as it has to be passed through the shredder three times to acquire an acceptable particle size. Mixing leaf and fluffy material also proved to be difficult as the second tends to clump together. Filling the upper corners of the box was also more difficult when using cattail material than when the Isofloc® material was used, but this issue may be solved with smaller particle sizes and better mixing. The density of the material may be a concern as it almost doubled the density of the reference material.

Tested thickness: 0.0875 m

Mass: 1.8kg and 1kg (cattail and Isofloc® material, respectively)

Surface area tested: 0.19 $m^2$

Density: 91.46 and 50.81 $kg/m^3$

*Table 1.* Temperature records of the empty box (blank) at a steady heat flow of 58,74 J/s.

| Time | Temperature | | Average temperature | Temperature difference | Thermal conductivity |
|---|---|---|---|---|---|
| | Warm side | Cold side | | | |
| min | °C | °C | °C | K | W/(m*K) |
| 0 | 22 | 21 | 21.5 | 1 | 26.87 |
| 1 | 36 | 21.2 | 28.6 | 14.8 | 1.82 |
| 2 | 43.8 | 21.6 | 32.7 | 22.2 | 1.21 |
| 3 | 49.8 | 22.6 | 36.2 | 27.2 | 0.99 |
| 4 | 54.6 | 23.4 | 39 | 31.2 | 0.86 |
| 5 | 58 | 24.4 | 41.2 | 33.6 | 0.80 |
| 6 | 60.8 | 25.2 | 43 | 35.6 | 0.75 |
| 7 | 63.8 | 26.4 | 45.1 | 37.4 | 0.72 |
| 8 | 65.4 | 27.6 | 46.5 | 37.8 | 0.71 |
| 9 | 67.2 | 28.2 | 47.7 | 39 | 0.69 |
| 10 | 68.6 | 29.4 | 49 | 39.2 | 0.69 |
| 11 | 69.8 | 30.2 | 50 | 39.6 | 0.68 |
| 12 | 70.6 | 31 | 50.8 | 39.6 | 0.68 |
| 13 | 71.2 | 31.6 | 51.4 | 39.6 | 0.68 |
| 14 | 71.8 | 32.2 | 52 | 39.6 | 0.68 |
| 15 | 72.2 | 33 | 52.6 | 39.2 | 0.69 |
| 16 | 72.6 | 33.6 | 53.1 | 39 | 0.69 |
| 17 | 73 | 34.2 | 53.6 | 38.8 | 0.69 |
| 18 | 73.2 | 34.6 | 53.9 | 38.6 | 0.70 |
| 19 | 73.6 | 35 | 54.3 | 38.6 | 0.70 |
| 20 | 73.8 | 35.2 | 54.5 | 38.6 | 0.70 |
| 21 | 74 | 35.6 | 54.8 | 38.4 | 0.70 |
| 22 | 74 | 36 | 55 | 38 | 0.71 |
| 23 | 74 | 36.4 | 55.2 | 37.6 | 0.71 |
| 24 | 74.2 | 36.6 | 55.4 | 37.6 | 0.71 |
| 25 | 74.2 | 36.8 | 55.5 | 37.4 | 0.72 |
| 26 | 47.2 | 37 | 42.1 | 37.4 | 0.72 |

| | | | | | |
|---|---|---|---|---|---|
| 27 | 74.4 | 37.2 | 55.8 | 37.2 | 0.72 |
| 28 | 74.4 | 37.4 | 55.9 | 37 | 0.73 |
| 29 | 74.6 | 37.4 | 56 | 37.2 | 0.72 |
| 30 | 74.4 | 37.6 | 56 | 36.8 | 0.73 |
| 31 | 74.6 | 37.8 | 56.2 | 36.8 | 0.73 |
| 32 | 74.6 | 37.8 | 56.2 | 36.8 | 0.73 |

*Table 2.* Temperature records of the box filled with cattail material (leaves and seedheads) at a steady heat flow of 58.74 J/s during the first 30 minutes and of 117.49 J/s thereafter.

| Time | Temperature | | Average temperature | Temperature difference | Thermal conductivity |
|---|---|---|---|---|---|
| | Warm side | Cold side | | | |
| min | °C | °C | °C | K | W/(m*K) |
| 0 | 22.6 | 22.6 | 22.6 | 0 | 0 |
| 0.5 | 28 | 22 | 25 | 6 | 4.48 |
| 1 | 29.6 | 22.6 | 26.1 | 7 | 3.84 |
| 1.5 | 30.4 | 22.6 | 26.5 | 7.8 | 3.45 |
| 2 | 31.6 | 22.8 | 27.2 | 8.8 | 3.05 |
| 2.5 | 32.6 | 22.8 | 27.7 | 9.8 | 2.74 |
| 3 | 33.8 | 22.8 | 28.3 | 11 | 2.44 |
| 3.5 | 34.6 | 23 | 28.8 | 11.6 | 2.32 |
| 4 | 34.6 | 22.8 | 28.7 | 11.8 | 2.28 |
| 4.5 | 35.4 | 22.8 | 29.1 | 12.6 | 2.13 |
| 5 | 36 | 23 | 29.5 | 13 | 2.07 |
| 5.5 | 36.8 | 22.6 | 29.7 | 14.2 | 1.89 |
| 6 | 37.6 | 22.8 | 30.2 | 14.8 | 1.82 |
| 6.5 | 37 | 22.8 | 29.9 | 14.2 | 1.89 |
| 7 | 37.6 | 23 | 30.3 | 14.6 | 1.84 |
| 7.5 | 37.8 | 22.8 | 30.3 | 15 | 1.79 |
| 8 | 38.2 | 23 | 30.6 | 15.2 | 1.77 |
| 9 | 39 | 22.8 | 30.9 | 16.2 | 1.66 |
| 10 | 39.4 | 22.8 | 31.1 | 16.6 | 1.62 |
| 11 | 39.6 | 23 | 31.3 | 16.6 | 1.62 |
| 12 | 39.8 | 22.8 | 31.3 | 17 | 1.58 |
| 13 | 40.2 | 23 | 31.6 | 17.2 | 1.56 |
| 14 | 41.2 | 23 | 32.1 | 18.2 | 1.48 |
| 15 | 42 | 22.8 | 32.4 | 19.2 | 1.40 |
| 16 | 41.6 | 22.8 | 32.2 | 18.8 | 1.43 |
| 17 | 42.4 | 22.8 | 32.6 | 19.6 | 1.37 |
| 18 | 42.4 | 23 | 32.7 | 19.4 | 1.39 |
| 19 | 43.2 | 22.8 | 33 | 20.4 | 1.32 |
| 20 | 43.2 | 23 | 33.1 | 20.2 | 1.33 |
| 21 | 42.8 | 22.8 | 32.8 | 20 | 1.34 |
| 22 | 42.8 | 23 | 32.9 | 19.8 | 1.36 |

| | | | | | |
|---|---|---|---|---|---|
| 23 | 42.6 | 23 | 32.8 | 19.6 | 1.37 |
| 24 | 43.8 | 23.2 | 33.5 | 20.6 | 1.30 |
| 25 | 45.4 | 23.2 | 34.3 | 22.2 | 1.21 |
| 25.5 | 46.6 | 23.2 | 34.9 | 23.4 | 1.15 |
| 26 | 46.6 | 23 | 34.8 | 23.6 | 1.14 |
| 26.5 | 48.4 | 23.2 | 35.8 | 25.2 | 1.07 |
| 27 | 47.2 | 23.2 | 35.2 | 24 | 1.12 |
| 27.5 | 47.4 | 23.2 | 35.3 | 24.2 | 2.22 |
| 28 | 49.6 | 23.2 | 36.4 | 26.4 | 2.04 |
| 28.5 | 53.4 | 23.2 | 38.3 | 30.2 | 1.78 |
| 29 | 56.4 | 23.2 | 39.8 | 33.2 | 1.62 |
| 29.5 | 58.8 | 23.2 | 41 | 35.6 | 1.51 |
| 30 | 61 | 23.4 | 42.2 | 37.6 | 1.43 |
| 30.5 | 62.8 | 23.4 | 43.1 | 39.4 | 1.36 |
| 31 | 64.4 | 23.6 | 44 | 40.8 | 1.32 |
| 31.5 | 65.8 | 23.4 | 44.6 | 42.4 | 1.27 |
| 32 | 67.2 | 23.4 | 45.3 | 43.8 | 1.23 |
| 32.5 | 68.2 | 23.6 | 45.9 | 44.6 | 1.21 |
| 33 | 69.4 | 23.4 | 46.4 | 46 | 1.17 |
| 33.5 | 70.2 | 23.6 | 46.9 | 46.6 | 1.15 |
| 34 | 71.2 | 23.4 | 47.3 | 47.8 | 1.12 |
| 34.5 | 72 | 23.4 | 47.7 | 48.6 | 1.11 |
| 35 | 72.8 | 23.6 | 48.2 | 49.2 | 1.09 |
| 35.5 | 73.2 | 23.6 | 48.4 | 49.6 | 1.08 |
| 36 | 73.8 | 23.4 | 48.6 | 50.4 | 1.07 |
| 36.5 | 74.4 | 23.6 | 49 | 50.8 | 1.06 |
| 37 | 74.8 | 23.4 | 49.1 | 51.4 | 1.05 |
| 37.5 | 75.2 | 23.4 | 49.3 | 51.8 | 1.04 |
| 38 | 75.8 | 23.4 | 49.6 | 52.4 | 1.03 |
| 38.5 | 76.2 | 23.6 | 49.9 | 52.6 | 1.02 |
| 39 | 75.8 | 23.4 | 49.6 | 52.4 | 1.03 |
| 39.5 | 76.2 | 23.4 | 49.8 | 52.8 | 1.02 |
| 40 | 76.6 | 23.6 | 50.1 | 53 | 1.01 |
| 40.5 | 77.2 | 23.6 | 50.4 | 53.6 | 1.00 |
| 41 | 77.4 | 23.6 | 50.5 | 53.8 | 1.00 |
| 41.5 | 77.6 | 23.6 | 50.6 | 54 | 1.00 |
| 42 | 78 | 23.8 | 50.9 | 54.2 | 0.99 |
| 42.5 | 78.2 | 23.6 | 50.9 | 54.6 | 0.98 |
| 43 | 78.4 | 23.6 | 51 | 54.8 | 0.98 |
| 43.5 | 78.8 | 23.8 | 51.3 | 55 | 0.98 |
| 44 | 78.8 | 23.8 | 51.3 | 55 | 0.98 |
| 44.5 | 79.2 | 23.8 | 51.5 | 55.4 | 0.97 |
| 45 | 79.4 | 23.8 | 51.6 | 55.6 | 0.97 |

*Table 3.* Temperature records of the box filled with Isofloc® material at a steady heat flow of 117.49 J/s.

| Time | Temperature | | Average temperature | Temperature difference | Thermal conductivity |
|---|---|---|---|---|---|
| | Warm side | Cold side | | | |
| min | °C | °C | °C | K | W/(m*K) |
| 0 | 23.2 | 23.2 | 23.2 | 0 | 0 |
| 0.5 | 32.6 | 23.2 | 27.9 | 9.4 | 5.72 |
| 1 | 37.8 | 23.2 | 30.5 | 14.6 | 3.68 |
| 1.5 | 42.2 | 23.2 | 32.7 | 19 | 2.83 |
| 2 | 45.6 | 23.2 | 34.4 | 22.4 | 2.40 |
| 2.5 | 48.6 | 23.2 | 35.9 | 25.4 | 2.12 |
| 3 | 51.8 | 23.2 | 37.5 | 28.6 | 1.88 |
| 4 | 56.6 | 23.2 | 39.9 | 33.4 | 1.61 |
| 5 | 60.2 | 23.2 | 41.7 | 37 | 1.45 |
| 6 | 64 | 23.2 | 43.6 | 40.8 | 1.32 |
| 7 | 67.2 | 23.2 | 45.2 | 44 | 1.22 |
| 8 | 69 | 23.2 | 46.1 | 45.8 | 1.17 |
| 9 | 70.6 | 23.2 | 46.9 | 47.4 | 1.13 |
| 10 | 72.6 | 23.2 | 47.9 | 49.4 | 1.09 |
| 11 | 74.2 | 23.2 | 48.7 | 51 | 1.05 |
| 12 | 75.4 | 23.4 | 49.4 | 52 | 1.03 |
| 13 | 76.4 | 23.4 | 49.9 | 53 | 1.01 |
| 14 | 77.2 | 23.4 | 50.3 | 53.8 | 1.00 |
| 15 | 78 | 23.4 | 50.7 | 54.6 | 0.98 |
| 16 | 78.6 | 23.6 | 51.1 | 55 | 0.98 |
| 17 | 78.6 | 23.6 | 51.1 | 55 | 0.98 |
| 18 | 79 | 23.6 | 51.3 | 55.2 | 0.97 |
| 19 | 79.2 | 23.8 | 51.5 | 55 | 0.98 |
| 20 | 79.8 | 24.2 | 52 | 55.4 | 0.97 |
| 21 | 80 | 24.4 | 52.2 | 55.6 | 0.97 |
| 22 | 80.2 | 24.4 | 52.3 | 55.8 | 0.96 |
| 23 | 80.6 | 24.4 | 52.5 | 55.8 | 0.96 |
| 24 | 80.6 | 24.8 | 52.7 | 55.8 | 0.96 |
| 25 | 81 | 24.8 | 52.9 | 56.2 | 0.96 |
| 26 | 81 | 24.8 | 52.9 | 56 | 0.96 |
| 27 | 81 | 25 | 53 | 55.8 | 0.96 |
| 28 | 81.2 | 25.2 | 53.2 | 55.8 | 0.96 |
| 29 | 81.4 | 25.4 | 53.4 | 56 | 0.96 |
| 30 | 82 | 25.4 | 53.7 | 56.6 | 0.95 |