Local biobased materials production for basic household needs

An exploration of opportunities for self-sufficiency in building, textile and furniture materials

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Institute: Wageningen Food & Biobased Research, Wageningen Environmental Research, Wageningen Plant Research

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Preface

After having worked as a consultant in sustainability and biobased economy, I had seen a lot of different innovations and approaches to sustainability. Most of them revolved around the concept of meeting a certain product demand with less resources, by using renewable resources or with less harmful emissions. I have always felt that an important element of true sustainability was missing in these projects. It was only when I read the ‘Permaculture Designer’s’ Manual’ by Bill Mollison that I started to realize that it is the eco-system itself which should be the starting point for any sustainable innovation. Eco-systems define the carrying capacity of a certain area or region. This implies that we harvest only excess renewable resources and preserve or preferably even strengthen (regenerate) the eco-system on which we depend.

Our globalized society has already breached seven out of nine planetary boundaries. We often feel helpless in taking action as our globalized production systems are managed by multinational companies which have little connection to the regions we live in. At the same time, this globalized system ensures that the environmental impacts of our consumption are less visible to us and often take place in the most vulnerable regions around the world. Of course, we can change our consumption patterns and choose sustainable products, but because we hardly experience the connection between our consumption and the consequential environmental impact in our own living environment, we only make sustainable choices based on morality (less environmental impacts is the right thing to do). Instead, a far more powerful motivator would be the actual local experience of dependence on the local eco-systems that provide us with food, materials and energy. Local production systems based on locally available resources can bring a lot of new perspective here and ensure that we stay within planetary boundaries because we are able to experience the very existence of these planetary boundaries on a local level.

As Kirkpatrick Sale, one of the founders of the concept of locally and eco-system oriented bioregional societies, puts it: *People will behave in a responsible way if they have been persuaded to see the (environmental) problem concretely and to understand their own connections to it directly. This can only be done at limited scale. If there is any scale at which ecological consciousness can be developed, at which citizens can see themselves as being the cause of the environmental effect, it is at the regional level. People do not pollute and damage those natural systems on which they depend for life and livelihood if they see directly what is happening.*

Three years ago, we were invited to perform this exploratory project on local production of biobased materials with funding by the Wageningen Knowledge Base Program. It was the perfect opportunity to elaborate ideas on local production and the role that biobased materials can play in this. By taking building materials, textiles and furniture as a main focus, we literally take the basic material needs as a kind of lower boundary on what material needs should be provided for by the local eco-system, next to food of course. We hope this study will provide you with new perspectives for local biobased material production and its opportunities for ecologically sound development of productive landscapes in bioregions.

Arjen van Kampen

Wageningen, November 2025

Summary

In this study, we have explored the opportunities for local and biobased production of basic household material needs in building, textiles and furniture. We mainly looked at (ligno)cellulosic materials, since the bulk of household materials can be made out of this type of biomass. Local was defined as self-sufficiency and processing of biomass at a national level for the Netherlands or at a smaller regional level when possible. The first question to be answered was to which extent locally produced biobased materials are available in sufficient quantities. Secondly, an assessment was made whether these materials meet current quality requirements and can be(come) a viable alternative to conventional materials. Thirdly, a sketch of productive self-sufficient and so-called soil-water guided landscapes was made.

Quantitative assessment

For the quantitative assessment, data were gathered on the whole value chain: from wood and fibre crop to conversion processes up till the final demand for building, furniture and textile materials. This allowed for the calculation of land footprints required to meet Dutch demand for building materials (455,000 ha), textiles (280,000 ha) and furniture (690,000 ha), when making these products largely biobased. Jointly, these land footprints amount to 1.4 million ha, which is about 65% of the Dutch agricultural plus forest area. This land footprint could be reduced to 1 million ha by the adoption of more circular (re-use/recycling) practices.

Even though the production of basic need materials at local or national level would require considerable surface areas which in the first place seem difficult to accommodate in the Netherlands, it should be noted that a fair comparison with current land-use can only be made if self-sufficiency would be the rule for Dutch agricultural land use for food production as well, because current Dutch food production is exported for about 50%. If for example the cattle and dairy farming sector would produce only for domestic demand, this could make available 639,000 ha which could be used for other forms of food production but also for fibre crops and forestry. Hemp, flax, straw and Miscanthus were shown to be the most economically viable crops, while also delivering a range of eco-system services, such as biodiversity, soil organic matter and soil life, ground and surface water quality, to mention a few. Production forests deliver more eco-system services than crops, but also require a longer period (60-80 years) before harvest can take place.

Qualitative assessment

For **building materials**, wood has been around as a building material since early human history. In modern construction, wood building techniques like Cross-laminated Timber (CLT), Glulam and Timber Frame Construction (TFC), complemented with other biobased materials like fibre boards and insulation, are increasingly becoming common practice. Many locally available tree species, like Scots pine, Larch, Douglas Fir, and other spruces can meet the C24 strength class typically used for CLT/Glulam and the C18 class for TFC. Wood is the current reference feedstock for the production of different types of particle board, which is made from residue streams from the (sawn) wood processing sector, but also from construction demolition wood waste. In principle, all strength classes (P1-P7) can be attained using a broad variety of wood species. Several other biobased fibre crops and fibrous residues meet the strength and stiffness requirements of P3-P5 strength classes, but fall short on the thickness swelling due to insufficient use of water repelling agents. Compared to fossil references, biobased insulation blankets of a variety of fibre types show a thermal conductivity similar to glass wool and rockwool (approx. 0.036-0.040 W/m.K), even though their average density is higher than glass wool and lower than rock wool.

For **furniture**, mechanical (strength) performance is relevant, though not key. Somewhat lower mechanical properties can be compensated by increasing material thickness. In principle, particle board strength class P2 is suitable for furniture applications, meaning that next to wood also hemp shives, cereal straw, reed and the stems from some plants can be used.

For **textiles**, it was more challenging to make a statement about the suitability of local biobased fibres, since current textiles are mainly composed of cotton and/or fossil polyester (and a range of other fibres). Based on

a very basic evaluation of GSM and fabric strength, it could be derived that it is possible to use (ligno)cellulosic fibres in all home and clothing textile applications. However, in order to come up with a local biobased alternative for the most common natural (but not locally available) textile fibre cotton, a range of other properties also need to be attained. Cotton is easily processed, has the desired comfort and physical properties. Cottonization of hemp/flax fibres (refining and shortening) and a higher share of viscose/lyocell may contribute to mimic some cotton properties in the fabric. Obviously, also recycled cotton could play a role here.

From value chain to landscape

The data obtained on biobased material demand, conversion ratios and biomass production, allowed to assess the potential for biobased self-sufficient landscapes, which was done on national level and regional level (de Achterhoek). For this, a landscape allocation rule was established based on land footprint for materials and food relative to the amount of inhabitants per hectare of arable land. This resulted in 68% of arable land use required for food and 32% for indicated materials: buildings, furniture and textiles. It also looked at the impacts of more land-efficient diets (circularity diet) and additional circularity of biobased materials.

The current population density for the Netherlands is 529 inhabitants per km^2. The average population density which can be provided for by a self-sufficient landscape design based on the above allocation rule *at current practice* corresponds to 282 inhabitants per km^2 of land, taking into account current shares of (non-productive) buildings and infrastructure and nature in the Netherlands. When also applying a circularity diet and circularity of materials, up to 455 inhabitants per km^2 can be provided for. When reducing the share of nature protection areas from 20% to 10%, the Dutch current population density's food and material demand could be provided for. A positive counter-effect of this approach would be that production forests make up a higher share of the landscape, resulting in a combined nature and production forest area of over 30%, a net increase of 10% compared to current nature protection area of 20%. This raises the question whether nature conservation areas can be productive to some extent and shows the potential benefit of productive landscapes for food and materials.

The same allocation rule was applied on regional level for De Achterhoek. The development of self-sufficient landscapes starts in the region by taking into account the specific characteristics of a region and optimally align with soil and water conditions (soil-water guiding principle).

Opportunities for implementation

A potential priority sector for local self-sufficiency would be the construction sector. There is a serious perspective for self-sufficiency for this sector. When circular practices are applied in the building industry, already with an additional forest area of 227,000 ha (Scots pine, Douglas, Spruce), an annual need of 70,000 houses per year could be met for ground-level houses on the long term (60-80 years). For textiles, the perspective for local production is more challenging as there is a lack of industry (particularly in the spinning step) which could work with local fibres. Key priority here is to first re-create this industry. Flax is an existing textile crop in the Netherlands, but its processing currently takes place abroad (France or even China). A first flax spinning facility would be a priority if local Dutch textile production is to be stimulated. Also for wool – an available high-quality fibre – bringing back a spinning facility (and sheep races like Merino) to make yarns is a priority in order to enable local textile production. Truly local production of viscose or lyocell from wood will be challenging in the Netherlands as it requires a large pulping and spinning facility which also requires a certain abundance and homogeneity of biomass which is not present in the Netherlands. As an alternative, discarded textiles could be a feedstock source for which SaXcell is planning to set up a factory at scale, as (waste) cotton would not have to be pulped as lignocellulose feedstocks like wood and plant stems would.

Complementary to the above sectoral strategies, an intersectoral approach to landscape development could be developed in which food and material production go hand-in-hand. After all, besides the advantages of local biobased materials, a key driver to local biobased production is the integrated design of robust, sustainable, (bio)diverse productive landscapes for food and materials. A perspective for local biobased material production in the Netherlands is certainly not straightforward and may be difficult to imagine. It requires a long-term perspective and strategy, which embraces the fact that setting up significant areas of forestry (key for all three sectors considered in this study) may take at least 60-80 years, but enables future generations to be self-sufficient in material production and benefit from the eco-system services delivered by these forests. Particularly in the Netherlands, where current intensive land-use puts a high burden on soil, air, water quality and biodiversity, the actual value of these eco-system services should be duly appreciated.

1 Introduction

Materials play an important role in our daily lives. Building materials, textiles and furniture are basic needs (next to food) and provide shelter, comfort and protection. The building materials applied in our houses protect us from the weather and create a comfortable environment for people to live, work and play. Textile materials are used in clothing, upholstery for furniture and household textiles which all bring comfort, protection and help us perform our daily activities. All these materials can in principle be produced from biomass, a renewable and sustainable resource. Since biomass is a resource which is available almost anywhere, biobased materials provide opportunities to set up value chains which are more locally oriented than most traditional building product value chains.

Biobased materials can contribute to significantly reducing environmental impacts which are needed to produce conventional building, furniture and textile materials[1]. A recent report showed that biobased building materials for example can decrease environmental cost by 18-35% compared to conventional materials[2]. The building and construction sector in the Netherlands for example is heavily based on mineral and fossil feedstock. Building materials and the construction process of buildings account for 11% of global energy related GHG emissions[3]. Also the production, transport, use and disposal of products used on a daily basis like clothing, furniture, packaging, etc. are fossil based to a large extent and involve a considerable environmental impact.

The biobased (renewable) character can play a role in mitigating these impacts in multiple ways. In long- term applications like building materials, biobased building materials can ‘store’ biogenic carbon and temporarily remove it from the atmosphere[4]. At the same time, biomass already has properties which make it suitable as a building material or textile. In order to establish an efficient and local biobased economy, it is key to use the properties of (components in) the biomass in an optimal way. The issue of optimally using the intrinsic quality of the biomass in relation to the performance requirements of building, furniture and textile materials is key to unlocking the possibilities of a more local biobased economy.

Before going further into the opportunities for the local production of biobased materials, it is important to briefly address current experience with local production in order to be better able to put local production of biobased materials in the right context. This experience to a large extent applies to food production, but is also increasingly spreading towards biobased material production.

1.1 Transition to local production in food and materials

In food, there is already an ongoing trend towards more local production. An increasing number of citizens, farmers, policy makers and social organisation is already working on setting up a more regionally oriented food production system. They are driven by a need to obtain more fair market prices, to restore soil health and biodiversity and to increase farmer-citizen collaboration and understanding[5]. They are a response to an existing agricultural system which is focused on cost competitiveness, ‘ever’ increasing scale and profit maximalization and which has turned out not to be the most sustainable system.

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[1] Harmsen, P., Post, W., & Bos, H. (2022). Textiles for circular fashion. Part 2, From renewable carbon to fibers. Wageningen Food & Biobased Research. https://doi.org/10.18174/568425

[2] van den Oever, M., Melchers, R., van Westerlaak, M., Bakker, B., Engelbrecht, E., Drissen, J., Weterings, H., de Munck, E., van der Burgh, F., & Verspeek, S. (2024). Bio-based building products in the Dutch Environmental Database (NMD): Part 3: Example calculations on the environmental impact of A) building products and B) reference buildings to show the effects of: 1) bio-based vs. conventional building products, 2) crediting biogenic carbon storage. (Report / Wageningen Food & Biobased Research; No. 2631). Wageningen Food & Biobased Research. https://doi.org/10.18174/683389

[3] https://worldgbc.org/advancing-net-zero/embodied-carbon/

[4] van den Oever, M., Vural Gursel, I., Weterings, H., de Munck, E., van der Burgh, F., Verspeek, S., & Drissen, J. (2024). Bio-based building products in the Dutch Environmental Database (NMD). Part 1, Proposal for crediting biogenic carbon storage. (Report / Wageningen Food & Biobased Research; No. 2545). Wageningen Food & Biobased Research. https://doi.org/10.18174/647711

[5] Hassink, J., Nassar, G., & Tacken, G. (2023). Duurzaamheid lokaal en regionaal voedsel. (Rapport / Wageningen Plant Research; No. WPR-1240). Wageningen Plant Research. https://doi.org/10.18174/631116

Local agriculture initiatives are highly diverse and include a range of different organisational approaches:

- The consumer is the initiator (community gardens, food collectives, housing collectives such as Almere Oosterwold, Sustainable Villages)
- Consumers and producers are partners (Community Supported Agriculture or CSAs, Herenboeren, co-operative shops, co-operative regional markets, many urban farms, cooperatives such as Land van Ons, Markelokaal Area Cooperative South-West Drenthe).
- Direct sales to consumers (meal boxes, farm shops, farmers' markets, roadside stalls, wholesalers such as Rechtstreex, The Regional farmer and producer collectives/trading houses such as Oregional, Local2Local or Boerenhart.

In total, it is estimated that there are over 500 local initiatives in the Netherlands, in which over 150.000 citizens are involved[6]. Very often, these initiatives are pioneering new models for food production and have to re-invent new principles about (land) ownership and forge new short food chains which benefit all parties involved:

- The short value chains enable a fair-share and transparent redistribution of value over farmer, citizen and other stakeholders in the value chain. Because of the local character, these stakeholders know each other personally and this increases the chance of a more fair distribution.
- New ownerships models (e.g. citizen-owned or a steward-owned land) allow for more room for experimentation with new sustainable models of agriculture, like regenerative farming and agroforestry. Land van Ons and Lenteland are examples of this type of initiatives.

For biobased materials, there is also a tendency to more local production. In the Netherlands, the Dutch National Policy for Biobased Building (NABB) strongly focuses on the creation of regional (often: provincial) biobased value chains for biobased building materials. The main focus is on biobased insulation and board materials from hemp, flax, Miscanthus and straw. In total, there are currently 16 regionally focused value chain projects[7]. In these regional value chains, collaborations of farmers, processors of fibrous biomass, builders and housing associations work together and make off-take agreements on the supply and application of biobased insulation and board materials.

1.2 From local initiatives to a locally oriented society

Whereas the above illustrates that local production is gaining traction in the Netherlands, it is certainly not the standard. It is interesting to explore the full potential of local biobased production, once it becomes the standard in society. This philosophy is embodied in the concept of bioregionalism, which emphasizes the importance of local populations becoming self-sustaining based on the resources available within their surrounding bioregions. Bioregionalism encompasses a variety of approaches, promoting local economic systems, participatory democracy, and sustainable practices in architecture, agriculture, and resource management. The movement encourages the use of local materials, emphasizes the significance of local culture and economy, and supports grassroots initiatives aimed at environmental preservation and community well-being[8].

Besides the more tangible environmental benefits of local production which have already been outlined above, there is a more philosophical argument in support of a more regionally oriented society based on renewable resources or "bioregional" society. Sustainable behaviour is currently mostly a *moral* issue of consumers making the right choices for sustainable products supplied by highly internationalized value chains. If production and consumption is organized on a regional scale and is based on locally available resources, sustainable behaviour becomes much more a *practical* thing to do. To quote Kirkpatrick Sale, one of the founders of the bioregional approach: "People will behave in a responsible way if they have been persuaded to see the problem concretely and to understand their own connections to it directly. This can only be done at

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6 Van Kampen, Lokale voedselgemeenschappen in Nederland, Inventarisatie en verkennend onderzoek, 2020
7 https://buildingbalance.eu/regioprojecten/
8 https://www.ebsco.com/research-starters/science/bioregionalism

limited scale. If there is any scale at which ecological consciousness can be developed, at which citizens can see themselves as being the cause of the environmental effect, it is at the regional level. People do not pollute and damage those natural systems on which they depend for life and livelihood if they see directly what is happening"[9]. This is illustrated by the figure below.

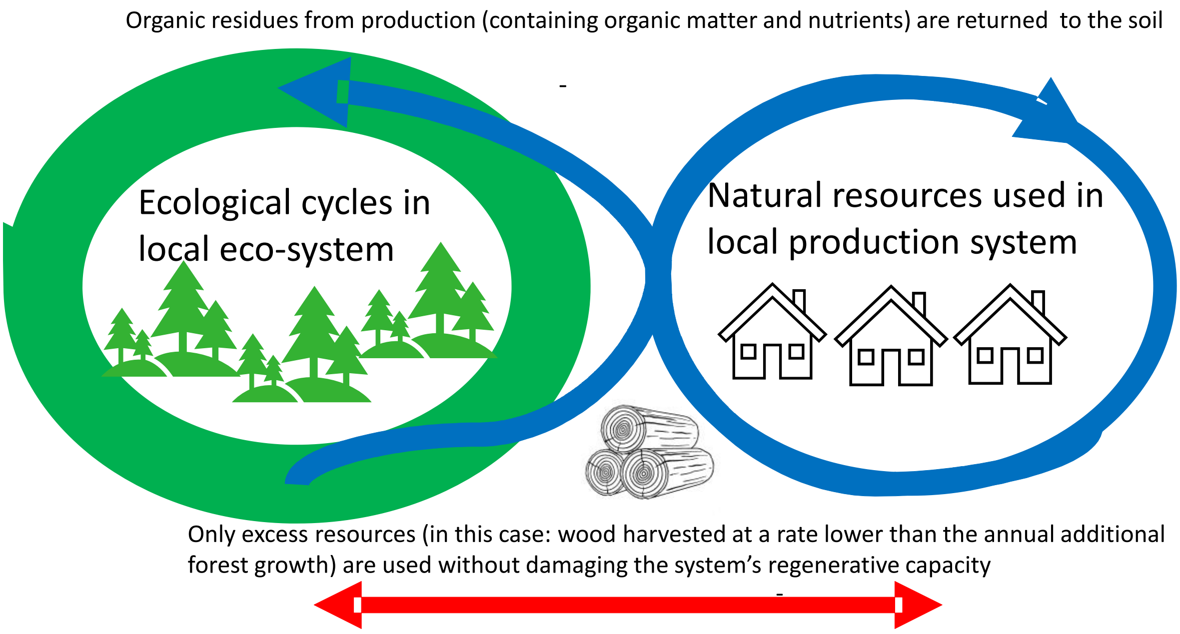

Figure 1 ***The bioregional approach illustrated: dependence of local community on local resources (in this case wood) ensure the community stays within the boundaries of the local eco-system.***

The figure shows that for example wood is grown in forests which are part of a local eco-system. In case this wood is locally applied for the construction of houses, residents from the community will become aware of their dependence on the nearby forest and be more inclined to protect it. More specifically, they will not harvest more from the forest than the forest can sustainably produce (so below the eco-system's regenerative capacity) because this would harm their future harvests. For the same reason they will be less inclined to pollute the forest because it would also jeopardize the future production capacity of the forest. It is exactly these feedback mechanisms which are often lacking in highly internationalized and often scattered value chains.

Taking full account of earlier experiences in local production and bioregional thinking, this study will focus on assessing what is possible on a local (national) level when we try to maximize the use of local biomass for basic need household materials in building, textiles and furniture materials.

1.3 Scope of this research

Materials for the construction of houses and for use within households are very diverse: concrete, steel, other metals, mineral wool, wood, (fossil based) polymers and rubbers, textiles, etc. Considering the function, biobased materials can replace large part in volume, taking into account that materials and products applied in building and households have to meet performance requirements; e.g. regarding mechanical strength of construction materials and low thermal conductivity of insulation products.

The biomass source which can be used in largest volumes for the construction of houses and within households comprises the group of so called (ligno)cellulose based materials like wood and crops like flax, hemp, Miscanthus, straws from cereals, etc. Also biobased plastics, resins and coatings can be made from biomass. However, since these materials are applied in a wide and diverse range of house(hold) products (e.g. coatings,

[9] Kirkpatrick Sale, Dwellers in the Land, *The Bioregional vision*, Athens, 2000

electric wire insulation, electric power wall outlets, electric device housings, etc.) and require completely different types of conversion technologies, they will not be included in this project in order to focus effort.

Focus is thus on (ligno)cellulosic biomass (trees, crops) of which it is known that they offer good possibilities to produce household materials. The term 'local' in this report is interpreted as the scale of the Netherlands as a whole, since the Netherlands is a small country and it is relevant to know till which extent the Netherlands could rely on locally produced biobased household materials. It is also the scale at which most data are available. Where possible, options for production at more (sub-)regional level will be sketched.

Other household needs which (may potentially) require large volumes of biomass include food and energy. Energy will not be covered in this study because besides bio-energy there are many other options to produce energy locally from natural resources (e.g. wind, solar, thermal). Food will not be an explicit focus of this study, but will be used as a reference as self-sufficiency in food is probably a pre-requisite before focusing on self-sufficiency in materials. This means that self-sufficiency in materials has to be studied within the context of self-sufficiency for food. This is particularly relevant in the development of a biobased landscape self-sufficient in the provision of household material needs.

1.4 Objectives

This study will explore the possibilities for a more locally oriented biobased material production in the Netherlands by studying the extent to which materials for building, furniture and textiles can be produced locally from locally sourced biomass. The specific objectives of this study are the following:

1. To determine to which extent basic material needs for a house and household (construction, furniture and textiles) can be met with lignocellulosic biomass, taking into account both the quality requirements of the final product, the availability of biomass in the Netherlands and the extent to which the biobased products can be made at local scale.
2. To explore to which extent material self-sufficiency is possible based on the value chains identified under the first objective, and how the crops and trees required for these local biobased value chains can be implemented in the landscape in an ecologically sound way.

1.5 Approach and methods

For the first objective, the steps which will be taken to obtain the necessary data are the following:

First, an overview will be made of the different building products and household items to be included in this study, the material quality requirements for these products and the quantities needed per household. This will be done based on literature study and practical case examples. This work will be presented in chapter 2.

Secondly, the biomass sources (crops and trees) available to produce these materials will be studied in detail. Their yields, cultivation conditions, economics and sustainability will be analysed. This will be done based on literature research and crop data which have been gathered by Wageningen University and Research in its annual KWIN-analysis. This is a methodology to analyse and compare the economic performance of a crop. This work will be presented in chapter 3.

Thirdly, the conversion routes from biomass to end-product will be identified in chapter 4, including conversion rates and the performance criteria which these products attain. This will be done based on conversion processes which are industrially well-known and for which data have been obtained from industries operating these processes.

Finally, the performance of (ligno)cellulosic based biobased materials for building, textiles and furniture will be compared to the quality requirements presented in chapter 5. This analysis allows for an initial selection on which biobased materials can be an alternative to fossil-based or mineral based materials.

Under the second objective, the following approach will be taken.

By using the data obtained after following the steps described above, the land footprint for house, furniture and textiles can be calculated. This land footprint will be used to assess to which extent local Dutch material self-sufficiency for households is a realistic concept square meter wise (chapter 6).

Finally, landscape typologies will be made for the main Dutch soil types in which the trees and crops which optimally match soil and water conditions in order to assess to which extent material self-sufficiency for households is realistic considering actual Dutch landscapes (chapter 7).

1.6 Scope of relevant materials

As outlined earlier, the study's focus will be on the basic material needs of a household for house, furniture and textiles. This section will define which materials are in scope of this research.

1.6.1 Building

In order to better define the type of materials, insight into the functions they fulfil in a building are presented in Figure 2. In earlier work by Wageningen Food & Biobased Research, the firm Orga Architects (Daan Bruggink) has made a framework to classify the main building materials[10]. In the picture below, a summary is provided of this framework as well as the main biobased materials used in a building.

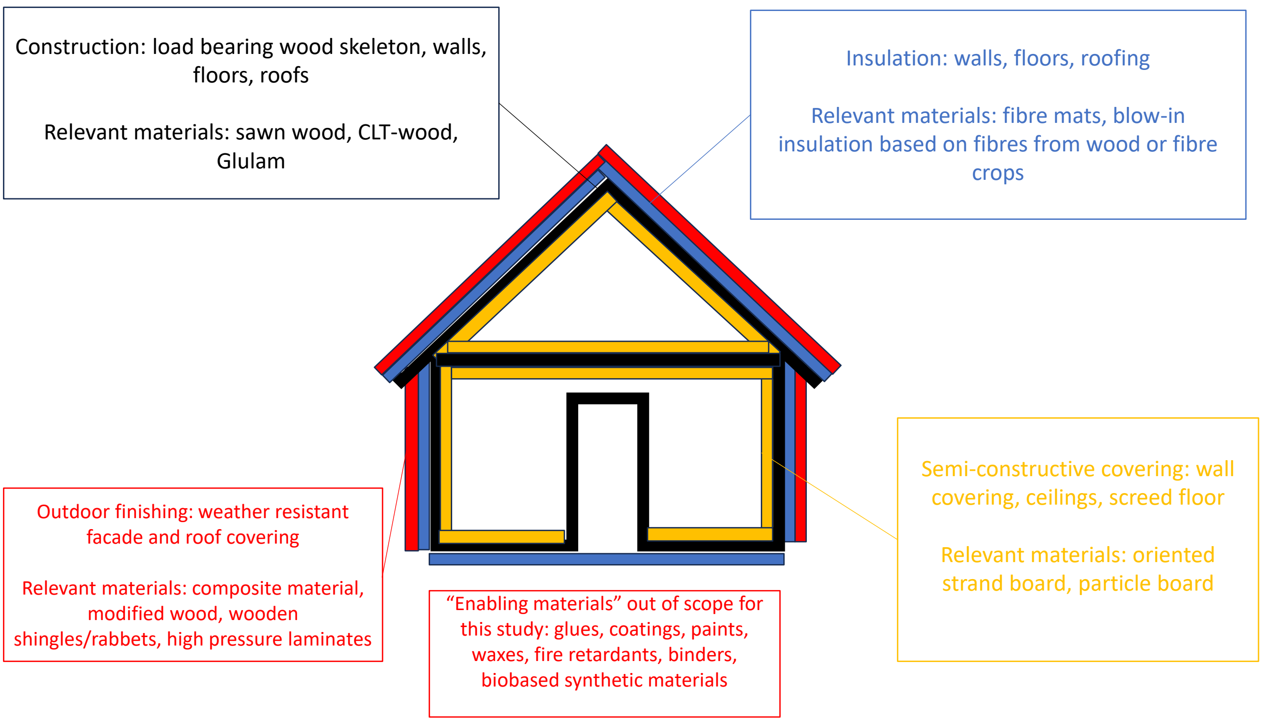

Figure 2 Main elements of the building and (biobased) materials used.

From this figure a couple of main applications can be distinguished for which specific materials are required:

- The primary building material to start with are the **constructive materials** which make up the core of the house and to which the other materials are attached. If the constructive part of the building is to be made of biobased materials, then wood is the primary choice. The main materials which are part of this category are sawn wood (e.g. beams for timber framework construction,

[10] Catalogus biobased bouwmaterialen 2019, Van Dam en Van Den Oever, Wageningen Food & Biobased Research, Wageningen 2019

TFC), cross laminated timber (laminated wood panels, CLT) and laminated wood (laminated sheets of wood, e.g. glulam).

- **Semi-constructive covering material** include panels which are applied to the constructive framework in order to create cover for the construction and help catch up shear and torsion stresses.
- **Insulation materials** are applied to avoid heat transfer and regulate the climate of the house. This includes insulation mats, insulation boards and blow-in insulation based on fibrous (e.g. cellulose, etc.) material.
- For **outdoor finishing,** weather-resistant materials are applied. Biobased options available here are modified wood (thermally or chemically), high pressure laminates (HPL) and biofibre composites.

The main focus of this research is on fibre based materials as they lend themselves better for local and relatively small-scale production and make up the bulk of the materials used to build a biobased house. Obviously, not all the materials are fibre based and there is a long list of materials which add key properties to the fibre based materials or are used in the construction process, like glues, coatings, paints, waxes and fire retardants. These materials are produced in chemical production plants and require a totally different production process and are therefore excluded from the scope of this research.

1.6.2 Textiles

The range of textiles used in a household is very broad. Each application has its own specific performance requirements. A first sub-division can be made between home textiles and clothing textiles. Home textiles refer to the textiles which are used in the house, like curtains, pillows and upholstery. Clothing textiles refer to textiles which are worn by the residents of the house. The figures below illustrate which applications fall under each category.

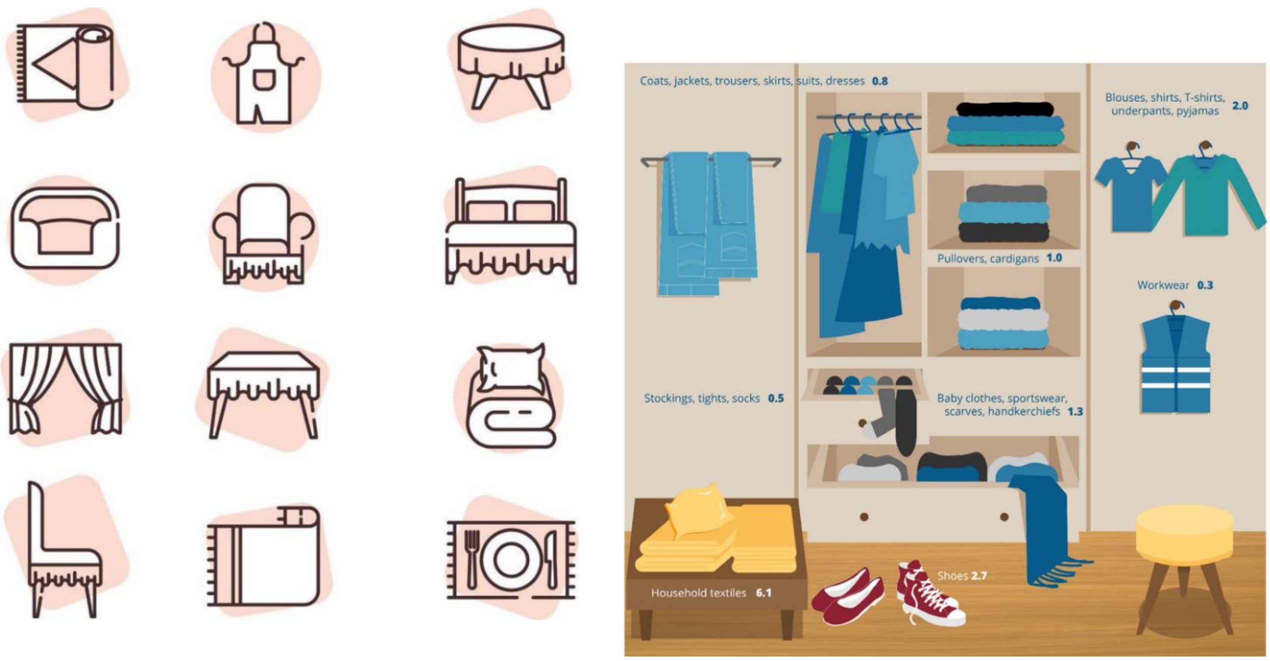

Figure 3 Home textiles (left) and clothing textiles (right) applied in a household[11].

The following applications have been included for home textiles in this study:

- Curtains
- Sheets and pillow covers
- Blankets
- Towels

[11] Textiles and the environment: the role of design in Europe's circular economy, European Environmental Agency, 2022

- Table linen
- Carpets
- Fabric for sofas and chairs (Upholstery)

For clothing textiles, the following types of garments are included

- Jackets
- Trousers/ suits
- Shirts
- Jeans
- Dresses
- Skirts
- Swimwear
- Sportswear
- Sleepwear

1.6.3 Furniture

For furniture, focus will be on the most common furniture used in a household:

- Kitchen cabinets
- Cupboards/cabinets
- Kitchen table and chairs
- Sofas
- Beds
- Wardrobes
- Fences

1.7 Reading guide

The following chapters will assess to which extent building, textile and furniture materials can be produced using local biobased materials, both from a quantitative and qualitative perspective.

Chapter 2 will describe the relevant materials more in detail and quantify the current demand for these materials.

Chapter 3 will describe the biomass sources (trees and crops) relevant for the Netherlands which could serve as a bioresource to produce biobased household materials. It will assess cultivation conditions, eco-system services and relevant applications. For agricultural crops, an economic analysis will be performed.

Chapter 4 will look at conversion routes from biomass to product and quantify conversion efficiencies per route. Together with data from chapter 2 and 3, these conversion efficiencies will be used to qualitatively assess the land footprint needed to locally produce biobased materials in chapter 6.

Chapter 5 is dedicated to a quality assessment of locally produced biobased materials. It will describe current quality requirements to these materials for building and household products, and review which biobased feedstocks can meet these quality requirements.

Chapter 6 will calculate the footprint of locally produced building, textile and furniture materials. It will also look at the contribution which re-use and recycling can make to reducing that footprint.

Chapter 7 will translate the findings of the earlier chapters to landscape design. More specifically, it will develop a landscape allocation rule for food, building, textile and furniture material production and design a model landscape for sandy soils (Achterhoek).

2 Demand for basic household materials

This chapter aims to provide insight in the (potential) demand in the Netherlands for use of biobased (lignocellulose) materials/products in house and household applications in terms of general type and estimated quantity. First, biobased options for large volume applications in housing construction and in household products have been listed (§2.1). Then, the potential volume demand of biobased building materials and household products are estimated (§2.2), subdivided in: Number and type of houses to be built in the Netherlands per annum over the next couple of years (§2.2.1.1); amounts of materials/products applied in these type of biobased houses (§2.2.1.2); estimated volume of construction materials required in an 'average' biobased house (§2.2.1.3); amounts of materials used for household items which may be biobased such as textile fabrics and furniture (§2.2.2).

In this study focus is on lignocellulosic materials which can be used as such (e.g. in wood) or which can be processed into fibres and/or particles to produce textiles, board or insulation materials.

2.1 Biobased materials for household applications

This section lists different types of applications in housing construction (§2.1.1) and household products in textiles and furniture (§2.1.2 and 2.1.3) for which requirements may be reasonably met by lignocellulosic biobased materials. Additionally, most appropriate materials and (potentially) suitable feedstock are included. Focus is on applications-materials-products which represent the largest share in volume. Biobased alternatives for chemistry based products, e.g. PUR/PIR foam, plastic products, coatings and paints, etc. are not considered in this study.

2.1.1 Buildings

Below, the main materials and biomass types are presented which are currently applied in biobased buildings.

Table 1 Biobased materials used for building applications.

Main application	Specific application	Type of material	Origin of biomass
Construction framework	Columns (vertical)	Sawn wood; Glulam (GL)	Wood (mostly: spruce)
	Girder beam (horizontal)	Sawn wood; Glulam	Wood (mostly: spruce)
	Load bearing walls	Cross laminated timber (CLT)	Wood (mostly: spruce)
	Floors	Sawn wood, CLT	Wood (mostly: spruce)
Water proofing facade cladding		Preserved wood boards (next to water proofing layer); Composite panels	Wood Hemp/flax fibres with biobased resin; Wood polymer composite (WPC)
Semi structural walls		Mineral bonded lignocellulose fibre	Hemp lime; Cereal straw based panels Alternative: Miscanthus
Constructive boards for Timber frame construction (TFC		Oriented strand board (OSB) Particle board (PB)	Wood (mostly: spruce) Alternative for PB: Cereal straw, reed
Non-load bearing interior walls		Low and medium density boards	Wood fibre (coniferous); Flax shives Alternative: Cereal straw; Reed (Phragmites); Sorghum; Cup plant (Silphia); Stalks from rapeseed and bell pepper; Hemp hurds
Insulation new buildings	Façade, roof, storey floors	Fibre mats (flexible); Boards (rigid);	Wood fibre; Cellulose fibre (recycled paper fibre); Flax and Hemp fibre; Sheep wool; Grass fibre. Wood fibre; Cork. Alternative: Cereal straw; Cattail; Miscanthus; Mycelium based.

	Blow in fibre or particles	Wood fibre; Cellulose fibre. Alternative: Miscanthus; Cattail; Sorghum; Cereal straw; Wood shavings; Sheep wool
Flooring	Parquet (Sawn wood); Laminate (medium density fibre board (MDF) covered with veneer)	Oak, Teak, Merbau Spruce, Pine Alternative: Hardwoods

From the table, the following main types of materials have been selected for this study:

- Wood: sawn wood, CLT and Glulam
- Board: low, medium and high density fibre boards, particle board, oriented strand board
- Insulation: fibre board, fibre mats, blow-in insulation.

2.1.2 Textiles

In order to produce a textile fabric, many steps should be taken to convert fibre feedstock into fabric and hence to final product. Fibres are the essential unit to make textile. From one or different types of fibres a yarn can be spun. There are different spinning techniques to make a yarn. The trick in spinning is to create friction between the fibres by applying a twist which links the fibres together to make a yarn. The yarn diameter, called 'count', and yarn strength are, among others, two key parameters which determine the final application of the fabric. Then the yarns are converted to fabric by interlacing, where the fabric is called 'woven', or by interlocking loops, where the fabric is called 'knitted'. The fabric constructed from bonding and felting the fibres is called 'nonwoven'. Finally, the fabric is converted to final products by finishing processes. The scheme below shows the steps involved to process fibres into final products. The material and process that is highlighted in purple will be explained in depth in this study.

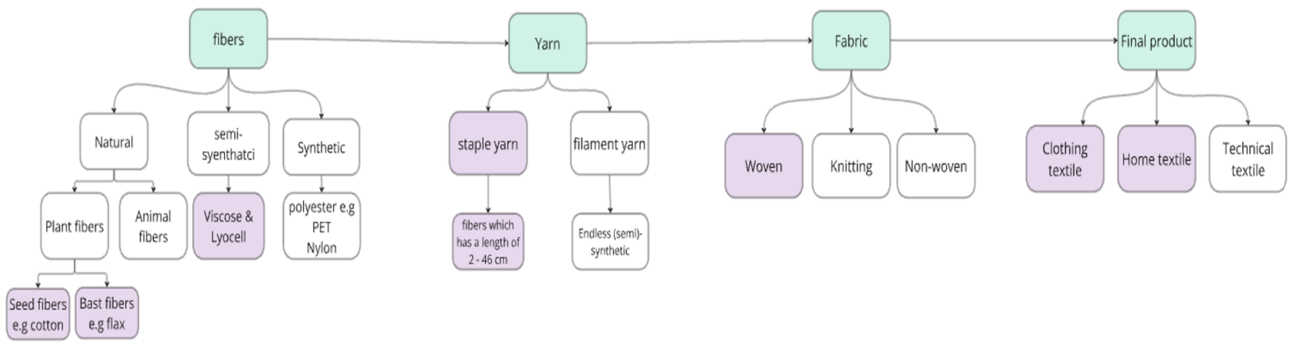

Figure 4 ***Schematic overview of materials from fibres to final textile products. Materials that are addressed in depth in this study are highlighted in purple.***

Fibres are the essential unit to make textile. From one or different types of fibres a yarn can be spun. The yarns are then converted to fabric by various techniques, which will be discussed later on (§4.2.2 and 5.3). In the table below, the main types of fibres are presented and the type of biomass from which they are made.

Table 2 ***Biobased fibres for textiles.***

Type of fibres	Type of material	Type of fibre	Origin of biomass
Natural fibres	Plant fibres	Seed Fibres	Cotton
		Bast Fibres	Flax, hemp Alternative: nettle
	Animal fibres	Wool, Silk	Sheep, Silkworm
Semi-synthetic	Regenerated fibres	Viscose/lyocell	Wood Alternative: Miscanthus

The locally available (ligno)cellulose biomass types are flax and hemp (bast fibres) and regenerated fibres (viscose/lyocell), which will be the main focus of this study. Cotton is not a local feedstock in the Netherlands and neighbouring countries. Wool is not a cellulosic source, it will not be studied in detail like the other types of biomass. It will however be included in chapter 6 in order to assess wool's potential contribution to local biobased production of textiles. Because it is not locally available, silk is excluded from this study. The focus will be on *woven* textiles, which is the most commonly used technique to produce fabrics for most of the products.

2.1.3 Furniture

Below, the main (ligno)cellulosic biobased materials for furniture are presented.

Table 3 Biobased materials used for furniture.

Application	Type of material
Flooring	Sawn wood; MDF
Kitchen cabinets	MDF; PB; hardboard (HDF)
Cupboards/cabinets	MDF; PB; HDF
Kitchen table and chairs	Sawn wood
Sofas	Sawn wood; PB; upholstery fabric
Beds	Sawn wood; PB
Wardrobes	MDF; PB
Fences	Sawn wood

For furniture, the following materials will be included in this study:
- Wood: sawn wood
- Board: low, medium and high density fibre boards, particle board
- Upholstery fabric

As alternative feedstock, different fibre crops and residue streams other than wood can be used.

2.2 Amounts of material used in the biobased household

Large part of the potential volume demand for biobased building and household products relates to the number and type of houses that may be built in biobased (§2.2.1.1); and to the amounts of materials/products in tonnes and/or m^3 that will be applied in these types of houses (§2.2.1.2). These data have been combined and elaborated in estimated material volume demand for the construction of an 'average' house (§2.2.1.3). The amounts of materials used for household items which may be biobased like e.g. textile fabrics and furniture have been estimated in section 2.2.2.

Focus in this study is on lignocellulosic materials. Volume demand will be based on rough yet quantified expert calculations. Results can be easily scaled, e.g. when there is a wish to estimate volumes for a region or when update assumptions become available.

2.2.1 Amount of building materials

2.2.1.1 Number and type of houses that will be newly built

The Dutch government forecasted in 2021 that about 1 million houses would need to be constructed by 2036.[12] It is estimated that in 2023 about 60,000 houses have been built.[13] The numbers per type of houses are not exactly known. Nieuwbouw Nederland does present data per type for a large number of houses being constructed in the Netherlands,[14] however, houses in project comprising 2 or more different types of houses

[12] https://www.volkshuisvestingnederland.nl/onderwerpen/berekening-woningbouwopgave
[13] https://www.rtl.nl/rtl-nieuws/artikel/5337463/nieuwbouw-bouw-woning-huizen-bouw.
[14] https://www.nieuwbouw-nederland.nl/projecten/ (accessed 22 May 2023).

are double counted.[15] In order to calculate required volumes of building materials – these volumes differ per type of house – we assume that the distribution per type for newly built houses corresponds to the existing stock, see table below.

Table 4 Housing stock and number of houses being built in the Netherlands, per type of house.

Type of house	Housing stock (as per 1 January 2022) *[16]	Derived estimate number of newly built houses per annum
Total	8,045,580	60,000
Detached house	1,042,650	7,778
2/1 roof	704,055	5,252
Corner house	1,018,885	7,601
Terraced house	2,361,261	17,615
Apartment flat	2,915,893	21,754
Not known	2,836	

Number of 'unknown type' in existing stock proportionally distributed over type of houses.

2.2.1.2 Amounts of building materials/products applied in different types of biobased reference houses

In a previous study, volumes of biobased building products for different type of houses were estimated.[17] CLT is assumed to be the basis for high rise buildings of > 30 m, Glulam the basis for apartment flats < 30 m, and timber frame construction (TFC) for ground level houses. The total volumes (m^3/house) for sawn wood, CLT, Glulam, OSB, particle board and insulation material per type of house have been presented in table below.

Table 5 Estimated volumes (m^3/house) of biobased building materials in different types of houses.*,§

	Wood	OSB	Particle board	Insulation
Apartment flat > 30 m	50 CLT	0.5		20
Apartment flat < 30 m	12.5 Glulam + 2.5 Sawn	2	2	25
Ground-level houses	12.5 TFC sawn	2.5	2.5	60

* Strength classes structural materials: C18 minimum for sawn wood; C24 minimum for CLT and Glulam. OSB3. P5 for particle board.
§ Insulation: λ = 0.040 W/m.K.

Assuming densities of 460, 470, 470, 620, 650 and 55 kg/m^3 for sawn wood, CLT, Glulam, OSB, particle board and insulation material, respectively, the amounts in tonne/house have been presented in the table below.

Table 6 Estimated volumes (tonne/house) of biobased building materials in different types of houses.

	Wood	CLT	Glulam	OSB	Particle board	Insulation
Apartment flat > 30 m		23.50		0.31		1.10
Apartment flat < 30 m	1.15		5.88	1.24	1.30	1.38
Ground-level houses	5.75			1.55	1.63	3.30

The exterior cladding may be biocomposite of e.g. 4 mm thickness. Considering exterior façade surfaces of 40 and 100 m^2 for apartment flat and ground-level houses, respectively, this corresponds to 0.16 and 0.40 m^3 of

[15] F.i., for a project of 10 detached houses and 20 terraced houses, both the selection 'detached houses' as well as 'terraced houses' count 30 houses.
[16] https://www.cbs.nl/nl-nl/cijfers/detail/85035NED
[17] 'Biobased grondstoffen voor hoogbouw' (in Dutch), https://edepot.wur.nl/651629

biocomposite. At an assumed fibre content of 30 vol.% and 1,400 kg/m^3, this translates into a demand of biobased fibre of 67 and 168 kg for apartment flat and ground-level houses, respectively.

2.2.1.3 Amounts of building materials/products applied in an 'average' biobased reference house

For further (scenario) analysis, it is useful to reduce the number of data and establish values for material demand for an average house. Combining the data from sections 2.2.1.1 and 2.2.1.2, and assuming that the apartment flats are equally distributed over buildings < 30 m and buildings > 30 m, the material footprint for an average house is as indicated in table 7.

Table 7 Estimated volumes of biobased building materials in an 'average' biobased house.

	Sawn Wood	CLT	Glulam	OSB	Particle board	Insulation
Volume (m^3)	8.42	9.06	2.27	2.05	1.96	46.40
Mass (tonne)	3.87	4.26	1.07	1.27	1.27	2.55
Density (kg/m^3)	460	470	470	620	650	55

If the exterior cladding is made of 4 mm biocomposite containing 30 vol.% fibre as specified in section 2.2.1.2, the demand per average house is 0.13 tonne of fibre.

2.2.2 Amounts of household textile and furniture items which may be biobased

In the table below, the amounts of materials are estimated for a household acquiring biobased household items. These numbers have been estimated by combining publicly available data for consumption of textiles and furniture. In addition, material estimates have been made based on a very detailed inventory of furniture and textile items in a single household, which includes measurements of the furniture items. The assumptions and data have been included in Annex 1, since this includes a long list of items with different sets of underlying data. Table 8 summarises volumes of biobased feedstock required per household for textile fabrics, sawn wood and wood based panels.

Table 8 Volumes, expressed in kg or m^3, of biobased household items per household (which in the Netherlands has on average 2.1 persons per household).*

Items	Fabric (kg)	Sawn wood (m^3)	MDF/PB (m^3)	Hardboard (m^3)
Textiles				
Clothes	38.27			
Curtains	18.75			
Bed linen and towels	6.40			
Furniture				
Upholstery	8.26			
Construction in sofas		0.052		
Kitchen table		0.097		
Coffee table		0.058		
Kitchen chairs		0.050		
Kitchen cabinets			0.266	0.015
Cabinet/Bookcase			0.152	0.014
Wardrobes		0.035	0.348	0.030
Beds		0.177	0.086	
Flooring		0.052	0.621	
Fences		0.495		
TOTAL	71.68	1.014	1.566	0.060

* Strength classes: P1-P3 for particle board.

Assuming densities of 460, 650 and 900 kg/m^3 for sawn wood, PB/MDF and HDF, respectively, the required amounts of materials in wood-like based household items per household are 0.466, 1.018 and 0.054 tonne for the respective materials. For further calculations in this report, the following numbers will be used:

- For furniture, 1.014 m^3 of sawn wood, 1.566 m^3 of MDF/PB and 0.060 m^3 of hardboard.
- For textiles, 71.68 kg of textiles which are *present* in a household, which are sub-divided over the different categories as follows:
    - Clothing textiles: 38.27 kg
    - Home textiles: 33.4 kg (18.75 kg of curtains, 6.4 kg of bed linen and towels and 8.26 kg of upholstery).

Furniture overall has a longer lifetime than textiles and it has been assumed that furniture in a household is replaced after ten years. Since the number of textile applications and their lifespan varies significantly, a translation should be made to obtain an annual textile consumption figure. Another study by the EEA[18] estimated an annual clothing and home textiles of 15 kg per person. If we apply a lifespan of 10 years to curtains (18.75 kg), 3 years to clothing (38.27 kg) and 5 years to bed linen and towels (6.4 kg), we come to a similar number of approximately 15 kg of textile consumption per year per person.

[18] https://www.eea.europa.eu/en/topics/in-depth/textiles

3 Biomass sources for household materials

This chapter will explore the productivity, cultivation conditions and economic potential of various biomass sources which can provide the (ligno)cellulose to produce building materials, textiles and furniture. The chapter is divided in two main sources:

- Wood, which is produced through forestry. Wood can be used as a building material in different forms: directly (sawn wood); as sawn wood glued together into laminated products; as particles or fibres in boards and insulation material; after cellulose extraction in textile fabrics.
- Fibre crops which are grown in agriculture and which can also be used for the production of board, textile fabrics and insulation.

3.1 Wood

Trees can be grown for many different reasons and in many types of systems. Such systems range from production-oriented intensive plantations with short rotations via extensively managed multi-purpose forests with a range of species and a more diverse structure, to (near-)natural forests without any wood production. Trees have a maximum life span that ranges from 50-60 years for pioneers up to many centuries for climax species. To get wood of sufficient size, rotation lengths of 20-40 years for pioneers and 80-150 years for climax species are very common. Such long rotations cause a temporal mismatch between demand and supply. By the time the trees are ready for harvesting, demands may already have shifted. Forests present nowadays may have been planted for markets that have disappeared already (like dedicated oak forests for building warships). Current societal and industrial demands will need to be fulfilled by forests that are currently present but where likely planted and managed for different purposes. Similarly, forests that will be planted now may not be harvestable in time for their foreseen purpose, but may still yield a valuable crop for unforeseen purposes. In this chapter we therefore look at a selection of tree species that are currently available in the Dutch forests in reasonable quantities, as well as species that may have potential for the future given their wood properties. Data for the Netherlands are obtained from Schelhaas et al[19] and background information on the species is partly derived from Ayanz et al[20].

In an earlier analysis[21], it was found that wood production from the existing forest area in the Netherlands could be increased by 370.000 m^3 of wood in 2060 by adopting forest management practices which aim for more forest rejuvenation. Since this is not in line with current management practice and many of these forests are Natura 2000 areas, this potential additional harvest from existing forests will not be considered in this study. Also, the quality of this additional harvest from existing forest is uncertain as they have not always been set up as a production forest. The focus will therefore be on the potential for new productive forests which are set up to deliver high-quality wood for construction purposes.

3.1.1 Coniferous tree species

For coniferous species, the following species have been included in the analysis.

Abies grandis (Grand Fir)is an introduced species, originally growing at the West Coast of North America. Its presence is currently very limited in Netherlands and Flanders but available in some quantity in Germany. It

[19] Schelhaas, M. J., Teeuwen, S., Oldenburger, J., Beerkens, G., Velema, G., Kremers, J., Lerink, B., Paulo, M. J., Schoonderwoerd, H., Daamen, W., Dolstra, F., Lusink, M., van Tongeren, K., Scholten, T., Pruijsten, I., Voncken, F., & Clerkx, A. P. P. M. (2022). Zevende Nederlandse Bosinventarisatie: Methoden en resultaten. (WOt-rapport; No. 142). WOT Natuur & Milieu.

[20] European Commission: Joint Research Centre, San-Miguel-Ayanz, J., De Rigo, D., Caudullo, G., Houston Durrant, T. et al., European atlas of forest tree species, San-Miguel-Ayanz, J.(editor), De Rigo, D.(editor), Caudullo, G.(editor), Houston Durrant, T.(editor) and Mauri, A.(editor), Publications Office of the European Union, 2016

[21] van den Oever, M., Telleman, Y., van Kampen, A., van der Voort, M., van der Weide, R., van Baren, S., & Jacobs, S. (2024). Biobased grondstoffen voor hoogbouw : geïndustrialiseerde modulaire en lage emissie hoogbouw in de G4. (Rapport / Wageningen Food & Biobased Research; No. 2551). Wageningen Food & Biobased Research. https://doi.org/10.18174/651629

can show very high growth on suitable soils, when medium to rich soils are present. The wood is suitable for packaging, plywood and panel production.

Larix leptolesis (Japanese Larch) is a synonym for Larix kaempferi. For application purposes in the industry no differences exist between different Larix species. Larix is a pioneer species found at high altitudes in Central Europe, but it is also planted in Northwestern Europe and Scandinavia because of its fast growth and durable wood. However, it proves to be susceptible to a shortage of water, which may be a limiting factor for cultivation under future climate conditions. It is in high demand for the industry, and is currently already harvested intensively. No increase in the relative share of this species in the harvest total is to be expected. Larch wood is used intensively in construction as load-bearing elements but also as window frame, doors, facade panelling, stairs, etc. Also in the furniture industry it is used. Because of its versatility demand for larch is very high.

Picea abies (Norway Spruce) is a very common coniferous species, originally growing in the mountain ranges of Central and Eastern Europe and throughout Scandinavia, but planted far outside its natural range mainly in Northwestern Europe. It is highly productive and in great demand with the industry. It is sensitive to the European spruce bark beetle (Ips typographus) that can kill mature trees under certain conditions. In the past, such outbreaks tended to be local, connected to the availability of downed and weakened trees after storm events. Nowadays outbreaks occur at much larger scale, driven by unfavourable summer conditions. This will form a severe threat to the future of this species, first of all in the areas where it was planted outside its natural range. Salvage fellings in Czech Republic for example are estimated to be twice as high the last years compared to the usual annual harvest quantity. At short term this may lead to an increased supply in some countries, but at longer term its share in the total harvest may be reduced. Spruce ("Vuren" in Dutch) wood is used intensively in load -bearing constructions, laminated or not. Also other construction applications are possible such as window frames, doors, stairs, flooring, plywood, chipboard and other household applications such as wardrobes. Next to this also pallets (for transport) and other packaging applications are used as the wood does not emit smell odour. Lastly spruce is used for the production of cellulose and paper.

Figure 5 Norway Spruce (Picea Abies) and Scots Pine (Pinus Sylvestris).

Pinus nigra (Black Pine) is a pioneer species growing mainly in the Mediterranean Basin, but is planted widely elsewhere in Western and Central Europe. Its wood is valued by the industry. It is drought-resistant, which may make it a more attractive species in the future. Applications can be the same as other pine species and spruce.

Pinus sylvestris (Scots Pine) is the most common tree species found in Europe and grows nearly everywhere. The wood is valued by the industry for a variety of purposes, including construction. However, the intensity of management varies across Europe, with in some regions (like Western Europe) a tendency to being under-utilized. This is partly connected to the importance of other forest functions in these areas, but also by a lack of (perceived) quality compared to the high-quality timber produced in Northern Europe. Scots pine was the preferred species to reforest the vast areas of severely degraded soils in Netherlands and Northern Germany in the early 20th century. Current stocks are mostly a consequence of reforestations in this time period, with limited young stands being established during the last decades. Scots pine ("Grenen" in Dutch) usage ability depends on the quality of the wood. A wide variety of applications is possible ranging from indoor applications such as doors, door frames, but also flooring. In the boating industry it is used as masts or oars. Also paper production, wood wool and veneer are possible.

Pseudotsuga menziesii (Douglas Fir) was introduced from the West Coast of North America to (Western) Europe in the 19th century. It proved to be a very productive species producing high-quality timber, with high demand from the industry. In some countries it is seen as a possible substitute for the cultivation of Norway spruce, although regulations may sometimes limit the use of this species for tree planting. It may well increase its share in the future harvest. Douglas fir wood is used in a wide variety of applications such as load- bearing constructions, window frames, plywood, facade panelling, etc. Also, veneer is produced from Douglas fir. In the boating industry many applications are possible such as the mast, deck and oars.

Taxodium distichum was introduced from the southeastern part of North America. It can grow under very wet conditions and can stand waterlogging for extended periods. Although being a conifer, it is a deciduous species. In Europe it is only planted as an ornamental tree in parks and along roads. There is no experience growing this species in forest stands, and it is not known to the wood industry. Due to its ability to grow under wet conditions, it is included here as a potential future species for afforestation in wet areas such as peat areas in the west of the Netherlands.

In the table below, an overview is provided of key growth, cultivation and economic data per species based on the sources mentioned at the beginning of this chapter. Strength class data have been obtained from a publication by Centrum Hout and apply to wood from North and Central Europe[22].

[22] Info paper, strength data of sawn and laminated wood, houtinfo/centrum hout, 2017

Table 9 Key growth, cultivation and economic data for selected coniferous tree species.

Aspects	Unit	Grand fir	Japanese Larch	Norway Spruce	Black pine	Scots pine	Douglas fir
Acreage and volume							
Latin name		Abies grandis	Larix kaempfaeri	Picea abies	Pinus nigra	Pinus sylvestris	Pseudotsuga menziesii
Current acreage NL	ha	400	16.500	9.800	13.000	102.500	17.000
Annual additional growth	m^3/ha/year	10,3	7,7	11,2	8.8	5,8	10
Cultivation aspects							
Harvest age	Years	80	60-80	60-80	60-80	60-100	60-80
Soil type		Sand	Sand or loamy soil	Sand or peat soil	Sand	Poor, dry, wet, acidic	Sand, loamy or clay
Soil pH	pH	4,5-5	3,5-6	3,5-6,5	4-7	4-6,5	3,5-4,5
Drought tolerance		Intolerant	Moderately tolerant	Intolerant	Tolerant	Tolerant	Moderately tolerant
Wet tolerance		Intolerant	Intolerant	Very intolerant	Very intolerant	Moderately tolerant	Intolerant
Soil fertility		Average/high	Average/high	Average/high	Poor/average/high	Poor/average/high	Average/high
Economic aspects							
Name wood		Pine	Larch	Spruce	Pine	Pine	Fir
Strength class (wood from N or C-Europe)		C16-C18-C24-C30	C16-C18-C24-C30	C18-C24-C30	-	C16-C18-C24	C16-C18-C24
Type of applications		For constructive applications, packaging, chipboard and plywood industries.	Constructive applications Window frames, panelling stairs, floors etc	Constructive applications Window frames, panelling stairs, floors etc	For constructive applications, packaging, chipboard and plywood industries.	Indoor applications like window frames, panelling, stairs, floors etc	Constructive applications Window frames, panelling stairs, floors etc
Special properties		Pine does not contain resin and does not spread any odour.	Also applied in furniture because of visual appeal	Only applied in cheap furniture because of lower quality. Quality highly variable.		Outdoor use usually after wood preservation treatment	Resistant to acids (used as barrels for chemical industry

3.1.2 Deciduous tree species

The following deciduous trees have been selected.

Acer campestre (field maple) is a common tree in Northwestern Europe. It usually occurs in limited numbers as admixture in stands of other species and hardly forms mono-species stands. It grows well on rich soils. Wood is used in a great variety of applications ranging from furniture, veneer, sporting equipment to cooking utensils and other home decoration applications.

Alnus glutinosa (Black Alder) is a very common tree in Europe. It grows fast but has a limited lifespan. It needs an abundant supply of water and can often been found on riverbanks and in marshes. Wood is used for small household applications like brooms, brushes and toys, sometimes for furniture and plywood.

Betula pendula/pubescens (Birch) is a pioneer species especially present in Northern Europe. It is commonly found to invade areas of heathland but also regenerates well under Scots pine stands. In Northern Europe it is used for high quality purposes such as furniture and plywood, but in the Netherlands the quality is lower but used in the panel industry and small household products.

Fagus sylvatica (Beech) is a widely distributed species in Europe, growing in temperate and mountainous conditions and being absent in Mediterranean and boreal conditions. It is a shade-tolerant species, able to invade existing stands and dominate the forest in the longer term. In Central Europe it is often used as admixture in Norway spruce stands to increase the diversity and resilience of these stands. Also in other regions it increases its share, either by natural processes or actively to increase tree species diversity. It has a very diverse range of usages in the industry, but is also a preferred species for fuelwood. In many regions it is an underutilised species, with a clear potential for an increase in harvest level. In some areas the wood quality may be a limiting factor for usage. At the moment it is used for household applications like cutting boards, brushes, wardrobes, doors, toys and flooring.

***Populus* species** (poplar) grow quickly and produce valuable wood that can be used for many purposes. Through selection and tree breeding, fast growing hybrids and clones have been introduced that were used to establish plantations with rotations of 20-25 years, such as Populus x canadensis. Poplar cultivation in the Netherlands has come to an end with the increasing intensification of the farming system and the share of poplars is decreasing fast. Naturally occurring poplars are Populus alba, P. nigra and P. tremula and are rarely harvested. Populus nigra has a wide distribution range in Europe (except Scandinavia), but is only found sparsely. It is considered as a threatened species. Poplar wood is used a lot as veneer application for plywood. Next to this also chipboard and wood wool cements is made from poplar. Also other small household articles can be produced such as cutting boards, clogs and kitchen utensils. Cellulose form poplars is also used in the production of speciality paper such as photocopy paper.

Figure 6 Oak (Quercus robur) and poplar (populus).

Quercus robur (English oak) has been of great value in Europe, in terms of timber production, fruit production for cattle, firewood, and also culturally. They are widely distributed but do not grow in boreal and Mediterranean climate. In general their potential for wood production is underutilised, but an increase in harvesting is hampered by wood quality issues, especially in those areas formerly managed as coppice.

Quercus rubra (red oak) was also introduced from North America, originally as an ornamental tree but it proved to regenerate easily in the European forests. Many forest owners and managers regard it as an invasive species that should be combatted, but it requires major efforts to eradicate or even control the species. The wood is not used extensively but is suitable for flooring and furniture.

Salix alba (white willow) is a typical pioneer species of riverine environments. It is fast growing and sprouts easily after pruning. The species is common on riverbanks and floodplain areas and can grow well under dynamic conditions. The species is not in use for wood production in the Netherlands. Willow wood is the best for the production of clogs. Next to this, small applications as toys and as handles for working tools are possible.

Robinia pseudoacacia (Black Locust) is introduced from North America already in the 17th century. It is not very widespread, but is considered an invasive species. It is one of the few insect-pollinated tree species and provides nectar for many insect species. It has been planted at some scale during the 1990s to produce wood in relatively short rotations (30 year) but many of these were not very successful. Although the wood is hard and durable, it is rather difficult to process and suffers from a very crooked growth form.

In the table below, an overview is provided of key growth, cultivation and economic data per species based on the sources mentioned at the beginning of this chapter. Strength class data have been obtained from a publication by Centrum Hout and apply to wood from North and Central Europe[23].

[23] Info paper, strength data of sawn and laminated wood, houtinfo/centrum hout, 2017

Table 10 Key growth, cultivation and economic data for selected deciduous tree species.

Aspects	Unit	Field maple	Common alder	Birch	Beech	Canada Poplar	English oak	White willow	Black locust
Acreage/volume									
Latin name		Acer campestre	Alnus glutinosa	Betula pendula	Fagus sylvatica	Populus x canadiensis	Quercus robur	Salix Aaba	Robinia pseudoacacia
Current acreage NL	ha	1.100	9.400	2.300	14.700	8.700	65.500	6.500	1.000
Annual additional growth	m^3/ha/year	10,8	6,6	4,4	6,3	8,6	6,4	7	9,1
Cultivation aspects									
Harvest age	Years	60-80	50-60	40-50	80-100	20-45	80-120	20-40	60-80
Soil type		Sand, loamy soil, clay	Peat, mineral soil	(very)dry soils	Sand, Sandy soil, light clay	All soils, except poor dry sandy	All soil types	Clay, wet soils	Dry light soils
Soil pH	pH	Neutral-Alkaline	3,5-7	4-6,5		4,5-6,5	4-6	4,5-6,5	4-6,5
Drought tolerance		Moderate tolerance	Intolerant	Tolerant	Intolerant	Intolerant	Moderate tolerance	Intolerant	Tolerant
Wet tolerance		Intolerant	Tolerant	Tolerant	Very intolerant	Intolerant	Intolerant	Tolerant	Very intolerant
Soil fertility		Rich soils	Poor/average/rich	Poor/average	Average/rich	Rich soils	Poor/average/rich	Rich	Poor/average/rich
Application									
Name wood		Maple		Birch	Beech	Poplar	Oak		
Strength class		NA	NA		D35-D40	C22	D30	NA	NA
Type of applications		Furniture, panelling, veneer and plywood, household articles and utensils.	Wooden utensils, plywood, furniture.	Panelling, furniture, plywood, wooden utensils.	Panelling, furniture, plywood, wooden utensils	Peeled veneer for the manufacture of plywood, wooden utensils, board, chipboard, cellulose source for paper	Highly versatile and attractive wood with broad range of applications, including construction, industrial applications, panelling, board, utensils and many others	Wooden shoes, other wood utensils	Construction applications, panelling, board, utensils and many others
Special properties		Distinctive markings in veneer			Very good bending properties	Populus nigra variant wet tolerant, populus alba fast growing (11,1 m^3/y)			

3.1.3 Sustainability and eco-system services selected tree species

A qualitative assessment of sustainability impacts and eco-system services has been made to compare forests with agricultural (fibre) crops based on agriculture and forest expert discussions[24]. The results are described below.

In the Netherlands, no herbicides, insecticides or fungicides are applied in forests, while these are used in a range of the crops considered. Important aspects for biodiversity are the provisioning of shelter, food and space to breed. Forests are managed less intensively than crops and have rotation times of at least a decade and usually many decades. They thus provide shelter year-round, while many annual crops provide no shelter in wintertime and perennial crops only partly, depending on the harvest cycle. Both vegetation types have a very specific associated biodiversity, where crops may provide more food and breeding possibility for insects and birds of open landscapes and forests provide a habitat for forest species. Generally, forests are seen as better for biodiversity as they are less intensively managed, but at the same time a diversity of vegetation types in the landscape is important for many species.

Forests have a very specific microclimate due to the sometimes dense canopy cover and high evapotranspiration. During hot periods, forests are therefore much cooler than open landscapes. Perennial crops may provide intermediate cooling between forests and annual crops. Also, forests have higher capacity of filtering air pollution such as dust and nitro oxides, which is negligible for crops.

Due to the low management and harvest intensity, forests provide better soil protection services. Due to the continuous canopy cover, nutrients do not leach easily, while a litter layer can build up, storing large amounts of carbon. Coniferous trees generally provide foliage litter that is not easily degradable, while many broadleaves (but not all) have easily degradable leaves. The litter type has a large influence on the soil fauna. Soil fauna will be totally different under crops, due to the higher nutrient inputs and the sometimes frequent soil disturbance.

Generally, annual crops tend to have a higher potential precipitation surplus than forests, since no precipitation is intercepted (and directly evaporated) during the winter season. However, it depends on the crop type and soil management how easily the water is infiltrated and how much will run off. Overall, the infiltration capacity in the forest would be considered higher than in crops. How much water is intercepted by trees depends strongly on the canopy cover. Deciduous trees will intercept less, while shade-tolerant wintergreen conifers will have high interception rates. Effects on groundwater and surface water quality depends mostly on the use of herbicides in crops, and how much nutrients are leached.

Both crops and trees can be sensitive for very wet or very dry periods, but it depends strongly on the species. Crops can in principle be irrigated during dry periods while this is never done in forests. Some tree species are considered as unsuitable for future climate conditions, such as Picea abies that suffers heavily from dry summers and successive attacks of bark beetles.

Forests are very attractive for recreation, where especially a mixture of species at larger scales is seen as attractive, depending on the type of recreation activity. But also certain crop types can be attractive, and especially a mixture of forests and open spaces can make a very attractive landscape.

Based on the above, forests generally have less environmental impacts and more eco-system service than crops. For crops, it is much more important to look at the specific differences per crop. As such, a more detailed quantitative assessment of eco-system services and environmental impacts will be made in 3.2.6.

[24] Shared expert opinion Wageningen Plant Research (agriculture) and Wageningen Environmental Research (forestry).

3.1.4 Conclusions tree species

In this chapter, we presented both coniferous and deciduous tree species and assessed their current acreage, cultivation aspects and economic aspects in the Netherlands. Scots pine is by far the most common coniferous tree species in the Netherlands, whereas oak is the most common deciduous tree species.

Within the coniferous tree species which are most common in the Netherlands, there are several species which are used as a source of high-quality building material producing C18 strength timber or more. These species are Scots pine, Japanese Larch, Grand fir, Douglas fir and Norway Spruce. This strength class has been validated for wood from these species originating from managed plantations in Germany, CE-Europe or N-Europe. The exact quality of Dutch timber for these species is unclear, particularly because most of the Dutch forest is not managed as a production forest. From this, it is concluded that there is potential for setting up new production forests to produce qualities of timber which are ideally similar to CE- and N-European qualities. Most of these species are also applied in chipboard and plywood industries.

Deciduous tree species are mostly applied as indoor panelling material for the construction industry or in furniture or wooden utensils. Oak is also applied in timber frame construction. The potential for faster growing deciduous species (a.o. poplar, maple and alder) is actively investigated in the Netherlands by for example the Hoogwaardig Houtgebruik project[25].

The selection of coniferous and deciduous species can in principle grow on a wide variety of soils with varying degrees of soil fertility. Several of the selected species are to some extent drought tolerant, such as Scots pine, Black Pine, Birch and Black Locust. A significantly lower number of tree species can tolerate inundation, such as Scots pine, common alder, white willow and black poplar.

Trees generally deliver a wider range of eco-system services than (fibre) crops. This also applies to production forests, both in case of monocultures but particularly so when multiple species are applied alongside each other in polycultures.

3.2 Fibre crops and fibrous side-streams

To evaluate how the demand for bio-based materials can be met by biomass produced through agriculture systems, several potential crops were assessed. The chosen crops were suggested by the stakeholders and experts involved in the field.[17] Some of the crops included are already cultivated in the Netherlands. Available information for these crops has been included from well-known sources such as CBS (Central Statistical Office) and the KWIN-AGV (Quantitative Information Arable and Vegetable crops). For the crops that are not or barely grown in the Netherlands, information was taken from literature. An overview of literature sources consulted has been added in Annex 6.

For all crops, in addition to information on acreage and volume produced, data on cultivation and economic and sustainability aspects was collected (see tables in next sections).

The biobased crops have been grouped based on the type of crop. Flax, hemp and nettles were grouped and evaluated for their potential as bast-fibre crops (section 3.2.3). The fibres of these crops all have potential applications in textiles. Miscanthus, reed, cattail, switchgrass and willow are combined as perennial lignocellulosic crops for board and other type of materials (section 3.2.4). The next group is cup plant and sorghum, which have been studied mainly as animal feed or as an energy crop for co-digestion (section 3.2.5). Roadside grass, as a non-agricultural crop, was added to this group. A final group of annual lignocellulosic crops comprises cereals, which provide straw as a by-product which can serve as a feedstock for biobased building materials (sections 3.2.1 and 3.2.2).

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[25] https://hoogwaardighoutgebruik.nl/project

The acreage per crop is based on CBS data. Dry matter yield is based on literature sources. Combined, this gives a picture of the volumes of the biomass currently produced. The price is based on the KWIN-AGV and/or literature. For a number of fibre crops, it is difficult to set a price, as there is not yet a mature market for these crops. At the same time, the Netherlands is putting considerable effort into growing fibre crops, validating and scaling up applications for these fibres. The application that may be the first to become available is blow-in insulation. This involves only limited mechanical processing and drying to obtain blow-in insulation material. To account for the fact that this application is not mature yet, a price for biomass of €100 per tonne of dry matter has been used. This is comparable to the price of cereal straw and below the hemp price of around €150 per tonne. Due to plant cell structure and the quality of the fibre, fibre crops like flax, hemp and nettle will in principle be able to get a higher price for the biomass than other fibre crops. The price of €100 should be considered a minimum price before blow-in insulation is fully validated as an application, but could eventually rise (also in combination with policy instruments like carbon credits). The validations for blow-in insulation are well on the way during the preparation of this report.

The crops presented in the KWIN-AGV include: flax, hemp, grain maize, barley, wheat, oats, rye and triticale. The net revenue stated is indicative and fluctuates for many crops in practice. Cultivation aspects are based entirely on literature sources. Various practical aspects about the included crops are stated under the cultivation aspects. The type of crop (annual/perennial) determines, together with soil type, wet or drought tolerance, how well the crop fits within a certain agricultural area or farm management. The purpose of cultivation indicates whether a crop is grown only for fibre (single-purpose) or that the fibre is a by-product (multi-purpose) of a main product with another application. The harvest time and frequency indicates when the biomass becomes available. This is potentially relevant for logistics and organisation in the supply chain of biobased building materials.

The economic aspects were taken from the KWIN-AGV. For this, the gross margin of the relevant crop was taken directly from this source. This includes flax, hemp, grain maize, barley, wheat, oats, rye and triticale. A gross margin calculation includes the yields and costs directly related to the cultivation of the crop, without the farm-specific costs. A gross margin calculation therefore allows an economic comparison between crops. For crops that are not or hardly grown in the Netherlands, the KWIN-AGV methodology for gross margins and prices were used to determine a gross margin based on literature data. For those crops, the amount of fertilisation, starting material and the cultivation method were taken from literature sources. The prices of e.g. fertilisation, crop protection and diesel were taken from the KWIN-AGV. The gross margin for perennial crops is calculated as an average over a 10-year period. Additionally included to the economic aspects is whether or not the crop falls under the Eco-Scheme of RVO (Netherlands Enterprise Agency) and under which part of the scheme. The eco-scheme offers farmers compensation for sustainable cultivation practises based on the number of measures they implement on their farms. The scheme is part of the Common Agricultural Policy (CAP) of the EU. Per crop is included whether it is eligible for a certain part of the scheme or not.

The crops will be discussed as follows:

- Common arable crops with multiple processing of both grain/seed and fibre. These are barley, wheat, oats, rye, grain maize, rapeseed and triticale.
- Annual bast-fibre crops. These are flax, hemp and nettle.
- Perennial lignocellulosic crops. These are miscanthus, reed, cattail, willow, switchgrass, roadside grass and cup plant. Also sorghum for fibre production (annual, single digests) is included here, even if it may be a grain producing crop as well.

3.2.1 Cultivation and economic aspects of (straw of) barley, wheat, oats and rye

The table below shows the main cultivation aspects of barley, wheat, oats and rye. The straw from these cereal crops can serve as feedstock for biobased building materials. In relation to soil health and the limited financial yield of straw, there is an increasing tendency to leave the straw on the field during grain harvest and plough it into the soil.

Table 11 Cultivation and economic aspects of barley, wheat, oats and rye.

Aspects	Unit	Barley	Wheat	Oats	Rye
Acreage and volume					
Current acreage	ha (av. 2016-2020)	33,562	115,377	847	1,086
DM Yield of straw	kg ds/ha	3,080	4,050	2,700	2,250
Total straw biomass	ton dm/year	103,371	467,277	2,287	2,444
Price straw biomass	EUR/ton dm	100	100	100	110
Grain yield	kg/ha	7,500	8,500	5,600	3,600
Grain price	EUR/ton	173	177	161	120
Cultivation aspects					
Rotational aspect	Annual/perennial	Annual	Annual	Annual	Annual
Purpose	Single/multi	Multi	Multi	Multi	Multi
Soil type		clay, sand, loam	clay, sand	Clay, sand	sand, loam
Soil pH	pH				
Drought tolerance		Good	Good	Good	Limited
Wet tolerance		Limited	Limited	Limited	Limited
Sow/plant period	month	Sep/Oct	Oct	Mar/Apr	Mar/Apr
Harvest period	month	Jul/Aug	Jun/Jul	Jul/Aug	Jul/Aug
Harvest frequency	Number	1	1	1	1
Economic aspects					
Gross income	EUR/ha	1,602	1,907	1,173	679
Rootstock	EUR/ha	98	110	83	104
Fertilizer	EUR/ha	99	182	195	154
Crop protection	EUR/ha	135	154	133	345
Energy	EUR/ha	158	160	155	157
Other agro inputs	EUR/ha	0	0	0	0
Marketing costs	EUR/ha	0	0	0	0
Other crop related costs	EUR/ha	126	118	68	54
Variable costs	EUR/ha	615	738	672	814
Contracted work	EUR/ha	0	0	0	0
Gross margin	EUR/ha	986	1,170	501	-134
Labour requirement	hours/ha	9.4	9.7	9	9.7
Eco-scheme					
Perennial crop	To be applied for	No	No	No	No
Wet cultivation	To be applied for	No	No	No	No
Fibre crop	To be applied for	No	No	No	No
Break crop	To be applied for	Yes	Yes	Yes	Yes
Cover crop	To be applied for	No	No	No	Yes
Catch crop	To be applied for	No	No	No	Yes

The cultivation of barley and wheat has substantial acreage in the Netherlands. Grain is included in many arable rotations as a crop and generally has a gross margin of €500 to €1,000 per ha. As a result, the volume within the Netherlands is substantial. Although rye has a negative gross margin, sometimes arable farmers still choose to grow rye. This is because of its soil health benefits and high drought tolerance. Rye is more common on light and drought-sensitive soils or as an organic cultivation under part of agricultural nature management using traditional arable crops.

The currently produced straw already has a destination in animal husbandry or flower bulb cultivation, for example. The higher gross margin of wheat and barley make both cereals more interesting than oats and rye. For growers, there is a choice between winter and summer cultivation. Included are the environmental aspects for conventional cultivation. All cereals can also be grown organically. As with other straw crops, a choice will therefore depend on the main product, rather than on straw byproduct.

As a result of the Ukraine war, prices for wheat and barley cereals have risen to €220 and €200 per tonne. This increases the gross margin by about €200 per hectare. The gross margins were taken from the KWIN-AGV 2022, which is based on data till 2021.

Subsidies from the eco-scheme have not been included in the gross margin calculation, but are partly applicable (especially under the break crop category of the eco-scheme).

3.2.2 Cultivation and economics aspects of grain maize, rapeseed and triticale

The table below shows the relevant cultivation aspects of grain maize, rapeseed and triticale. Straw from different crops is a potential feedstock for biobased building materials. In contrast to other crops included, maize straw is normally not harvested.

Table 12 Cultivation and economics of straw of grain maize, rapeseed and triticale.

Aspects	Unit	Grain maize	Rapeseed	Triticale
Acreage and volume				
Current acreage	ha (av. 2016-2020)	10,490	1,812	767
DM Yield	kg ds/ha	6,500	2,700	2,610
Total biomass	ton dm/year	68,185	4,892	2,002
Price biomass	EUR/ton dm	100	120	100
Grain yield	kg/ha	10,600	3,750	5,400
Grain price	EUR/ton	124	329	162
Cultivation aspects				
Rotational aspect	Annual/perennial	Annual	Annual	Annual
Purpose	Single/multi	Multi	Multi	Multi
Soil type		All	All, clay	clay/sand
Soil pH	pH	7	n.b.	n.b.
Drought tolerance		Limited	Poor	Poor
Wet tolerance		Poor	Limited	Poor
Sow/plant period	month	April	Aug/Sep	Oct/Nov
Harvest period	month	Sep/Oct	Jun/Jul	Jun/Jul
Harvest frequency	Number	1	1	1
Economic aspects				
Gross income	EUR/ha	1,967	1,562	1,137
Rootstock	EUR/ha	198	96	104
Fertilizer	EUR/ha	264	148	161
Crop protection	EUR/ha	164	379	218
Energy	EUR/ha	136	105	154
Other agro inputs	EUR/ha	0	0	0
Marketing costs	EUR/ha	0	0	0
Other crop related costs	EUR/ha	32	46	38
Variable costs	EUR/ha	793	774	675
Contracted work	EUR/ha	735	340	0

Aspects	Unit	Grain maize	Rapeseed	Triticale
Gross margin	EUR/ha	439	448	462
Labour requirement	hours/ha	11.4	7.1	9.3
Eco-scheme;				
Perennial crop	To be applied for	No	No	No
Wet cultivation	To be applied for	No	No	No
Fibre crop	To be applied for	No	No	No
Break crops	To be applied for	No	Yes	Yes
Cover crop	To be applied for	No	No	No
Catch crop	To be applied for	No	No	No

All three crops fit within an arable rotation and have positive gross margins. The gross margin of all three crops are close to each other. However, the gross margins are lower as compared to wheat and barley. Since straw of grain maize is normally not harvested the data on maize straw comes from a research project[26]. The project researched the use of grain maize straw as an energy biomass source. The crops are close to each other in terms of gross margin. The choice may therefore depend largely on the main products, rather than on straw byproduct.

3.2.3 Cultivation and economics aspects of flax, hemp and common nettle

The table below shows the main cultivation aspects of flax, hemp and nettle. As mentioned, flax, hemp and nettles have similarities in the fibres produced. All fibres have the option of application for textiles. Of course, the number of application areas is wider as mentioned.

Table 13 Cultivation and economics of flax, hemp and common nettle.

Aspects	Unit	Flax	Hemp	Nettle
Acreage and volume				
Current acreage	ha (av. 2016-2020)	2,357	2,046	1
DM Yield	kg ds/ha	6,500	8,000	4,000
Total biomass	ton dm/year	18,856	16,368	4
Price biomass	EUR/ton dm	676	150	290
Cultivation aspects				
Rotational aspect	Annual/perennial	Annual	Annual	Perennial
Purpose	Single/multi	Multi	Multi	Single
Soil type		All, clay	All, loam	All, clay
Soil pH	pH	>4.5	6-7	5.5-7.5
Drought tolerance		Reasonable	Reasonable	Reasonable
Wet tolerance		Poor	Poor	Limited
Sow/plant period	month	Mar/Apr	Apr/Mei	Jul
Harvest period	month	Jun/Jul	Aug/Sep	Jul/Aug
Harvest frequency	Number	1	1	1
Economic aspects				
Gross income	EUR/ha	4,397	1,200	1,160
Rootstock	EUR/ha	247	154	425
Fertilizer	EUR/ha	117	149	133
Crop protection	EUR/ha	195	0	0

[26] van der Voort, M. P. J. (2012). Korrelmaisstro als biomassa, voor energie of grondstof. Praktijkonderzoek Plant & Omgeving. https://edepot.wur.nl/242120

Energy	EUR/ha	78	57	19
Other agro inputs	EUR/ha	0	0	0
Marketing costs	EUR/ha	0	0	0
Other crop related costs	EUR/ha	26	24	22
Variable costs	EUR/ha	664	385	599
Contracted work	EUR/ha	1,621	0*	450
Gross margin	EUR/ha	2,111	815	111
Labour requirement	hours/ha	5.9	5.9	2.1
Eco-scheme;				
Perennial crop	To be applied for	No	No	No
Wet cultivation	To be applied for	No	No	No
Fibre crop	To be applied for	Yes	Yes	No
Break crop	To be applied for	No	No	No
Cover crop	To be applied for	Yes	No	No
Catch crop	To be applied for	Yes	No	No

* For hemp, harvesting is carried out on contract but not invoiced. This is offset against the product price. As a result, it is not included in the gross margin as such.

Flax and hemp are both annual crops and therefore fit into an arable crop rotation. Common nettle is a perennial crop. The use of any of these fibre crops is related, among other things, to the suitability of the fibres for the intended application. With (almost) equal suitability for a given application, possibly one or more of the aspects below will lead to a choice for the most viable crop.

Based on current cultivation data, from the three bast fibre crops nettle is the least interesting crop for the farmer. The main reason is that the gross margin per hectare is close to zero. Another aspect is that nettles are hardly grown in the Netherlands. As a result, the crop is not included in the eco-scheme (part of the CAP). There is an option for application during the annual application round. This makes it possible to have a crop included in the eco-scheme.

Flax has a positive gross margin that is also higher than that of other crops which produce fibres (e.g. barley and wheat) with balances of up to €1,000 per ha. This high gross margin is linked to the market for long flax fibres towards textiles (about 95% of long flax fibres is used for linen), allowing a high fibre price to be obtained. For hemp, only part of the fibres have the right quality for textiles, a large part of the fibres are used for other applications including towards building materials (insulation, lime hemp, sheet material), automotive industry (composites), horticulture (growing substrate mats) or animal husbandry (bedding). However, there is an existing industry for hemp in which some kind of optimisation has already taken place of marketing different sub-parts of the plant in different markets.

If delivered to the factory gate, the price of hemp straw is around €270 per tonne (early 2024). Prices vary and in this case latest price indications are going up.

Subsidies from the eco-scheme are not yet included in the gross margins above, but are applicable (especially for flax as a fibre, cover and catch crop). Nettle is, as mentioned, not included in the eco-scheme yet.

3.2.4 Cultivation and economics aspects of Miscanthus, reed, cattail, switchgrass

Miscanthus, reed, cattail, willow, switchgrass are perennial lignocellulosic crops that are well adapted to wet growing conditions. The yield given in the table below under ‘acreage and volume’ refers to a fully productive crop. The gross margin refers to the average annual yield over 10 years production. This therefore includes a number of less productive first years after planting before the crop production really takes off.

Table 14 Cultivation and economics of miscanthus, reed, cattail, switchgrass.

Aspects	Unit	Miscanthus	Reed	Cattail	Willow	Switchgrass
Acreage and volume						
Current acreage	ha (av. 2016-2020)	258	6,000*	N.b.	50	N.b.
DM Yield	kg ds/ha	20,000	15,000	9,500	10,300*	14,000
Total biomass	ton dm/year	4,257	90,000	-	515	-
Price biomass	EUR/ton dm	100	100	100	100	100
Cultivation aspects						
Rotational aspect	Annual/perennial	Perennial	Perennial	Perennial	Perennial	Perennial
Purpose	Single/multi	Single	Single	Single	Single	Single
Soil type		All, Loam	All	sand/clay	All	sand/clay
Soil pH	pH	5.5-7.5	N.b.	N.b.	7-8	4.5-9
Drought tolerance		Good	Good	Good	Good	Reasonable
Wet tolerance		Poor	Good	Good	Good	Reasonable
Sow/plant period	Month	Mar/Apr	Sep/Nov	Mar/Apr	Feb/Mar	Jan/Mar
Harvest period	Month	Feb/Mar	Feb/Mar	Feb	Feb/Mar	Feb/Mar
Harvest frequency	Number	1	1	1	1	1
Economic aspects						
Gross income	EUR/ha	1,650	1,350	855	1,030	1,260
Rootstock	EUR/ha	180	250	250	270	261
Fertilizer	EUR/ha	140	123	123	66	62
Crop protection	EUR/ha	3	0	0	0	14
Energy	EUR/ha	19	8	5	22	21
Other agro inputs	EUR/ha	0	0	0	0	0
Marketing costs	EUR/ha	0	0	0	0	0
Other crop related costs	EUR/ha	16	17	18	17	17
Variable costs	EUR/ha	358	398	395	373	374
Contracted work	EUR/ha	240	945	598	340	261
Gross margin	EUR/ha	1,052	6	-138	317	625
Labour requirement	hours/ha	1.7	50.3	50.3	2	2.1
Eco-scheme;						
Perennial crop	To be applied for	Yes	No	No	No	No
Wet cultivation	To be applied for	No	Yes	Yes	No	No
Fibre crop	To be applied for	Yes	No	No	No	No
Break crop	To be applied for	No	No	No	No	No
Cover crop	To be applied for	No	No	No	No	No
Catch crop	To be applied for	No	No	No	No	No

* The area of reed is based on reed harvest data from nature reserves.
* Yields are based on a fully productive crop, mostly after one, two or three years. For Miscanthus, reed, cattail and switchgrass, gross margin yields are therefore lower than the product of (maximum) DS yield and price of this biomass. For willow, this is an average per hectare per year. Harvesting is mostly done once every two or three years.

The acreage of reed is based on data on reed harvest from nature reserves. This is not agricultural acreage. All crops are perennial and thus may not fit as well into an arable rotations. Some of the crops have already been investigated as an option on peatlands in relation to a ground water level rise. In particular, reed and cattail are suitable as crops for cultivation under wet conditions. Willow can also cope well with prolonged periods of wet conditions. This makes these three crops interesting in areas where water drainage in the soil is a challenge in the Netherlands.

The economic assumptions are based on literature. For reed and cattail, harvesting under wet conditions is done with specialised mechanisation. This makes the cost of contracted work high. In addition, for reed and cattail the planting material is expensive and planting has to be done manually. Another aspect for reed and cattail is that both crops are currently not cultivated as agricultural crops.

Miscanthus in particular is economically interesting from a cultivation perspective. The gross margin is at a similar level as of the cereal crops, such as barley and wheat. It should be noted, however, that Miscanthus is a perennial crop. Therefore Miscanthus cannot be combined in a rotation with high-yielding arable crops, such as sugar beet or potato, and which is possible with barley and wheat. Sugar beet and potatoes have gross margins between €3,000 and €4,000 per hectare. Any subsidies from the eco-scheme for miscanthus (fibre crop and perennial crop) have not been included in the gross margin.

The current practise is that harvesting for Miscanthus is done with maize chopper. This makes the availability of mechanisation for the harvest high. Whereby the harvest period also does not coincide with the maize harvest.

Willow and switchgrass both have a lower gross margin. They have a similar cost structure (more expensive starting material, less fertilisation) as Miscanthus, but a lower biomass dry matter yield per hectare.

Crop protection is included for miscanthus and switchgrass. Especially at the start of the crop, weed control is needed. Literature shows that mechanical weed control could be an option. Organic cultivation is thus possible for miscanthus and switchgrass

3.2.5 Cultivation and economics aspects of road side grass, cup plant and sorghum

Cup plant (Silphium perfoliatum L.) and sorghum (sorghum spp.) have been combined, because both are researched in different literature sources as crops for co-fermentation or animal feed. Both crops were included based on literature and partly foreign research. Both crops are currently not or barely cultivated in the Netherlands. In addition, roadside grass is included in this group as a non-agricultural crop. Roadside grass is often composted or used as a co-product for fermentation.

Table 15 Cultivation and economics of roadside grass, cup plant and sorghum.

Aspects	Unit	Cup plant	Sorghum*	Verge Grass**
Acreage and volume				
Current acreage	ha (av. 2016-2020)	1	0	42,373****
DM Yield	kg ds/ha	15,000***	7,000	3,500
Total biomass	ton dm/year	15	-	148.304
Price biomass	EUR/ton dm	100	100	-30/-50
Cultivation aspects				
Rotational aspect	Annual/perennial	Perennial	Annual	Perennial
Purpose	Single/multi	Single	Single	Single
Soil type		All	All	All
Soil pH	pH	5.6-5.7	6-8.5	6 – 7
Drought tolerance		Limited	Good	Reasonable
Wet tolerance		n.b.	Poor	Good
Sow/plant period	month	Apr/Jul	May	Mar/Sep
Harvest period	month	Feb/Mar	Aug	May/ Sep
Harvest frequency	Number	1	1	2
Economic aspects				
Gross income	EUR/ha	1,500	700	N/a
Rootstock	EUR/ha	155	14	N/a
Fertilizer	EUR/ha	328	74	N/a

Aspects	Unit	Cup plant	Sorghum*	Verge Grass**
Crop protection	EUR/ha	4	0	N/a
Energy	EUR/ha	103	107	N/a
Other agro inputs	EUR/ha	0	0	N/a
Marketing costs	EUR/ha	0	0	N/a
Other crop related costs	EUR/ha	20	11	N/a
Variable costs	EUR/ha	611	206	N/a
Contracted work	EUR/ha	281	405	N/a
Gross margin	EUR/ha	608	89	N/a
Labour requirement	hours/ha	5.3	8.4	N/a
Eco-scheme;				
Perennial crop	To be applied for	Yes	No	N/a
Wet cultivation	To be applied for	No	No	N/a
Fibre crop	To be applied for	No	No	N/a
Break crop	To be applied for	No	No	N/a
Cover crop	To be applied for	No	Yes	N/a
Catch crop	To be applied for	No	Yes	N/a

* Biomass Sorghum has been assumed for sorghum, where the plume of grain is not or of minor importance. It has therefore been categorised as a single purpose crop. Next to 'biomass Sorghum', 'grain Sorghum' delivers a significant amount of grains, and still a reasonable amount of lignocellulose biomass.
** Verge grass is not an agricultural crop and can therefore not be evaluated as such. The economic aspects are therefore not included.
*** Yield Cup plant based on full plant silage
**** Area based on total amount of roads and estimated average verge width

The acreage of these crops has been almost zero in recent years, ranging between 1 and 2 hectares for cup plant and 0 to 4 hectares for sorghum. Sorghum is an annual crop, which makes it a better fit for an arable rotation. The downside of biomass sorghum is that it has a low gross margin; grain Sorghum would be a much more feasible option, however, limited data is available to fully evaluate this option.

Cup plant is a perennial crop, making it a less obvious choice for arable farming. The gross margin for cup plant is lower than a similar perennial crop such as Miscanthus, but it still could be attractive to some farmers. Although, from German cultivation experience and gross margin data it becomes clear that cup plant has comparatively more expensive rootstock material[27]. At the same time, cup plant contains relatively high protein content, making it less suitable for direct use in construction. The high protein content could potentially attract pests. Alternatively, the protein may be extracted prior to application as a construction material, but this would require the development of a new biorefinery process.

Roadside grass has no competition with agricultural crops and in fact has a negative price of up to €50, because in absence of clear applications it is composted. This possibly means that roadside grass offers potential for biobased building materials. If a fibre revenue of €100 per tonne can be realised (see introduction section 3.2), the total revenue sums up to €150 per tonne. However, the pressing step required to produce good fibre from grass still has bottlenecks including the treatment of waste water generated during processing and the costs involved. So it is currently uncertain when the process will be scaled up.

3.2.6 Sustainability aspects and eco-system services of crops

Part of the consideration of whether or not to scale up certain fibre crops also depends on the sustainability aspects of cultivation. In this section, we will systematically assess the sustainability aspects and eco-system services of different fibre crops.

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[27] Landesanstalt fur Landwirtschaft (LfL Bayern),Deckungsbeiträge und Kalkulationsdaten - Durchwachsene Silphie (https://www.stmelf.bayern.de/idb/durchwachsenesilphie.html)

3.2.6.1 Eco-system services of crops

As a first step, the primary ecosystem services of crops that can be used for biobased materials were selected. For this, the overview of ecosystem services evaluated for Dutch ecosystems provided by de Knegt et al.[28] was used as a starting point. In this section, we focus on the plant level, specifically evaluating their potential to provide ecosystem services.

De Knegt et al. distinguished three categories of ecosystem services: "production services", "regulating services", and "cultural services." For this study, production services were excluded, as the crops selected for evaluation were already chosen based on their production value for biobased building materials. Additionally, the cultural services were grouped under the broader category of "recreational value", as it is not feasible to attribute other cultural values, such as "symbolic value" and "cultural heritage" to individual plant species. Finally, the regulating services were categorized into specific functions and services of the plant species. Our focus was on the species' impact on ecosystem functioning and their contribution to biodiversity. Also, the crops' tolerance to more extreme weather conditions (both dry and wet) were included, as climate change is increasingly altering growing conditions. This has resulted in the eco-system service indicators which are jointly presented in figure 7. Below, each indicator and the approach to measure it will be discussed.

The following key indicators for which quantitative data have been found (e.g. through KWIN-AGV/Bio-Grace or CLM Environmental Yardstick for Pesticides) are separately presented in Annex 2: Nitrogen efficiency, Nitrogen (removal), Nitrogen (supply), Energy input, GHG-emission, Crop protection, MBP-water life, MBP-soil life, MBP-ground water, Soil org. Matter. Additional literature sources which have been consulted are added in Annex 6.

Need for pesticides and their impact on water and soil life

A key negative environmental impact that agricultural crops can have on ground and surface water and soil life, is caused by the use of pesticides (herbicides, fungicide, insecticide). To assess this impact, the 'CLM Environmental Yardstick for Pesticides' methodology is used. This methodology involves a scoring system that indicates how harmful a pesticide is to the environment. Included in this study are risks to aquatic life (surface water), risks to soil life and risks of leaching to groundwater. Based on CLM's methodology, the quantity of the pesticide is combined with the environmental burden in points (MBP) per 1 kilogram or litre of the pesticide. This gives a score for the respective pesticides used for each crop. CLM uses a score between 0 and 100 as acceptable (green), a score between 100 and 1,000 as moderate and a score higher than 1,000 as bad.[29] See Annex 2 for specific scores per crop.

Biodiversity

The value for biodiversity was determined taking into account the value of the crop for: shelter, food habitat and breeding habitat for animal and bird species. The value was considered to be slightly positive if the crop provided one of these values and positive if it provided two or more of these values. In addition, an assessment was made for which animal and bird species actually benefit from the crop. The impact on this aspect was studied by means of literature review. Further qualitative information about biodiversity impacts and sources consulted can be found in annex 7.

Cooling

This eco-system service encompasses the shade provided by the crops, the evaporative cooling, and the moderated surface temperatures offered by green crop area. The impact on this aspect was studied by means of literature review and expert discussion. All crops were awarded a slightly positive score (light green) and to willow (tree) a positive score (dark green). The argumentation has been provided under 3.1.3 that trees generally make a higher contribution to cooling than crops.

Soil

The impact on soil was sub-divided into the following indicators:

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[28] de Knegt, B., Lof, M. E., Le Clec'h, S., & Alkemade, R. (2025). Growing mismatches of supply and demand of ecosystem services in the Netherlands. Journal of Environmental Management, 373, Article 123442. https://doi.org/10.1016/j.jenvman.2024.123442

[29] https://www.milieumeetlat.nl/nl/bereken-open-teelt.html

- Contribution to soil organic matter by the crops. This was assessed by literature review. Justification of the scores is provided in Annex 7.
- Impact on nutrients in the soil. Input and output have been determined for each crop based on the KWIN-AGV or literature. Crop inputs from the gross margin were calculated based on Mortimer[30], Gaillard[31] and BioGrace Values. See Annex 2 for the exact scores per crop.
- Impact on soil life. This scoring has been done based on the MBP values per crop provided in Annex 2.
- Other impacts on soil, like phytoremediation by the crop or impact on soil structure, which was assessed by literature review. More information is provided in Annex 7.

Water

The impact on water was sub-divided into the following indicators:

- Water infiltration. This was assessed by literature review, results are provide in Annex 7.
- Flood prevention. This was assessed by literature review, results are provided in Annex 7.
- Effect on ground water quality. Here, the CLM Environmental Yardstick for Pesticides scoring system was used as an indicator for this aspect. Scores can be found in Annex 2.
- Effect on surface water quality. Here, the CLM Environmental Yardstick for Pesticides scoring system was used as an indicator for this aspect. Scores can be found in Annex 2.

Climate change

Resilience to climate change was measured with two indicators (assessed by literature review):

- Resilience to dry periods. See tables in 3.2.1 till 3.2.5.
- Resilience to wet periods. See tables in 3.2.1 till 3.2.5.

In addition to the databases consulted and literature which was reviewed, several ecological experts have been consulted about specific aspects of the above described ecosystem services. For the eco-system services which have been assessed by literature review, a total of 79 sources were consulted and a comprehensive list of these sources is provided in Anne 6. The results and argumentation for eco-system services assessed by literature review have been provided in Annex 7.

3.2.6.2 Eco-system services table

In figure 7, the results for the eco-system service assessment per crop are presented. A scoring was assigned to the eco-system service per crop based on literature review (annex 7), quantitative data available (annex 2) and complemented by expert opinion. By looking at how the various crops performed compared to each other, colours were assigned in the eco-system services table (figure 7). Explanation of the colours in the table:

- Red: negative impact
- Orange: slightly negative impact
- Yellow: neutral impact
- Light green: slightly positive impact
- Dark green: positive impact
- Grey: no information found

The data obtained for the indicators described above refer to the entire cultivation of the crop and no breakdown has been made by main product and by-product, e.g. grain and straw in the case of cereals. The data are also based on the average cultivation method. In practice, there are differences between farmers in cultivation methods and thus in agronomic practices, in fertiliser application or crop inputs. For example in an organic cultivation system the use of chemical crop protection products is completely eliminated. Consequently, the sustainability aspects included present an average performance, whereas in practice the variation within a crop may be significant.

[30] Gaillard, Gerard, Crettaz, Pierre, Hausheer, Judith, 1997. Umweltinventar der landwirtschaftlichen Inputs im Pflanzenbau : Daten fuer die Erstellung von Energie- und Oekobilanzen in der Landwirtschaft, Institut d'Aménagements des Terres et des Eaux (TATE), Ecole Polytechnique Fédérale de Lausanne (EPFL), CH1015 Lausanne

[31] Mortimer, N.D., Elsayed, M.A., Horne, R.E., 2004, Energy and Greenhous gas emissions for bioethanol production from wheat grain and sugar beet, Sheffield Hallam University, Report no. 23/1, January 2004

It is important to recognize that selecting suitable crops for a particular region requires a more thorough and extensive analysis than what this table provides. Such analysis should consider how crops integrate into the landscape, their suitability within the processing chain for producing biobased products, and, crucially, their fit within the agricultural planning of a farmer (such as crop rotation). While this table can provide insights into the overall characteristics of a crop and aid in making an initial selection of crops that might be of interest for further investigation in a specific region or processing chain, it is not a substitute for a comprehensive evaluation.

Theme	Eco-system service	Flax	Hemp	Miscanthus	Reed	Cattail	Energy willow	zonnekroon / sylpl	Nettle	Roadside grass	Straw (oil seed rap	Straw (barley)	Straw (tarwe) / str	Straw (winter oats	Straw (rye)	Straw (triticale)	Straw (maize)	Sorghum
	Need for crop protection (herbicide, fungicide, insecticide)	Orange	Dark green	Yellow	Dark green	Dark green	Dark green	Yellow	Dark green	Dark green r	Red	Red	Red	Red	Red	Red	Red	Dark green
Biodiversity	Value for species (presence of shelter, food, nesting habitat)	Dark green	Dark green	Yellow	Yellow	Dark green	Dark green	Dark green	Dark green	Light green	Dark green	Grey	Grey	Grey	Grey	Grey	Yellow	Grey
	General Value	Dark green	Dark green	Yellow	Light green	Dark green	Dark green	Dark green	Dark green	Light green	Dark green	Grey	Grey	Grey	Grey	Grey	Yellow	Grey
Cooling	Shade and evaporative cooling	Light green	Light green	Light green	Light green	Light green	Dark green	Light green	Light green	Light green	Light green	Light green	Light green	Light green	Light green	Light green	Light green	Light green
Soil	Effect on organic soil matter	Light green	Light green	Dark green	Light green	Grey	Grey	Grey	Grey	Grey	Light green	Light green	Dark green	Dark green	Dark green	Dark green	Light green	Grey
	Effect on nutrients	Dark green	Light green	Dark green	Light green	Dark green	Dark green	Dark green	Grey	Light green	Dark green	Grey	Dark green	Grey	Dark green	Light green	Red	Light green
	Effect on soil life	Orange	Dark green	Yellow	Dark green	Dark green	Dark green	Yellow	Dark green	Light green	Orange	Orange	Orange	Orange	Orange	Orange	Orange	Grey
	Other	Light green	Light green	Dark green	Grey	Dark green	Dark green	Dark green	Grey	Grey	Grey	Light green	Grey	Light green	Light green	Grey	Red	Light green
Water	Contribution to water infiltration	Dark green	Dark green	Dark green	Dark green	Light green	Dark green	Dark green	Dark green	Dark green	Dark green	Dark green	Dark green	Dark green	Dark green	Dark green	Red	Dark green
	Contribution to flood prevention	Dark green	Dark green	Light green	Light green	Dark green	Dark green	Dark green	Grey	Grey	Dark green	Orange	Grey	Dark green	Dark green	Dark green	Red	Dark green
	Effect on ground water quality	Orange	Dark green	Dark green	Dark green	Dark green	Dark green	Yellow	Dark green	Dark green	Red	Orange	Orange	Red	Red	Red	Orange	Orange
	Effect on surface water quality	Orange	Dark green	Dark green	Dark green	Dark green	Dark green	Yellow	Dark green	Dark green	Orange	Orange	Orange	Orange	Orange	Orange	Orange	Orange
Climate change	Tolerant for drought periods	Light green	Light green	Light green	Light green	Light green	Light green	Orange	Light green	Light green	Red	Dark green	Dark green	Dark green	Dark green	Red	Orange	Dark green
	Tolerant for wet periods	Red	Red	Red	Dark green	Dark green	Dark green	Dark green	Orange	Dark green	Orange	Orange	Orange	Orange	Orange	Red	Red	Red

Figure 7 ***Eco-system services table for relevant fibre crops. Red-negative impact; Orange - slightly negative impact; Yellow - neutral impact; Light green - slightly positive impact; Dark green - positive impact; Grey - no information found.***

3.2.6.3 Analysis emissions and eco-system services for fibre crops

Looking at the overall picture of all the crops assessed, the following pattern emerges regarding emissions and eco-system services:

Annual food/feed crops (Barley, Wheat, Oats and Rye, Grain maize, Rapeseed and Triticale) which deliver a fibrous side-stream (straw) are relatively sensitive to pests and diseases and require weed and disease control. This results in significant MBP values (>100) for soil, water life and ground water. Nitrogen inputs for food/feed crops (120 - 185 kg N/ha) are relatively high compared to dedicated single purpose fibre crops, which indirectly increases nitrogen emissions, particularly if crops have a low nitrogen efficiency and effectively use a low share of this nitrogen. Their annual nature requires annual soil tillage, but compared to other food crops (sugar beets, potatoes) they are generally considered to have a beneficial effect on soil quality because of their root structure and humus producing residues. Maize is an exception and overall has a negative impact on soil and water quality (particularly: water retention capacity). Generally, these crops are sensitive to wet periods and therefore have limited capacity to adapt to climate change. No significant contributions to biodiversity have been found, except for rapeseed which' flowers attract bees and butterflies.

Annual (bast) fibre crops (flax, hemp and nettle) show a mixed picture for soil, water and ground life. For flax, the use of plant protection products is common and results in significant MBP values (>100) for soil, water life and ground water. The lower performance for aquatic life is caused by insecticide use. For soil life, this concerns insecticides and fungicides. Hemp and Common nettle are less susceptible to diseases and pests, so no crop protection is needed. Nitrogen inputs are low compared to food/feed crops (15 - 80 kg N/ha). Their annual nature requires annual soil tillage, but compared to food crops (cereals, sugar beet, potatoes) they are generally considered to have a beneficial effect on soil quality (particularly for hemp, to a lesser extent for flax). All three crops are relatively tolerant to dry periods, but sensitive to wet periods. Concerning biodiversity, they provide shelter to field birds and pollinator insects (hemp, flax) and nettle is a food plant for various butterflies and seed-eating birds.

Perennial fibre crops (Grass, Cup plant, Miscanthus, Reed, Cattail, and willow) require very little pesticides (Miscanthus and cup plant only chemical weed control in first year) or no pesticides at all, which makes their impact on MBP soil, water life and ground water life over their entire growth period (typically at least 10 years) very low. For several species nitrogen inputs vary a lot: low for Miscanthus (25 kg N/ha); average for switchgrass and willow (70-80 kg N/ha); high for cup plant, reed and cattail (>120 kg N/ha, but usually grow under natural circumstances and not as actively managed agricultural crops). All perennial fibre crops generally have a positive impact on soil quality (structure, nutrient capture, organic matter). They also have positive impact on biodiversity as a shelter crop for small gain (Miscanthus) and for a variety of (pollinator) insects, birds or even amphibians (cattail).

3.2.7 Conclusions fibre crops

The sections above have evaluated a broad range of fibre crops and fibrous side-streams on several aspects which define their potential as a crop for textile, furniture and building applications.

First, the economic potential of each crop has been evaluated based on their ability to competitively provide fibres for the production of insulation, boards and textile yarns. In arable rotations, competition between crops plays a role as well. Break crops are an essential part of this rotation and this role can be played both by food crops and biobased crops. The gross margin of the crop (price/yield and cultivation costs) plays an important role in the design of the rotation and an optimum balance between cash crops (sugar beet, potato, onion) and break crops (cereals, hemp) needs to be found. An arable rotation always includes grain crops for soil health aspects. In principle, many of the annual biobased crops included can replace grain crops for this purpose and flax and hemp are probably the first candidates because of their positive net revenue. The choice of the crop often does not depend on the farmer revenue alone, but also depends on the other crops in the rotation, soil health (including nematodes and soil diseases), root formation in the soil by certain crops in the rotation, fertilisation, soil type and harvest security. Perennial crops cannot be applied in a rotation, because then the area will be occupied by one crop for a longer time, up to 10 – 20 years, and rotation with typical cash crops is not possible. Consequently, the choice for biobased perennial crops has an impact on the revenue since high-margin crops such as potatoes and sugar beet cannot be cultivated during that period of time. For a slightly longer dormant period, say 5 years, crops like alfalfa and grass seed are a financially more logical choice for an arable farmer compared to perennial biobased crops.

Some fibre crops already have an established position as a fibre crop, like hemp (mainly applied as insulation material, in composites and as animal bedding) and flax (mainly applied as textile fibre and insulation material). These annual fibre crops also fulfil the function of break crop in crop rotation, similar to grain crops. Unsurprisingly, hemp and flax have a positive gross margin per hectare, which is equivalent to (hemp) or significantly exceeds (flax) the margin of grain crops. The high margin for flax is mainly due to the application of the long fibres in textiles (linen). This may also be possible for hemp, even though the cultivation of hemp for textiles requires other hemp varieties which are tailored for the production of fine long fibres needed for textiles. Nettle also produces fibres which are suitable for textile production, but the economic evaluation of nettle shows that competitive cultivation of nettle is challenging. Of the fibre crops suitable for textiles, hemp seems to be the most sustainable option. Hemp is less susceptible to diseases and pests, so no crop protection is needed for cultivation.

Other fibre crops (such as Miscanthus/cattail/cupplant/reed/willow/sorghum) do not contain long fibres suitable for textile production. These crops are a potential source of particles for board production, short fibres for insulation production and cellulose for regenerated textile fibre (viscose/lyocell) production and a lower price of €100 per ton has been assumed for the biomass. Only Miscanthus and to a lesser extent cup plant showed a clearly positive margin comparable to (miscanthus) or slightly lower (cup plant) than grain crops. Due to their perennial nature, the application potential is mainly in marginal lands or in the replacement of grass lands.

Emissions and eco-system services (biodiversity; soil, water and air quality; adaptability to climate change; recreation) may increasingly become a factor in the viability of a crop, besides its purely economic gross margin. Overall, the following pattern emerges when considering emissions and eco-system services for the crops assessed in this study:

- Annual food/feed (cereal) crops show the highest emissions to soil, water life and ground water because of crop protection agents. They are followed by several annual fibre crops (hemp, nettle), which have a lower emission profile because of no need for crop protection agents. Flax is also an annual fibre crop but shows higher emissions to water because of insecticide and fungicide use. It must be noted however that all mentioned crops can also be produced organically. In organic cultivation, there is, partly depending on the disease and pest pressure, a chance of lower yields.
- The perennial fibre crops show the lowest emissions because of low plant protection requirement (or only in first year of at least 10 years of productive cultivation) and low nitrogen need. Some more nitrogen requiring perennial fibre crops (reed, cattail) usually grow under natural conditions and are not actively managed as agricultural crops.
- Greenhouse gas emissions from the cultivation of fibre crops are lower than for food and feed crops, 350 – 800 versus 1,300 – 1,660 kg CO_2 eq./ha. Within the cultivation of fibre crops, the greenhouse gas emissions for perennial crops are lower than the annual crops.
- Nitrogen emissions to the air are roughly proportional to the application of animal manure on the land, and depend on the application method. Nitrogen emissions are therefore proportional to the average required requirement (supply) of animal manure. Annual and perennial fibre crops generally have a lower nitrogen requirement (<100 kg N/ha) than food/feed crops (120 – 185 kg N/ha).
- Over the broader spectrum of eco-system services, the contribution of cereal crops to soil (structure, organic matter and water retention) and water quality is lower than that of annual and perennial fibre crops. In addition, annual and perennial fibre crops usually have a higher contribution to biodiversity, mainly: shelter for various animals or sometimes pollinators.

4 From biomass to product

In this chapter, the different conversion routes which are available to make building materials and household products out of biomass will be described and quantified. The chapter is divided along three axes:

1. Production of lumber for building products and furniture. Wood is the only source for lumber for buildings and furniture. By using wood for the production of lumber, the functionality of the biomass is optimally used, while at the same time residues becoming available can be used as a feedstock for other materials such as particle board.
2. Production of fibres for textiles and insulation products from bast fibre crops. Bast fibre crops - mainly hemp and flax – contain fine long fibres which is suitable for textile production. This is a unique property of bast fibre crops, which makes them an attractive biomass source for textiles, optimally using the functionality of the biomass. At the same time, processing facilities for hemp geared towards building products are available.
3. Production of particle board, insulation and dissolving cellulose pulp from (ligno)cellulosic biomass. These products can in principle be produced from a broad range of (ligno)cellulosic biomass through generic production processes.

4.1 Production of wood-based products

Wood is used for many different products, ranging from old-fashioned fuelwood and paper to modern engineered wood products in the building sector like cross-laminated timber (CLT). During processing, significant amounts of side-products become available. These can serve as inputs for other products like particle board, insulation mats or textiles, or can be used to generate heat and/or electricity, either for use in the production process itself or to be sold externally.

The wood sourced from different species varies greatly in properties, making certain species better suited for specific purposes than others. In addition, the actual quality of the stems varies greatly, depending on the growth and management history of the tree. Common quality indicators are the evenness of the size of the tree ring widths, presence of knots and defects, discolorations, and diameter, curvature and taper of the stem. Each of these, single or in combination, may qualify or disqualify the stem for specific purposes. However, modern technologies are able to overcome part of such defects, such as the possibility to cut out large knots and glue the different parts back together. As a consequence, sawmills may greatly differ in conversion efficiencies, depending on feedstock, type of products and equipment present.

Figure 8 gives an overview of ways of processing stems into wood products.

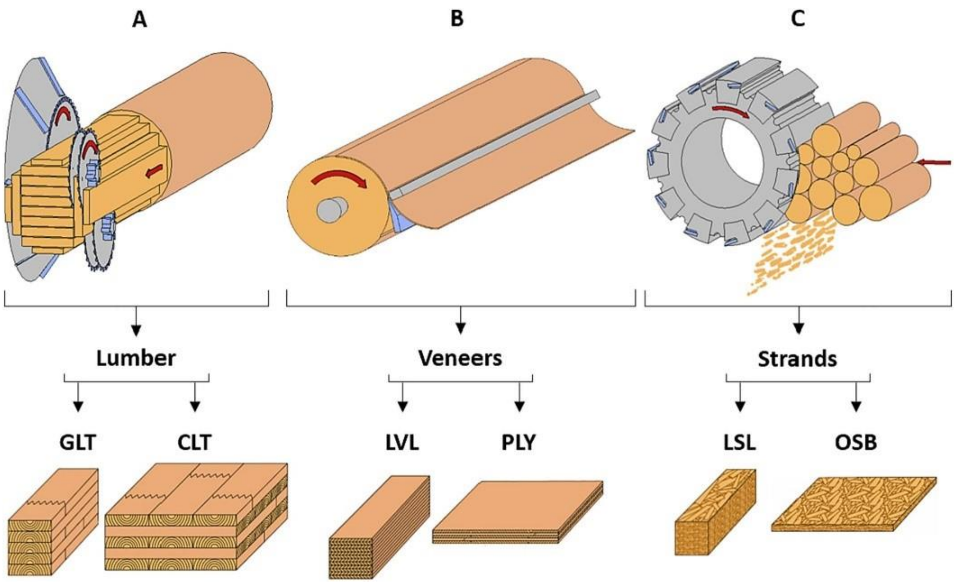
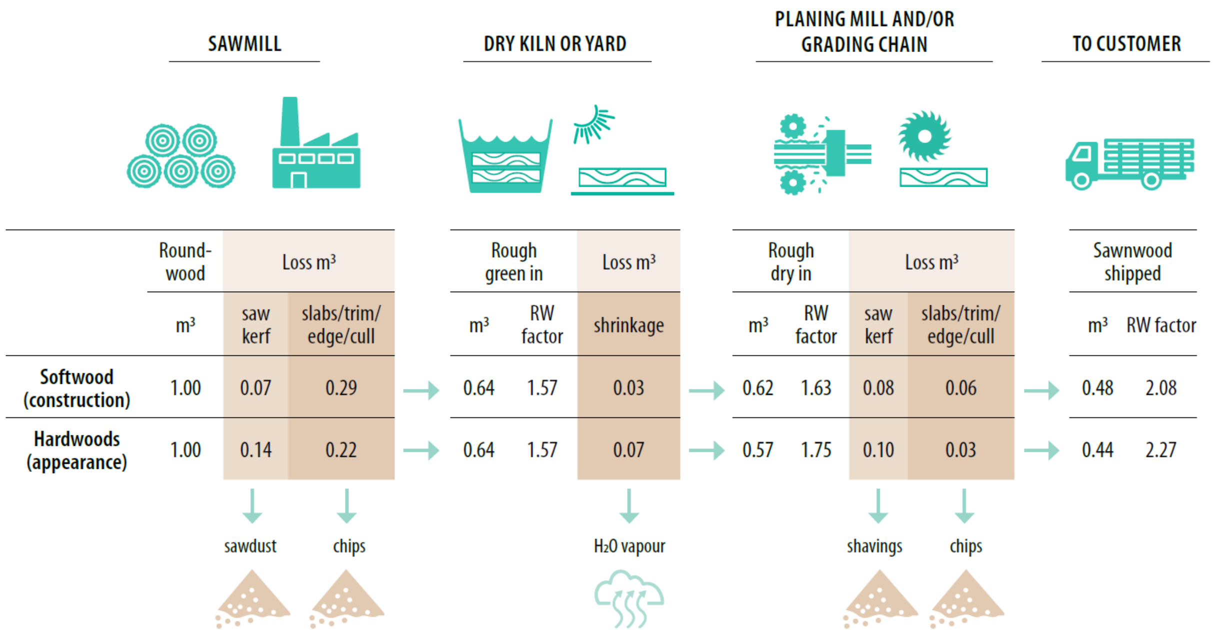


Figure 8 ***Schematic view on different ways of processing wood. Lumber can be applied directly or used in engineered wood products GLT = Glued laminated Timber (GLULAM), CLT = Cross Laminated Timber, LVL = Laminated Veneer Lumber, PLY = Plywood (multiplex), LSL = Laminated Strand Lumber and OSB = Oriented Strand Board[32].***

Building materials are generally sourced from softwoods. Douglas fir and larch are locally sourced in the Netherlands and often used for beams and planks applied in TFC buildings. CLT is usually made from Norway spruce. This is generally sourced from outside the Netherlands, due to low amounts and too low quality present. Hardwoods are often used in interior products due to their nice appearance and other wood properties. Such wood can be sourced both inside and outside the Netherlands. Detailed conversion factors are provided in the figure below.



	Roundwood	Loss m³		Rough green in		Loss m³	Rough dry in		Loss m³		Sawnwood shipped	
	m³	saw kerf	slabs/trim/edge/cull	m³	RW factor	shrinkage	m³	RW factor	saw kerf	slabs/trim/edge/cull	m³	RW factor
Softwood (construction)	1.00	0.07	0.29	0.64	1.57	0.03	0.62	1.63	0.08	0.06	0.48	2.08
Hardwoods (appearance)	1.00	0.14	0.22	0.64	1.57	0.07	0.57	1.75	0.10	0.03	0.44	2.27

Figure 9 ***Conversion losses during the production process of construction (softwood) and wood for interior use (hardwood). Copied from FAO[33].***

[32] Pramreiter, M., Nenning, T., Huber, C., Müller, U., Kromoser, B., Mayencourt, P., & Konnerth, J. (2023). A review of the resource efficiency and mechanical performance of commercial wood-based building materials. Sustainable Materials and Technologies, e00728

[33] Forest product conversion factors, published FAO, ITTO and UNECE, Rome 2020

The production of lumber from softwoods has a conversion efficiency of about 0.48 (Figure 9). The conversion efficiency of lumber to CLT is 83% (Pramreiter et al.), making an overall efficiency of 0.40 m^3 CLT per 1 m^3 roundwood. The efficiencies in figure 9 above will be applied in calculations related to sawn wood. The figure takes debarked roundwood as input. The conversion factor for debranching and debarking is taken as 83% in order to account for biomass losses in wood before entering the sawmill. After combining the debranching and debarking conversion factor and the conversion factors from the figure above, the following conversion efficiencies are applied for the different products:

- Lumber from softwood: 40% (from standing forest to beam). In a local biobased production system, this wood will be mainly applied in TFC construction.
- Lumber from hardwood: 37% (from standing forest to beam). In a local biobased production system, this wood will be mainly applied in furniture making.
- CLT or glulam from softwood: 33% (from standing forest to beam). In a local biobased production system, this wood will be mainly applied in CLT construction.
- Chips from softwood: 26% (from standing forest to chips). In a local biobased production system, these chips, being a residue stream from lumber production, could serve as feedstock for board production, (blow-in) insulation or viscose for textiles.
- Chips from hardwood: 19% (from standing forest to chips). In a local biobased production system, these chips, being a residue stream from lumber production, could serve as feedstock for board production, (blow-in) insulation or dissolving cellulose pulp for textiles.

In the Netherlands, losses during processing (chips, sawdust) are mostly used to generate energy for the production process (electricity, heat for drying the wood). A smaller part is sold to be used in the panel industry. In further material use calculations in chapter 6 for wood-based products (a.o. board/insulation/viscose), all chips are assumed to be applied in materials. The sawdust is assumed to be applied as energy resource in the saw mill.

4.2 Conversion of bast fibre crops into products

Flax and hemp are bast fibre crops which have relatively long and high-quality fibres, which are suited for a broad number of applications, including textiles. Whereas current flax processing is mainly optimized for the extraction of a long fibre suitable for textiles (linen), hemp processing in the Netherlands is positioned mainly for the production of building materials, like insulation and for composites for the automotive sector. Below, two different set-ups for hemp will be described:

- The current processing of hemp towards building materials
- A potential future set-up based on other hemp varieties optimized for textile production (similar to current flax processing).
    - The relevant conversion factors for flax will also be discussed in this section.

This section provides estimates for these conversion routes for:

- Conversion efficiency per process step in wt.%: Expert estimate.
- Cumulative quantities in kg: Calculation based on conversion efficiency, assuming 100 kg starting weight.
- Prices of raw materials (€/ton): From section 3.2.
- Product prices (€/ton): Prices of online offerings, divided by factor 2, as an indication of ex-factory cost price.
- Scale of conversion processes (tonnes/year): Based on information available online and expert knowledge.

4.2.1 Conversion of hemp towards building materials

Figure 10 visualises the successive processing steps for making insulation blankets from hemp fibre. Given the versatile applications of hemp fibre, the production of insulation blankets is linked to the use of hemp shives and other applications of hemp fibre. The process steps are as follows:

- Harvesting, retting, drying: Harvesting is done with special machines[34]. When harvesting, the hemp stems are slightly bruised and placed on a windrow for 'retting'. Retting is the biological process in which microorganisms loosen the bond between the bast fibres and the core fibres under the influence of temperature and moisture (dew, rain), such that they can be mechanically separated in a subsequent processing step. Before the stems are stored, the stems must be dry.
- Pressing and storing: Once the stems are sufficiently retted and dried, the hemp can be pressed into bales. Storage usually is done at the processor's facilities.
- Separating bast fibres and core fibres: Using special equipment, the stems are separated into bast fibres (usually called 'hemp fibres') and core fibres (usually called 'shives').
- Making various products:
  - Insulation blankets: Density approximately 40 kg/m^3
  - Needle punched fibre mats: Density approx. 50-100 kg/m^3 for use in composite, growing medium, garden mulch
  - Shives can be used directly as animal bedding. Shives can be processed with lime binder into building panels and blocks.

The main products of hemp – the fibres and the shives – must be marketed in the appropriate proportions. Scaling up a fibre application also requires scaling up the sales of the shives. Shives could be used in hemp-lime insulating building panels and blocks. With increasing demand for biobased construction, the demand for these building materials may also increase. Currently, the insulation blankets marketed in the Netherlands are produced in southern Germany and the Czech Republic. Hemp insulation blankets are transported at approximately the density at which they are installed, about 40 kg/m^3; production in the Netherlands would avoid significant transport costs and environmental impact.

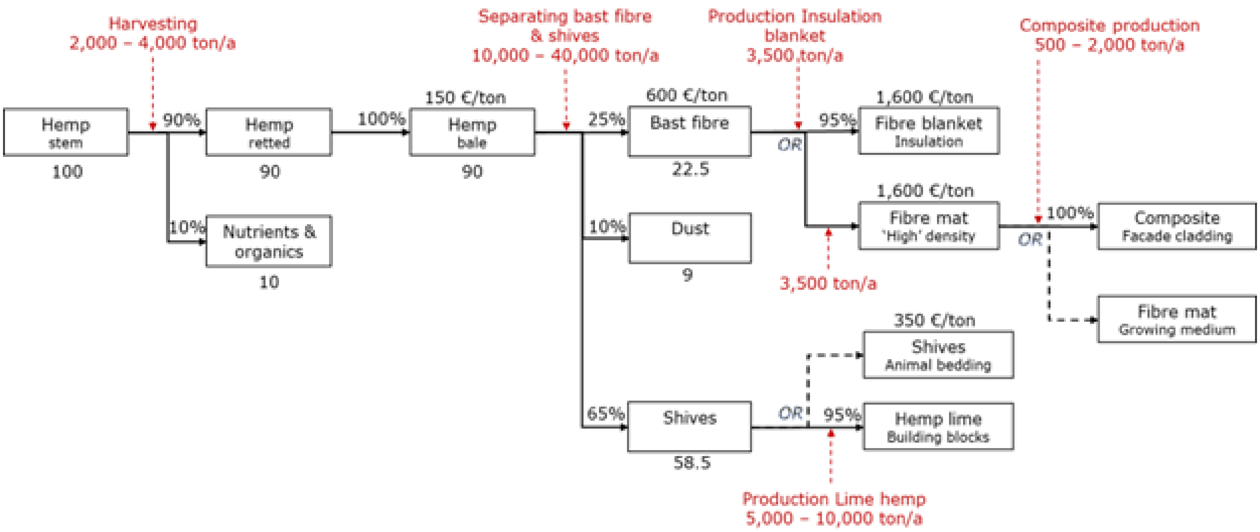


Figure 10 Scheme for conversion of hemp into technical applications: fibres into flexible insulation mats or composites, shives into building blocks. Conversion efficiencies as wt.%; cumulative amounts in kg[35].

Similar processing steps apply for flax, with the difference that flax is primarily grown for the use of the long bast fibres in textiles. The lowest qualities of bast fibres are used in, among other applications, insulation blankets. Scaling up flax for use in insulating blankets is therefore more complex than scaling up hemp for insulating blankets. Assuming a bast fibre yield for flax of 25 to 30%, the vast majority of which goes to textile applications, it is estimated that approximately 5% of the crop could be used for the production of insulation blankets. The approximately 70% shives can be used for particle boards (or animal bedding).

[34] https://edepot.wur.nl/644008
[35] Based on earlier work from: van den Oever, M., de Wagenaar, D., Hosper, G., Reinders, M., Vermeire, S., de Raeve, A., Scheffer, M., Sauveur, R., Calciolari, L., Jurrius, A., Mirizzi, F., Hosper, G., Reinders, M., Vermeire, S., de Raeve, A., Scheffer, M., Calciolari, L., Jurrius, A., Mahy, J., & Mirizzi, F. (2023). Handbook of hemp cultivation, processing and applications : from farm to products. (Report / Wageningen Food & Biobased Research; No. 2509). Wageningen Food & Biobased Research. https://doi.org/10.18174/642557

4.2.2 Conversion of hemp towards textiles

Production of hemp textiles is already taking place at scale. Similar to current flax processing, in this case the long fibre is the main (highest value) product, followed by short fibres and the shives. Based on the knowledge about the composition of hemp varieties used for the production of textiles, it is possible to derive a conversion scheme. This scheme is presented below:

- The processing steps from field to fibre are similar to those described in the previous paragraph: Harvesting, retting, drying, pressing and storing.
- Then, fibres are separated in different qualities. At the stage of scutching and hackling hemp and flax, long fibres are the high value fibres used for wet ring spinning to obtain fine yarn (26-38 tex for hemp; 17-38 tex for flax), whereas the short fibres deliver more coarse yarns, in the range 67-330 tex for hemp.
- Similar to the previous hemp processing scheme for building materials, shives and dust are the final products coming from the process and can be valorised as animal bedding, or in board material or hemp lime products.

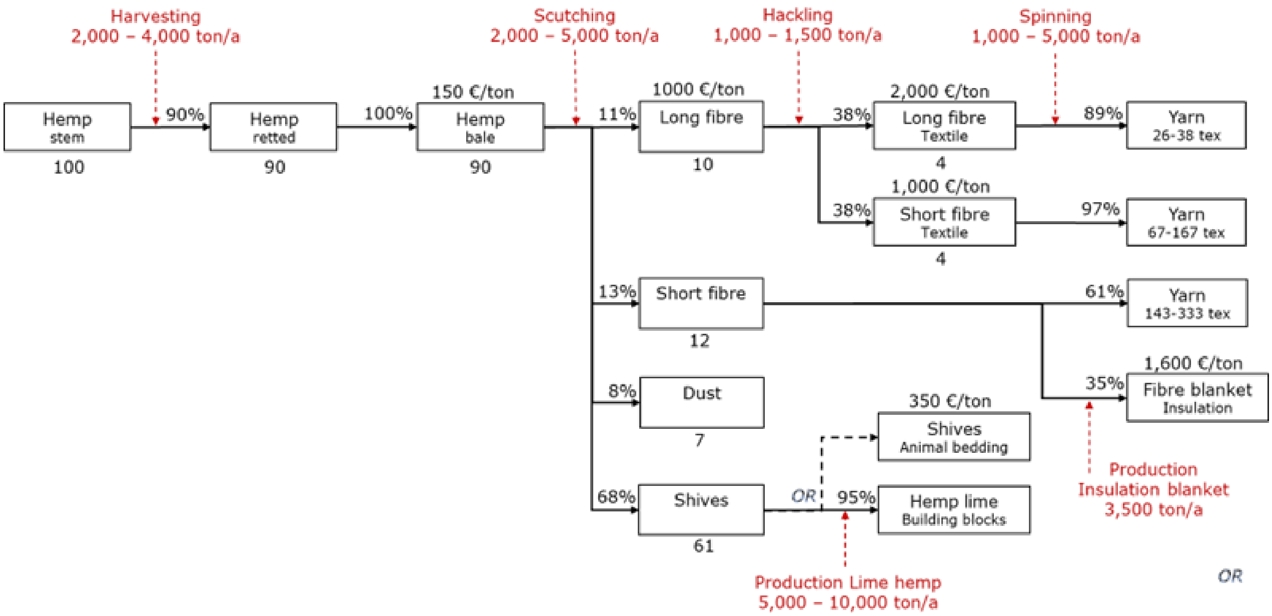


Figure 11 ***Scheme for conversion of hemp into textiles: fibres into various qualities of textile fibre, shives into building blocks. Conversion efficiencies as wt.%; cumulative amounts in kg[36].***

Scheme for flax is similar to that for hemp, however, with higher yields of long fibre and lower yields of shives since the share of long fibres is higher than in hemp. For the conversion of flax and hemp fibre to textile product, the following conversion efficiencies[37] are used:

- 60% for apparel
- 76% for home textiles

4.3 Conversion of (ligno)cellulosic feedstocks into products

This project reviews a couple of conversion routes based on fibrous crops (and residual flows):

- Production of particle boards from lignocellulose feedstock (§4.3.1)

[36] Based on earlier work from: van den Oever, M., de Wagenaar, D., Hosper, G., Reinders, M., Vermeire, S., de Raeve, A., Scheffer, M., Sauveur, R., Calciolari, L., Jurrius, A., Mirizzi, F., Hosper, G., Reinders, M., Vermeire, S., de Raeve, A., Scheffer, M., Calciolari, L., Jurrius, A., Mahy, J., & Mirizzi, F. (2023). Handbook of hemp cultivation, processing and applications : from farm to products. (Report / Wageningen Food & Biobased Research; No. 2509). Wageningen Food & Biobased Research. https://doi.org/10.18174/642557

[37] Fiber Conversion Methodology 2019, Textile Exchange, August 2019

- Production of blown-in insulation from fibrous raw materials (§4.3.2)
- Production of textile fabrics from lignocellulose feedstock through dissolving cellulose pulp route (§4.3.3)

This section provides estimates for these conversion routes for:
- Conversion efficiency per process step in wt.%: Expert estimate.
- Cumulative quantities in kg: Calculation based on conversion efficiency, assuming 100 kg starting weight.
- Prices of raw materials (€/ton): From section 3.2.
- Product prices (€/ton): Prices of online offerings, divided by factor 2, as an indication of ex-factory cost price.
- Scale of conversion processes (tonnes/year): Based on information available online and expert knowledge.

4.3.1 Particle boards from lignocellulose feedstock

Figure 12 visualises the successive processing steps for making particle board from lignocellulosic raw materials in a diagram:
- Harvesting, drying: This can be carried out by contractors with existing machines. These machines can be used for harvesting multiple crops, with or without adjustments; therefore a wide range for the scale is given.
  - If the raw material during harvest is dry enough for storage, the fibre raw material can be reduced in size with a chopper during harvesting.
  - If the fibre raw material is too wet for storage at the moment of harvesting, it makes sense to let the raw material dry as much as possible on the land and then press and store.
- Storage: This can take place, for example, at the farmer.
- Comminution to particles: Strictly speaking, the reduction can be done decentral, e.g. at the farmer. Due to the importance of particle size for particle board quality, the manufacturer may want to carry out the (final) comminution step in-house.
- Hot pressing into particle boards: Particles of desired size are sprayed with glue, formed into a 'mat' and hot pressed into boards. Typical density of particle boards is 650 – 750 kg/m^3. The plates are conditioned for some time before they leave the factory.

The scale of crop harvesting and comminution is relatively small compared to making particle board; noting that state-of-the-art particle board factories have a capacity of the order of 600,000 m^3/year (ca. 400,000 tons/year), and that the 30,000 tons/year relates to a once planned factory for 'niche' particle board based on straw & reed. For reference: Linex produces around 25,000 tons/year of flax chipboard. Roughly speaking, the diagram below applies for a variety of raw materials: Miscanthus, reed, Sorghum, cup plant, cereal straw, stalks of sunflower, rapeseed, bell pepper and tomato plants; and flax and hemp shives.

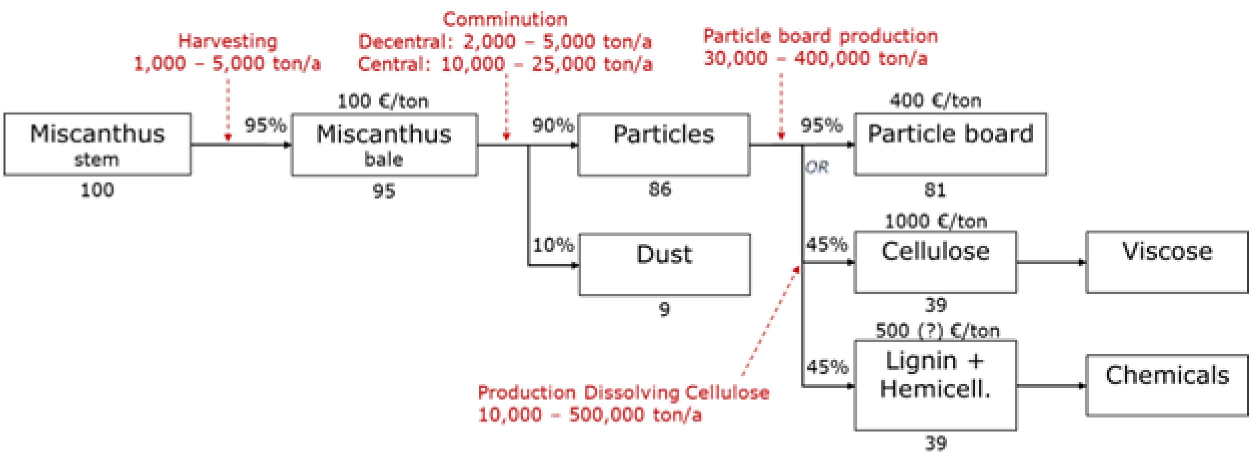


Figure 12 ***Scheme for conversion of Miscanthus into particle board. Or eventually into viscose fibre for textiles. Indicative conversion efficiencies as wt.%; cumulative amounts in kg.***

4.3.2 Blow-in insulation from fibrous raw materials

Figure 13 visualises the successive processing steps for making blow-in insulation from lignocellulosic raw materials:

- Harvesting, drying, storing: As for particle board (§ 4.3.1).
- Comminution to particles: This will preferably be done decentrally to minimize transport costs.
- Blowing in: During renovation this is done per building using a mobile module. In the case of prefabrication of building elements, this is done at the factory. The capacity of blow-in devices, however, is relatively small, which means that prefabrication can also be called decentralized. Typical density of blow-in insulation is 100 kg/m^3.

The scale of all processing steps is relatively small, making local/decentralized cultivation, processing and application possible.

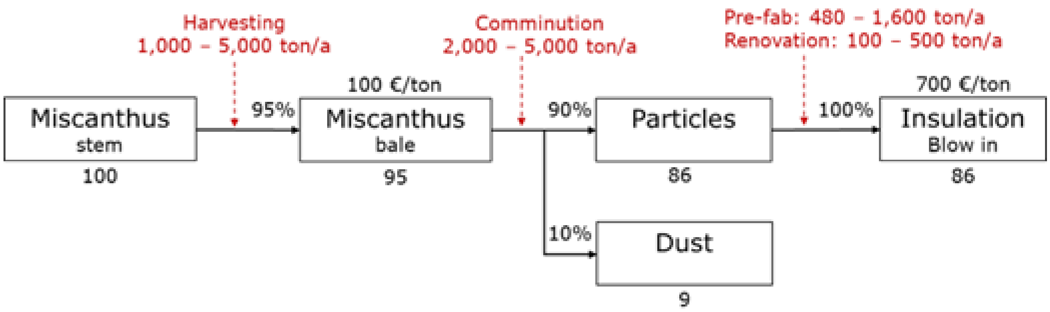


Figure 13 Scheme for conversion of Miscanthus into blow-in insulation. Conversion efficiencies as wt.%; cumulative amounts in kg.

The scheme above can be used for a variety of raw materials: Miscanthus, cattail, cereal straw like from wheat, and straw from Sorghum. Grain Sorghum comprises straw (7 ton/ha.a) and panicle (6 ton/ha.a).

4.3.3 Dissolving cellulose pulp for textiles from lignocellulosic feedstock

Another important route to textiles which is less dependent on a specific type of biomass (unlike for example mechanical separation of fibres from bast fibre crops) is to first isolate the cellulose from lignocellulosic biomass and make new cellulose-based fibres. The standard raw material for this so-called regenerated cellulose is wood, for instance beech wood, but also other cellulose-containing feedstock is or can be used, like cotton linters and bamboo. The below description of the different variants of this process (viscose/Lyocell and the Modal variant of the viscose fibre) is based on Harmsen & Bos[38].

To produce regenerated fibres, first the cellulose-containing biomass is treated in a pulping process (resembling production of paper pulp) where nearly all non-cellulosic substances like lignin and hemicelluloses are removed to produce a highly pure cellulose fraction (>90%) called dissolving pulp.

For the traditional viscose process, the dissolving cellulose pulp is treated with carbon disulphide in order to form cellulose xanthate, which is subsequently dissolved in sodium hydroxide. The fibres are then produced by wet spinning: the solution of cellulose xanthate is extruded and forced through a spinneret, a plate with thousands of small holes of circa 50 μm in diameter, into a bath containing sulfuric acid, sodium sulphate and zinc sulphate. In the bath the cellulose xanthate reacts back (is regenerated) to cellulose, forming the viscose fibre. During the regeneration process the core of the fibre shrinks, which causes the outer layer to wrinkle. This gives viscose fibres their typical jagged cross-sectional shape and striations along their length. After extrusion, thousands of filaments lie parallel to each other and form a tow. The tow is drawn in order to increase its strength and is then usually cut into staple fibres of approximately 40 mm length. The staple fibres are spun into a yarn, optionally after blending with other types of fibres. Modal is a viscose fibre which is spun in a slightly different way, into a bath with a different chemical composition, to obtain a stronger fibre which is very soft to touch.

[38] Textiles for Circular Fashion, Part 1: Fiber Resources and Recycling Options, Harmsen and Bos, Wageningen, 2020

Lyocell is also produced from dissolving pulp, but the process is chemically less complicated because the cellulose is dissolved directly in a solvent called N-methylmorpholine-N-oxide (NMMO). NMMO is an amine oxide, a highly polar and water-soluble compound, in which cellulose can be dissolved at 100 °C. The fibres are spun by a so called dry-jet wet spinning process. After leaving the spinneret and before entering the water bath, the fibres pass through an air gap, where the filaments are stretched and given a strong orientation of the polymeric molecules. The NMMO can be recycled, which makes this process much more sustainable compared to the traditional viscose process.

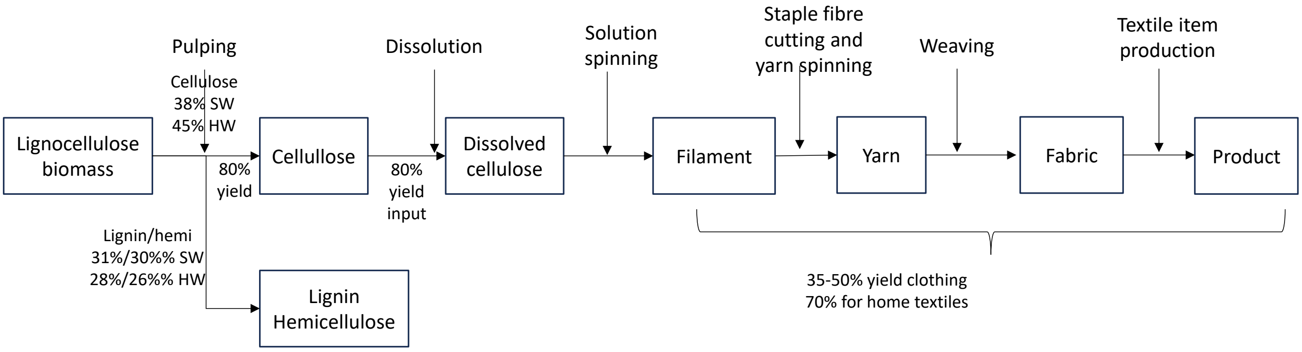


Figure 14 Main steps in the regenerated cellulose route. The Lyocell route uses the highly effective and 99% recycled solvent (NMMO), the Viscose process in practice involves harmful chemicals which need to be discarded.

For pulping and dissolution towards viscose, efficiencies of 80% have been assumed based on expertise available within WFBR. For viscose fibre towards the final product, the following yields[39] are applied:

- 35-50% for apparel.
- 70% for home textiles

The current biomass sources for regenerated cellulose production are various wood sources with high cellulose content. The main European industry producing regenerated cellulose – Lenzing – comes from eucalyptus, but also beech wood, spruce, birch wood and pinewood are used[40]. As for potential agricultural candidate feedstocks for regenerated cellulose, the four fibre crops which have been identified as crops with the highest revenue will be evaluated below:

- The fibres from hemp/flax have a cellulose content, up to 74-75%[41], which would make them an attractive source for regenerated cellulose production. At the same time, the natural bast fibres as they are present in the crop already have an established value as a fibre for textile production. Therefore, breaking them down into regenerated cellulose does not optimally use the functionality of the original bast fibre.
- Miscanthus has been evaluated for its potential as a feedstock towards regenerated cellulose. The outcomes show a mixed picture. On the one hand, Miscanthus phytoremediation ability can lead to inhibitors (e.g. metals) in the biomass, which can be avoided by growing the Miscanthus on soils with lower metal concentrations. Nevertheless, when using the right cellulose isolation process, it is possible to produce a regenerated cellulose fibre similar to current Lyocell standards[42]. Another important challenge is related to Miscanthus' qualitative composition of lignin, distribution of lignin in cell walls and its morphological features compared to for example birch wood. As a result, delignification selectivity for Miscanthus giganteus stems is worse than that of birch wood, which comes with significantly lower cellulose yield. Based on currently available sulphite pulping methods, Miscanthus may not be a competitive material compared to currently used wood feedstocks. However, Miscanthus may be a complementary feedstock to hardwood[43]. The fact that Miscanthus is being used for paper production by WEPA[44] does show there is potential for Miscanthus as a cellulose source.

[39] Hugill R, Ley K, Rademan K (2020) Coming full circle: Innovating towards sustainable man-made cellulosic fibers. Fashion for good.
[40] https://www.lenzing.com/sustainability/production/resources/wood-and-dissolving-wood-pulp
[41] https://edepot.wur.nl/647711
[42] Preparation of Lyocell Fibers from Solutions of Miscanthus Cellulose, Makarov et. al, 2024
[43] Comparison of Miscanthus Giganteus and birch wood NSSC Pulping, Part 1: the effects of technological conditions on certain pulp properties, Joachimiak et. al., 2018
[44] https://vnp.nl/toiletpapier-miscanthus/

- Also wheat straw has been piloted as a feedstock for cellulose (micro-fibrillated cellulose or MFC) production. Fortum and Spinnova have developed prototype clothing already in 2019[45]. However, the current status of the technology is unclear.

4.4 The locality of the different conversion processes

The above description of the different conversion processes enables an assessment of the estimated locality of these processes. In table 16 below, typical scales for the various conversion processes are presented including an indication whether these scales are typically regionally oriented or operate on a national scale.

Table 16 Typical scales[46,47] for conversion of biobased feedstock into materials and (semi-finished) products.

Feedstock	Conversion technology	Products/Purpose	Typical conversion scale	Level *
Wood	Sawing	Beams	1,000 – 100,000 m^3/a	Regional/national
Wood	Gluing	CLT columns, beams, panels	50,000 - 100,000 m^3/a	National
Hemp	Decortication	Insulation, composites	10 – 40 kton/a	Regional
Hemp, Flax fibres	Scutching	Fibres for textiles	2 – 5 kton/a	Regional
Hemp, Flax fibres	Hackling	Fibres for textiles	1 – 1.5 kton/a	National/Regional*
Hemp, Flax fibres	Spinning	Yarns for textiles	1 - 5 kton/a	National/Regional*
Hemp, Flax yarn	Weaving	Fabrics for textiles	0.01 – 0.1 kton/a	Regional
Hemp, Flax, Grass fibres, Wool	Fibre mat manufacturing	Insulation mat	50,000 - 100,000 m^3/a 2 - 4 kton/a	National/regional*
Hemp, Flax fibre	Fibre reinforced comp. man.	Composite facade	0.5 – 20 kton/a fibre	Regional
Woody biomass	Milling (decentral)	Particles for boards & blow-in	2 - 5 kton/a	Regional
Woody biomass	Milling (central)	Particles for boards & blow-in	10 - 25 kton/a	Regional
Woody biomass	Board manufacturing	Particle boards	40,000 - 600,000 m^3/a 30 – 400 kton/a	National/regional*
Fibrous biomass	Blow in (factory)	Blow-in insulation	500 - 16,000 m^3/a 0.5 – 1.6 kton/a	Regional
Fibrous biomass	Blow in (directly in building)	Blow-in insulation	1,500 - 3,000 m^3/a 0.15 - 3 kton/a	Regional
Woody biomass	Chemical extraction	Dissolving pulp for viscose	50 - 850 kton/a	National
Woody biomass	Solution spinning	Viscose for textiles	50 - 100 kton/a	National
Hemp shives	Building block manufact.	Building blocks	4 - 6 kton/a shives	Regional

* Regional or national level at which the conversion technology may be operated.

From the table, the possibilities for regional or national processing per product can be derived.

[45] https://spinnova.com/news/press-releases/fortum-and-spinnova-present-the-worlds-first-wheat-straw-based-clothing/

[46] van den Oever, M., Vural Gursel, I., Elbersen, W., Kranendonk, R., Michels, R., & Smits, M.-J. (2023). Regional supply of herbaceous biomass for local circular bio-based industries in the Netherlands. (Report; No. 2415). Wageningen Food & Biobased Research. https://doi.org/10.18174/630159

[47] van den Oever, M., Telleman, Y., van Kampen, A., van der Voort, M., van der Weide, R., van Baren, S., & Jacobs, S. (2024). Biobased grondstoffen voor hoogbouw : geïndustrialiseerde modulaire en lage emissie hoogbouw in de G4. (Rapport / Wageningen Food & Biobased Research; No. 2551). Wageningen Food & Biobased Research. https://doi.org/10.18174/651629

For construction, saw mills producing the beams for TFC-construction can have a relatively small capacity and operate at regional scale (1,000 m^3/a or more). The same applies to particle board production plants, which can have both a regional orientation (40,000 m^3) or operate at national scale (600,000 m^3). Also insulation material can be produced at regional or at national scale.

For textiles, the picture is more mixed. Hemp and flax are currently mostly processed in relatively small scale facilities (between 2-5 kton/a). This small scale is mainly due to the fact that hemp and flax are relative niche crops for textiles. In case of hemp/flax becoming more mainstream – for example in a more locally oriented system – the scale of these plants could increase to a larger national scale plant or multiple regional plants of the same capacity. For regenerated fibres (viscose/Lyocell) a large scale pulping plant is the essential first step to produce dissolving cellulose for the production of yarns. This is a chemical process which is only viable at large scale. Because of the size of this operation, also the subsequent spinning process (also involving chemical steps) is significantly larger than the spinning processes for hemp and flax.

4.5 Local presence of conversion industries

A key condition for the transition towards a more locally oriented biobased economy, is the presence of relevant industries and initiatives which can carry out the conversion steps needed to get from tree or fibre crop to household product. As a final paragraph in this chapter, we will now evaluate to which extent these industries are already present in the Netherlands.

To start with wood processing, the Netherlands currently has over 60 saw mills which process roundwood[48]. These saw mills are spread over the whole country. Some are specialized in hardwood, others in softwood or poplar. Some can process both hardwood and softwood.

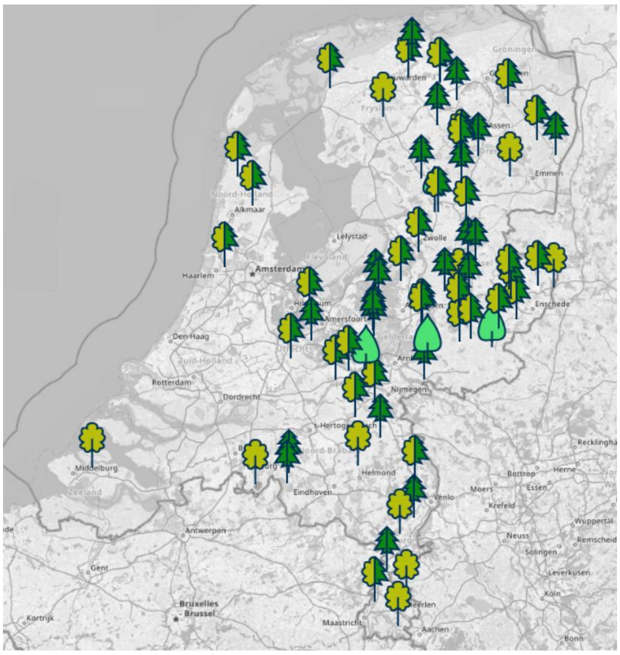


Figure 15 Roundwood sawmills for softwood, hardwood and poplar in the Netherlands.

Also wood construction is well represented in the Netherlands. There are multiple TFC (sometimes combined with CLT) pre-fab production plants, operated by a.o. Plegt-Vos, Barli, Ballast Nedam, BAM, De Groot Vroomshoop, Dijkstra Draisma, Heijmans, TBI, Hurks en Dura Vermeer. Their joint estimated capacity in 2024 was up to 13.200 houses per year[49]. In addition, there are many start-ups with own biobased housing concepts based on wood or other biobased materials, including FLETTS, TALA, Lister Buildings, BOOM, Uuthuuskes (The

[48] https://rondhoutzagerijen.nl/
[49] Information provided by Building Balance during Sounding Board meeting, 15 October 2024

New Makers), Unbrick, Van Goeden Huizen, Harwoonie, CirclWood, Eco+Bouw, Bouw*Novum, Eco Home, QYUUBS, MeerHout, Megaplex[50].

Wood furniture construction is also an existing sector in the Netherlands with a long list of companies active in this field. Some of these companies even focus on the use of Dutch wood, like Houtwerk Hattem, Van der Drift, Houtvermaeck and Nederhout.

Regarding chips and fibre processing towards board and insulation, there are a number of relevant companies in the Netherlands:

- Board production: SAM Panels (furniture and construction), Plantics (furniture) and VanHier (furniture).
- Insulation: Isovlas, Dunagro, Hemkor/Kingspan, Greeninclusive for insulation mats. For blow-in insulation, Bioblow, Strobouwer, Ecococon, Orange Elephant.

For textiles, the presence of processing industry in the Netherlands is more limited.

For the bast fibre route, there is only some industry activity towards textiles in flax with only a minor part of the shorter bast fibres being converted into insulation mats by Isovlas. Growing and processing (scutching and hackling) of fibre flax is concentrated in Dutch Flanders with 2 processors. The companies Van de Bilt, and Bruijns are active in scutching; hackling is carried out by Van de Bilt. Most of the spinning usually takes place in Asia, but recently four new spinning mills in Europe have been established, with a production capacity of 2,600 tonnes of flax yarn in 2021. These mills are on top of existing five flax spinning mills in Europe with a combined production capacity of 10,800 tonnes of flax yarn per year[51]. Hemp is not converted into textiles in the Netherlands, but only to building products, horticulture and animal bedding.

There is no viscose or lyocell producer in the Netherlands. Lenzing in Austria is the only European producer of Lyocell. Since a viscose or Lyocell plant requires large amounts of biomass, it will probably be very challenging to establish such a plant in the Netherlands. Miscancell is an initiative which produces cellulose out of Miscanthus, but so far the application potential of this cellulose is unclear.

For fibre processing towards textiles, particularly the spinning step is poorly represented in the Netherlands. SaXcell is a start-up initiative which aims to produce new filaments out of discarded textiles. Another semi-industrial initiatives in spinning in the Netherlands has been Spinning Jenny, which makes new yarns out discarded textiles. In addition, there are some more artisanal initiatives to make fibres from flax (Joline Jolink) and reed (Rietgoed). For hemp, there is an initiative by RVO, together with Fibreshed and other partners, to set up a hemp textile chain in the Netherlands.

Also the weaving sector is not that well presented in the Netherlands anymore. Few weaving mills focusing on clothing include Enschede Textielstad and A.C. ter Kuile. For home textiles, still several weaving mills exist, like Artex (curtains, upholstery), Vescom (curtains, upholstery, wallcovering), EE Exclusives (wallcovering, interior, clothes) and Natweave (carpets).

4.6 Summary

This chapter has presented the different routes to get from biomass to a building material, textile or furniture. Wood is a unique material and can only be produced from trees. It is the key material which can be used for constructive (bearing) applications in building. During the conversion process to sawn wood, various side-streams are obtained (chips and sawdust) which can be applied in the production of board, insulation or even textiles (viscose). This combination of a high-quality building material (timber) and valuable side-streams is what makes trees unique as a highly valuable biomass source.
Bast fibre crops (hemp, flax) produce a unique quality of (long) fibre which is suitable for textile production. Part of the (shorter) fibres is also suitable for insulation mat production. The shives, which form the core of the stem, are applied as animal bedding, in board material or in hemp lime building blocks. For both flax and

[50] Trends in de houtbouwtransitie, Rijksdienst voor Ondernemen Nederland, juni 2023
[51] van den Oever, M., Vural Gursel, I., Elbersen, W., Kranendonk, R., Michels, R., & Smits, M.-J. (2023). Regional supply of herbaceous biomass for local circular bio-based industries in the Netherlands. (Report; No. 2415). Wageningen Food & Biobased Research. https://doi.org/10.18174/630159

hemp there is an established industry which is able to mechanically separate long fibre, short fibre and shives. Spinning of long fibres into yarns takes place outside of the Netherlands (mostly in China, but also in France there are spinning facilities).

Then, there is a broad range of crop types which do not have distinctive high quality fibre suitable for textiles, but which can be applied as a general source of particles for board production or blow-in insulation. From the economic analysis performed in chapter 3.2, it was shown that only high-yielding Miscanthus and to a lesser extent cup plant have a positive net revenue. For Cup plant however, there is little experience with application of the biomass in materials. For Miscanthus there is more experience, applications as blow-in insulation are being developed and it is applied as a cellulose source for paper making. This latter application may also suggest that Miscanthus may have potential for regenerated cellulose production for viscose/Lyocell for textiles.

With regard to scale, for most of the conversion processes discussed in this chapter, either regionally oriented or nationally oriented production facilities could be set up. In principle, processes which include chemical conversion steps are large scale and would require biomass supply at national scale in order to convert it into a product in an economically viable way. Examples of these processes are the production of dissolving pulp (extraction of cellulose) and spinning of dissolving pulp into viscose/lyocell. Other example is CLT production and board production in which significant amounts of glue are used. However, for board production also more regionally oriented small scale initiatives have been set up.

In order to transition to a more local biobased production, a pre-requisite for scaling up is the presence of industry or at least the knowledge and equipment to perform certain processing steps. Saw mills for wood production are still present in the Netherlands. The same applies for insulation mat production (flax and hemp). For board production there are some fairly small-scale initiatives, but no established industry. The textile value chain in the Netherlands is incomplete, since there is basically no spinning industry left in the Netherlands and also weaving for clothing has practically disappeared. There are still some weaving industries, but these are mostly in home textiles rather than clothing.

5 Performance of biobased materials

In this chapter, a comparison will be made between the performance criteria which exist for the different construction and household products and the actual performance of a variety of locally available feedstocks in such products. For each type of application, the performance requirements will first be discussed. Then, the performance potential of biobased materials will be reviewed against these requirements.

5.1 Building materials

5.1.1 Building product quality parameters and performance requirements

Performance requirements for building and construction in the Netherlands are laid down in the so called 'Besluit Bouwwerken Leefomgeving (Decree on construction works and living environment), formerly known as 'Bouwbesluit' (Building decree), and related regulations. In subsections below relevant requirements for a range of building application functions have been summarized.

5.1.1.1 Mechanical properties of load-bearing wood-based beams

The strength and rigidity of a construction has to be such that the building remains upright during service life without any problems. Safety is anchored through design, material quality and safety factors. Rules for design of timber building structures are based on material properties as well as on safety factors in order to guarantee that stresses and deformation stay within safe limits. Design rules for timber structures are given in a.o. EN 1995-1-1.[52]

Material quality

To streamline communication on wood material properties, key performance parameters (material properties) of wood have been classified in so called 'strength classes' in EN 338[53]. Key properties include bending strength, stiffness and density. The mostly used strength classes for structural timber in the Netherlands are C18 and C24[54], where the C stands for 'coniferous' and the number indicates the so called 'characteristic bending strength' expressed in MPa. Indeed, most commonly used wood in Dutch construction is conifer (also called 'softwood'), in particular spruce, but also Scots pine, larch and Douglas fir.

For TFC usually at least C18 quality is used[5], however, C24 is recommended for structural applications[55]. CLT is often based on C24[56].

As trees are limited in size, so are solid wooden beams. In order to manufacture larger dimensions of wooden beam products than can be sawn from roundwood, wooden slats may be glued to so called 'glued laminated timber', or Glulam. This material can be produced in 2 ways:

- All slats are from the same strength class. This is indicated by adding an 'h' (from 'homogeneous') behind the strength class code: e.g. GL24h.
- The outer slats are from a higher strength class than those in the middle. This is indicated by adding a 'c' (from 'combined') behind the strength class code: e.g. GL24c.

Much used qualities include GL24, GL28 and GL32.[5]

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[52] EN 1995-1-1, Eurocode 5: Design of timber structures - Part 1-1: General - Common rules and rules for buildings. https://www.nen.nl/en/nen-en-1995-1-1-c1-a1-2011-nb-2013-nl-183519
[53] EN 338, Structural timber – Strength classes. https://www.nen.nl/en/nen-en-338-2016-en-218592
[54] https://www.houthandelonline.nl/Houtwijzer_naaldhout-in-de-bouw.pdf
[55] https://www.sleiderink.nl/kennisbank/de-sterkteklasse-van-hout
[56] https://www.mm-holz.com/BSP-Merkblatt_Cross_Laminated_Timber_August_2021.pdf

The characteristic bending strength as indicated by the strength class number, e.g. 18 in 'C18', equals the so called 5-percentile value[57] of 4-point bending tests parallel to the wood grain as described in EN 384 and EN 408. Test conditions include: sample height of 150 mm; span length of 18x sample height; distance between inner load points of 6x sample height[58],[59]. Further, a critical section at which failure is expected to occur based on visual or other inspection shall be selected in each piece of timber.8 The 5-percentile value is the test value for which 5% of the values ranked in ascending order are lower or equal. Accordingly, the characteristic strength is much lower than the average bending strength of wood (e.g. compare values in EN 338 and in a table with softwood properties presented by HoutInfoBois[60]).

Based on extensive experience, strength classes also can be sorted visually by evaluating aspects which affect strength: knots; splits; annual ring width; wood grain. Still, mechanical testing gives more certainty about the strength. The performance requirements for key properties of most relevant wood strength classes in the Netherlands has been presented in Table 17.

Table 17 Requirements for bending strength, stiffness and density for most relevant wood strength classes in the Netherlands.

Property	C18	C24	GL24h	GL24c
5-percentile bending strength parallel to grain (MPa)	18	24	24	24
Mean bending stiffness parallel to grain (GPa)	9	11	11.5	11
5-percentile density (kg/m^3)	380	420	385	365
Average density (kg/m^3)			420	400

The higher the strength class of the timber, the less material is required to meet the design rules. However, it may be considered that, e.g., the availability of C24 wood is only about 10% of C18[61].

Safety factors

The safety factors depend on duration of load (e.g. self-weight, storage, wind), climatic conditions (relative humidity), and type of use (e.g. residential, office, storage).

5.1.1.2 Visual quality of wood

Another quality class comprises visual quality, which is graded A – D:

- A indicates very high visual quality for e.g. framework ('lijstwerk') and furniture. Availability of this type of wood is limited.
- B grade wood contains a small amount of knots, is core-free, meets strength class C24 and is used for visual applications which require high strength like e.g. window frames, doors, ceilings, façades, stairs.
- C grade may contain knots, should not be entirely core-free, meets strength class C18 and is used for e.g. constructive applications like e.g. covered flooring, rafters ('spanten'), purlins ('gordingen'), supporting wooden framework in buildings[62].
- D grade is used for applications which require hardly any visual appearance and no strength performance.

[57] EN 1990, Eurocode - Basis of structural design. https://www.nen.nl/en/nen-en-1990-2002-en-37350
[58] EN 408, Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties. https://www.nen.nl/nen-en-408-2010-en-149814
[59] EN 384, Structural timber – Determination of characteristic values of mechanical properties and density. https://www.nen.nl/en/nen-en-384-2016-a1-2018-en-253139
[60] HoutInfoBois, Tabel Naaldhout. https://www.houtinfobois.be/wp-content/uploads/2015/08/Tabel-Naaldhout.pdf
[61] https://www.houtwereld.nl/blog/paradoxaal-materiaal/
[62] https://www.bouwbestel.nl/blog/verschil-vuren-klasse-b-en-c.html

5.1.1.3 Mechanical properties of construction panels for timber frame construction

To stabilise timber frame constructions (TFC), especially against gusts of wind, at least type P5 panel quality (Load bearing boards for use in humid conditions)[63] is required[64]. For particle boards having 13 – 20 mm thickness, this implies the following specifications:

- Bending strength: > 16 MPa (also called Modulus of Rupture, MOR)
- Bending stiffness: > 2400 MPa (also called Modulus of Elasticity, MOE)
- Internal bond: > 0.45 MPa
- Thickness swelling: < 10% after 24 h soaking in 20 °C water

Also OSB3 board can be used as constructive panel for TFC.[65] For OSB having 10 – 18 mm thickness, this implies the following specifications:

- Bending strength: > 20 & 10 MPa in major and minor axis
- Bending stiffness: > 3500 & 1400 MPa in major and minor axis
- Internal bond: > 0.32 MPa
- Thickness swelling: < 15% after 24 h soaking in 20 °C water

The requirements for the full range of particle boards at given thickness as specified in EN 312 are listed in Table 18, together with typical applications.

Table 18 Requirements[63] and typical applications[66] of particle board having thickness 13-20 mm.

Board type	Purpose	Bending strength (MPa)	Bending stiffness (MPa)	Internal bond (MPa)	Thickness swelling (%)	Typical applications
P1	General	>11.5		>0.24		Packaging
P2	Interior fitments	>13	>1,600	>0.35		Furniture; doors
P3	Non load-bearing in humid conditions	>14	>1,950	>0.45	<14	
P4	Load-bearing in dry cond.	>15	>2,300	>0.35	<15	
P5	Load-bearing in humid cond.	>16	>2,400	>0.45	<10	Modular construction and the building industry (flooring, walls, roofing)[14]
P6	Heavy duty load-bearing in dry cond.	>18	>3,000	>0.50	<14	Flooring; walls; roofing; shelving
P7	Heavy duty load-bearing in humid cond.	>20	>3,100	>0.70	<8	

- For other thickness ranges, different requirements apply.
- Bending test (EN 310): Sample width is 50 mm; Support span, L, is 20x thickness, d; Loading rate is such that max load is reached in 60 s. Typical value for loading rate is 0.005*L2/(6*d) in mm/min.
- Internal bond test (EN 319): Sample dimension 50 * 50 mm; Loading rate is such that max load is reached in 60 s. Typical value for loading rate is 0.08*d in mm/min.
- Thickness swelling (EN 317): After 24 h in 20°C water.

The requirements for the full range of OSB grades at given thickness as specified in EN 300 are listed in Table 19, together with typical applications.

[63] EN 312, Particle boards – Specifications. https://www.nen.nl/en/nen-en-312-2010-en-150750
[64] Gerard Jonker (Oldenboom), personal communications.
[65] Fred van der Burgh, personal communications.
[66] https://www.elka-holzwerke.de/en/trademark-products/particleboard

Table 19 Requirements[67] and typical applications of OSB having thickness 10-18 mm.

Board type	Purpose	Bending strength (MPa)	Bending stiffness (MPa)	Internal bond (MPa)	Thickness swelling (%)	Typical applications
OSB1	General; Interior fitments	>18 / 9	>2,500 / 1,200	>0.28	<25	Furniture[18]
OSB2	Load-bearing in dry cond.	>20 / 10	>3,500 / 1,400	>0.32	<20	
OSB3	Load-bearing in humid cond.	>20 / 10	>3,500 / 1,400	>0.32	<15	Flooring, roof decking and wall sheathing[68]
OSB4	Heavy duty load-bearing in humid cond.	>28 / 15	>4,800 / 1,800	>0.45	<12	

- For other thickness ranges, different requirements apply.
- Values for major and minor axis, respectively.
- Bending test (EN 310): Sample width is 50 mm; Support span, L, is 20x thickness, d; Loading rate is such that max load is reached in 60 s. Typical value for loading rate is 0.005*L2/(6*d) in mm/min.
- Internal bond test (EN 319): Sample dimension 50 * 50 mm; Loading rate is such that max load is reached in 60 s. Typical value for loading rate is 0.08*d in mm/min.
- Thickness swelling (EN 317): After 24 h in 20°C water.

5.1.1.4 Thermal insulation of outer shell

To reduce/minimise energy demand for heating/cooling of buildings, insulation materials are applied. The Dutch law “Besluit Bouwwerken Leefomgeving” requires specific thermal insulation performance for roofs, exterior walls and ground floor, respectively[69] The thermal insulation actually is the resistance to heat flow of a construction system, Rc. The present minimum Rc required for new houses according to NTA 8800 are[70]:

- Roof: Rc = 6.3 m^2.K/W
- Facade: Rc = 4.7
- Floor: Rc = 3.7

The insulation performance of the outer shell of a building construction is the sum of the insulation performance of the individual components, Rd, e.g. façade cladding, insulation material, interior wall cladding:

$$Rc = Rd,1 + Rd,2 + Rd,3 \quad (m^2.K/W) \qquad \text{(equation 1)}$$

The insulation performance of an individual material is proportional to its thickness, d, and inversely proportional to its thermal conductivity, λ (W/m.K).

$$Rd = d/\lambda \qquad \text{(equation 2)}$$

For example: The thermal conductivity of biobased insulation materials like flax and hemp fibre mats is typically around 0.040 W/m.K. As an indication, and assuming that thermal insulation has to be provided entirely by such insulation material, the required thicknesses to achieve the required insulation performance ranges from 14.8 cm (floor) to 25.2 cm (roof).

Other relevant properties of insulation materials are the damp diffusion coefficient (damp open construction), heat capacity (delay of summer heat entering the house) and sound insulation (dB).

5.1.1.5 Fire resistance – burning rate

The required duration of a building’s fire resistance before it collapses relates to building height: the higher the building, the more time people may need to leave the building, the longer the required fire resistance time. The Dutch Decree on Construction Works and Living Environment (‘Besluit bouwwerken leefomgeving’) requires the following times[71]:

- highest floor is below 7 m above ground level: 60 minutes
- highest floor is between 7 and 13 m: 90 minutes

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67 http://osbinform.ru/doc/EN300.pdf
68 https://countyonline.co.uk/osb3-structural-board
69 https://wetten.overheid.nl/BWBR0041297/2025-01-01
70 https://www.timax.nl/energie-prestatie/beng/rc-waarde/ , https://www.sabprofiel.nl/nieuwe-rc-waarden-volgens-nta-8800/
71 https://rijksoverheid.bouwbesluit.com/Inhoud/docs/wet/bb2012/hfd2/afd2-2/par2-2-1

- Highest floor is above 13 m: 120 minutes

Buildings above 70 m height are considered high-rise buildings and additional requirements need to be met. These requirements are not detailed on a national level, however in close consultation with competent authorities, usually represented by the fire brigade, specific measures are determined and included in the environmental permit for building[72].

The design and material performance parameters of timber structures applicable in case of fire are given in EN 1995-1-2[73]. Apart from safety factors, the basis of these parameters is the residual cross-section after relevant burning (charring) times. The charring depth is proportional to burning time, t, and relates to charring rate (mm/min), ß0, which differs per type of wood and also relates to density. The effect of corner roundings and fissures is captured in a notional charring rate, ßn. In Table 20 the design charring rates for different wood based products are presented.

Table 20 Design charring rates for different wood based products[73].

Wood product type	$ß_o$ (mm/min)	$ß_n$ (mm/min)
Softwood solid timber, $\rho_k \geq 290$ kg/m³ *	0.65	0.8
Softwood Glulam, $\rho_k \geq 290$ kg/m³	0.65	0.7
Hardwood solid timber or Glulam, $\rho_k \geq 290$ kg/m³	0.65	0.7
Hardwood solid timber or Glulam, $\rho_k \geq 450$ kg/m³	0.50	0.55
Laminated veneer lumber, $\rho_k \geq 290$ kg/m³	0.65	0.7
Plywood, $\rho_k \geq 450$ kg/m³ and thickness ≥ 20 mm	1.0	
Other wood panels, $\rho_k \geq 450$ kg/m³ and thickness ≥ 20 mm	0.9	

* ρk = characteristic density = 5-percentile value.

From the data in Table 20 it can be calculated that one-dimensional charring depth for unprotected softwood beams or CLT panels is 39, 59 and 78 mm after 60, 90 and 120 minutes of burning, respectively. The residual cross-section should be able to bear design loads. This translates into significantly thicker beams & panels than required for structural design under normal conditions, even if the design values of material properties are slightly higher than the standard characteristic (5 percentile) values applied for regular design.

In order to avoid 'over dimensioning' of biobased constructions to meet fire resistance requirements, often (glass fibre reinforced) gypsum boards are used. Thickness of about 30 mm is required to achieve 60 min fire resistance.[74] Specific gypsum board systems can provide up to 180 min fire resistance[75].

<u>Insulation</u>

Insulation materials do not contribute to the load bearing structure of a building. However, they can spread fire when not flame retarded or covered properly (gypsum). The Dutch Decree on Construction Works and Living Environment ('Besluit Bouwwerken Leefomgeving') requires the following fire classes for façade insulation material[76]:

- Façade up to 13 m: Class D
- Façade above 13 m: Class B for first 2.5 m and above 13 m
- Façade above 70 m: Specific requirements may be set by competent authorities, usually represented by the fire brigade.

Smoke production should meet class 's2' ('average')[77].

[72] https://brandveiliggebouw.nu/vragen/item/gelden-er-speciale-regels-voor-hoge-gebouwen
[73] EN 1995-1-2, Eurocode 5: Design of timber structures – Part 1-2: General – Structural fire design. https://www.nen.nl/en/nen-en-1995-1-2-2005-nb-2011-en-156689
[74] https://knauf.com/brandveiligheid/wandsystemen
[75] https://www.gypsumceilingkenya.co.ke/gypsum-boards-fire-resistance/
[76] https://www.platformgevelisolatie.nl/Nieuws/Brandveiligheid-isolatiematerialen
[77] https://wetten.overheid.nl/BWBR0041297-paragraaf-3.2.7

The procedure for fire classification of construction products and building elements is defined in EN 13501-1[78]. Most lignocellulosic materials have fire class E, which can be upgraded to class B by addition of flame retarders. Less than half of the EPDs and ETAs found for biobased insulation materials met class B (as well as 's2' for average smoke production and 'd0' for no after-flaming of particles) as a result of added flame retardants, the other insulation products were classified by class E, i.e. containing no flame retardant.

5.1.1.6 Durability

Durability of bio-based building products very much depends on the way they are applied/installed. Proper application should result in durability of at least 75 years; for reed roofing 30 years service life is considered.

5.1.2 Performance of local biobased feedstock for building materials

5.1.2.1 Wood for constructive applications

In Europe, **CLT** is mainly made from Norway spruce (*Picea abies*), delivering strength class C24 and higher. However, research is also being done into other types of wood for use in CLT, because theoretically it is possible to make CLT from any type of wood that is available. However, each type of wood has its own properties that must be determined in advance before it can be used as CLT in construction. European research has looked at, among other species: Scots pine (*Pinus sylvestris*), Beech (*Fagus sylvatica*), Ash (*Fraxinus excelsior L.*), Aspen (*Populus tremula L.*) and Silver birch (*Betula pendula R.*)[79] and has shown that it is possible to manufacture CLT from other types of wood than just Norway spruce. Actually, the research concludes that in comparison to Norway spruce these hardwood species feature higher rolling shear properties, a key performance parameter for CLT. In particular, these of European beech and European ash were roughly three-times higher. These hardwoods, however, also have a higher density.[80]

Internationally, other species that are abundant in a specific region are being examined and how they can be applied in CLT, such as: Radiata pine[81] and Eucalyptus[82]. In addition, experiments are being conducted with the use of recycled wood for use in CLT[83], also in the Netherlands[84].

Like CLT, at the moment **Glulam** is mainly made of Norway spruce, delivering strength class GL24 and higher. However, also Scots pine, larch, Douglas fir and other spruces, and oak can be used.[85,86] There are also examples of Glulam made of beech and a combination of beech and Norway spruce.[87]

For **sawn wood**, Norway spruce is often used, but also Scots pine, larch and Douglas fir are used.[88] These are all coniferous wood species that are common in Europe and suitable for e.g. **timber frame construction** (TFC), delivering C18 and higher. The market is geared towards these coniferous wood species, however, also hardwood species may be used, having higher density and higher prices. It is expected that in the future the

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[78] EN 13501-1, Fire classification of construction products and building elements - Part 1: Classification using data from reaction to fire tests. https://www.nen.nl/en/nen-en-13501-1-2019-en-254374
[79] Ehrhart, T., Brandner R., Rolling shear: Test configurations and properties of some European soft- and hardwood species, Engineering Structures, Volume 172, 2018, Pages 554-572, ISSN 0141-0296, https://doi.org/10.1016/j.engstruct.2018.05.118
[80] https://www.houtdatabase.nl/infobladen/Infoblad_Houteigenschappen-Sterktegegevens.pdf
[81] Li, X., Ashraf, M., Subhani, M., Kremer, P., Li, H., & Anwar-Us-Saadat, M. (2021, October). Rolling shear properties of cross-laminated timber (CLT) made from Australian Radiata Pine–An experimental study. In Structures (Vol. 33, pp. 423-432). Elsevier.
[82] Ettelaei, A., Taoum, A., Shanks, J., & Nolan, G. (2022, August). Evaluation of the bending properties of novel cross-laminated timber with different configurations made of Australian plantation Eucalyptus nitens using experimental and theoretical methods. In Structures (Vol. 42, pp. 80-90). Elsevier.
[83] Rose, C. M., Bergsagel, D., Dufresne, T., Unubreme, E., Lyu, T., Duffour, P., & Stegemann, J. A. (2018). Cross-laminated secondary timber: Experimental testing and modelling the effect of defects and reduced feedstock properties. Sustainability, 10(11), 4118.
[84] https://www.theurbanwoods.com/newsroom/238959-from-pallet-to-palace-state-of-the-art-high-rise-made-from-waste-wood/
[85] https://www.glued-laminated-timber.com/glued-laminated-timber/wood-species/mn_42532
[86] https://www.bucklandtimber.co.uk/timber-species/
[87] https://www.glued-laminated-timber.com/glued-laminated-timber/glued-laminated-timber-made-of-beech-and-hybrid-beams-made-of-beech/spruce/mn_44337
[88] https://www.houthandelonline.nl/media/upload/houtwijzer_naaldhout-in-de-bouw.pdf

variety of wood species applied in CLT will increase. For example, already small scale tests with CLT made from recycled wood are currently being performed in actual building projects[89].

In principle, also trees grown in the Netherlands can be used for constructive applications.[21] Upscaling of timber production in the Netherlands would require dedicated forest management.

5.1.2.2 Particle board

5.1.2.2.1 Particle board from wood

Wood is the current reference feedstock for the production of different types of particle board. Feedstock for boards and insulation products are mainly residue streams from the (sawn) wood processing sector, but also from construction demolition. This means that coniferous wood is mostly used. However, also hardwoods can be used, such as beech and oak, e.g. for particle board, MDF, plywood.[90] Typical strength classes of wood based particle boards and OSB have been presented in tables 18 & 19). Suitable tree species which are common in the Netherlands have been discussed in chapter 3. In principle, all these strength classes (P1-P7) can be attained using a broad variety of wood species.

5.1.2.2.2 Particle board from crops

Next to wood (mostly spruce), cereal straw and flax shives are being used to produce particle boards. Other crops have been investigated for their performance in particle boards. The table below presents an overview of performance data for a wide range of lignocellulosic fibre crops reported in (scientific) literature.[91]
Colours indicate to which extent the performance meet the requirement specifications for particle board (section 5.1.1.3). Green colour means that the reported properties meet P5 (structural application), yellow that P1 (general) is met and red that the minimum requirements are not met.

Table 21 Properties of particle boards based on different fibrous feedstocks. Source type of the data in rightmost column. Green: meets P5 requirements; Yellow: meets P1; Red: Does not meet minimum requirements.[91]

	Density		Bending Strength		Stiffness (MoE)		Thickenss Swelling @ 24 h			Source
	(kg/m3)	range	(MPa)	range	(MPa)	range	(% TS)	range	n=	
Hemp shives	571	465-700	10.5	3.2-17.9	1868	654-3400	19.5	14.1-28	6	Website/Literature
Flax shives	510	350-657	10.8	5-18.2	1983	900-3290	17.6	16.9-18.4	4	Brochure/Literature
Wheat straw	798	650-910	26.6	13.7-38.3	3218	2292-4100	16.0	14-18	6	EPD/TDS/Literature
Reed	916	864-968	21.0	12-30	4015	2660-5370			2	Literature
Cattail	399	318-480	3.9	1.01-7	240	150-330	8.5	@ 2 h	2	Literature
Miscanthus	625	600-650	9.7	6.5-12.8	1671	1650-1692	30.4	12.7-48	2	Literature
Sorghum	769	725-800	17.0	1-34.1	2802	200-5200	22.6	9-60	6	Literature
Cupplant	600	600	11.3	9.7-12.3	1943	1700-2100	30.4	@ 2 h	4	Literature
Rape seed stem	692	684-700	12.4	11.7-13	2449	1798-3100	66.0	50-82	2	Literature
Bell pepper stem	720	700-730	11.5	10.1-12.3	2542	1856-3221	61.0	44-90	3	Literature
Tomato stem	765	660-870	10.5	6-15	675	550-800	27.0	24-30	2	Literature
Paulownia	583	550-650	20.0	18-23	2512	2000-3100	27.2	13.6-40	3	Literature
Willow	610	585-650	11.2	9.5-13.3	1816	1400-2664	36.7	24-49	4	Literature
'Paper fibre' (SAM)	950	950	35.2	32.4-40.8	4493	4202-4815			4	Pers. Comm.
Particle board P5	642		16.6	13.3-25	2780	2400-3300	10.3	10-12	6	DOP/TDS

The strength and stiffness data indicate that all raw materials mentioned in the table below, except cattail and tomato stem, are basically suitable for making particle board of any quality class:

- P5: Wheat straw, Sorghum, Paulownia fast growing tree, reed, residual (paper) fibre
- P3: Hemp shives
- P2: Miscanthus, sunflower, flax shives, rapeseed stems, willow
- P1: Bell pepper stem

89 https://www.houtwereld.nl/nieuws/platen-clt-gemaakt-van-pallets-worden-toegepast-in-gebouw/
90 https://www.houtinfo.nl/sites/default/files/Houtinfoblad%20Index%20Houtachtige%20Plaatmaterialen%20Jan2022.pdf
91 https://edepot.wur.nl/651629

The thickness swelling however is (considerably) higher than the standard in almost all cases. This is probably the result of not using moisture repelling agents in the scientific studies. In industrial production, paraffin or similar products are used to improve moisture resistance of particle boards. Data from literature indicate that adding paraffin/wax has little influence on bending strength and stiffness; however, the so-called 'internal bond' decreases by approximately 30%.[92]

5.1.2.3 Insulation materials

Lignocellulose and some other biobased raw materials generally have low thermal conductivity and are therefore basically suitable as an insulating material. This insulating effect can be improved by processing these raw materials into products that contain stagnant air: Fibre mats, blankets or panels and lightly compressed loose fibres or particles (blow-in).

The raw materials can have different origins:

- Specially grown for insulation: Hemp fibres (mats, blankets) and hemp shives (hemp-lime building panels and blocks); Miscanthus; Cattail
- By-product from cultivation/production of another product: Flax (textile is the main product); Cereal straw; sorghum straw; Stems of tomatoes, bell peppers, etc.; Roadside grass (infrastructure, nature); wood fibres and shavings (sawn wood is main product); Sheep wool (meat is main product); Cork (wine bottle stopper)
- Recycling from another product: Cellulose (waste paper); Waste textiles (usually a blend of cotton, polyester and other fibres)
- Intermediate form: Mycelium-bound lignocellulose residual flows

The table below provides an overview of the thermal conductivity of insulating materials; the lower the conductivity value, the better the insulation performance. Where available, this data is based on EPDs or European Technical Assessments (ETAs); this concerns commercially available insulation materials. The data contained in such documents have been independently determined and certified. A second source concerns 'technical data sheets' (TDS): data that product owners explicitly disclose as product performance. A third source includes company websites and 'personal communications', where product performance is often incorporated into a story, with pieces of information often left unmentioned. Finally, the public (scientific) literature was consulted; for these studies it is often difficult to determine the extent to which the measurement methods and test design used correspond with the measurement methods and design used by certification bodies. The table below indicates from which type of source data were obtained; 'n =' indicates the number of sources consulted.

The table above also shows the density of the insulation materials; where available. Fibre blankets and blow-in fibres clearly have lower densities (= factor 2 to 3 less raw material required) and lower thermal conductivity (= approximately 20% better insulation) than blow-in particles and pressure-resistant insulation panels. But there are also differences within these groups. For new sources like Miscanthus, cattail, corn straw and mycelium based insulation materials, no certified insulation performance was found. No insulation performance data at all were found for a number of other crop stems: sorghum, sunflower, pepper and tomatoes.

Compared to fossil references, biobased insulation blankets of a variety of fibre types show a thermal conductivity very similar to glass wool and rockwool, even though their average density is higher than glass wool and lower than rock wool. Most of the insulation panels show a higher conductivity, whereas for blow-in cellulose, sheep wool and wood fibre perform similar to glass wool and rock wool. EPS and especially PIR-PUR have a significantly lower conductivity.

[92] Kasim et al., Properties of Particleboard Manufactured from Commonly Utilized Malaysian Bamboo, Pertanika J. Trap. Agric. Sci. Vol. 24(2), 2001, pages 151 - 157. https://core.ac.uk/download/pdf/42990634.pdf

Table 22 Thermal conductivity (λ) and density of insulation materials.

	λ (W/m.K)		**Density (kg/m^3)**		**n =**	**Source**
	Average	Range	Average	Range		
Blankets (flexible)						
Sheep wool	0.036	0.033-0.039	22	18-31	7	EPD/TDS/Websites
Cellulose (recycled paper)	0.036		32		1	Brochure
Wood fibre	0.037	0.036-0.038	55	50-60	4	EPD/TDS
Flax fibre	0.038	0.035-0.040	36	28-47.5	5	ETA/TDS
Cotton (Recycled)	0.039	0.038-0.039	32	20-55	3	TDS
Hemp	0.040	0.040-0.041	38	35-41.5	4	EPD/ETA/TDS/Website
Verge grass	0.040	0.040-0.041	40		3	ETA/TDS
Panels (rigid)						
Cellulose fibre	0.038		75		1	TDS
Wood fibre	0.044	0.037-0.051	186	110-270	6	EPD/TDS
Cork	0.045	0.039-0.052	190	110-325	6	EPD/TDS
Cattail	0.052	0.044-0.061	244	200-400	4	Literature
Straw panels/bales	0.053	0.049-0.057	100		2	ETA/Pers. Comm.
Mycelium-Lignocellulose	0.057	0.040-0.088	113	94-135	6	TDS/Literature
Flax shives	0.071		350		1	Website
Loose (blow in)						
Cellulose fibre	0.038	0.037-0.043	44	31.5-56.5	12	EPD/ETA/TDS/Website
Sheep wool	0.038		18		1	TDS
Wood fibre	0.038	0.038-0.039	33	25-40	3	EPD/Website
Cereal straw	0.044	0.037-0.052	92	68-110	3	ETA/Pers. Comm.
Cork	0.044	0.041-0.047	90	65-115	2	TDS/Brochure
Grain corn straw	0.046		98		1	Literature
Wood shavings	0.047		70		1	EPD
Miscanthus particles	0.050	0.036-0.061	143	86-190	3	Literature/Pers. Comm.
Reed	0.056	0.055-0.056	164	138-190	2	Literature
Traditional fossil references						
Glass wool mat	0.038	0.036-0.039	15	11-24	4	EPD
Rockwool mat	0.039	0.030-0.050	90	60-120	4	EPD
EPS board	0.033	0.031-0.035	19	15-22	2	EPD
PIR-PUR board	0.025	0.023-0.026	33	32-33	2	EPD

5.2 Furniture

5.2.1 Furniture performance requirements

Furniture like chairs and tables are subject to daily ‘abuse’. For such applications higher density hardwood is more suitable than softwood. Examples of suitable hardwoods for chairs and tables include maple, elm, mahogany, walnut, and oak. Generally, class A wood having basically no knots and visual defects is desired for furniture applications.

Shelves for cupboards, cabinets, drawers and closets may have to bear heavy loads like crockery, tableware, books, etc. Key performance parameter is material strength, but even more so limited deflection under load. Often, an allowable shelf deflection limit of span/240 is used[93]. The required panel board performance then relates to expected maximum load, shelf span, and board thickness. In practice, this means that staying within this shelf deflection limit can be attained by using an appropriate grade of board material (e.g. P7 with very high modulus of elasticity) or by increasing the thickness of the shelf or shortening the length of the shelf. A couple of example calculations (See Annex 3) show that a 25% increase in shelf thickness can reduce the required board quality from P7 (high modulus of elasticity) to P3 (significantly lower modulus of elasticity). For furniture, it is therefore key to obtain a good balance between board grade, thickness/length of the board and the design of the furniture.

5.2.2 Performance of local biobased feedstock for furniture materials

For furniture, mechanical (strength) performance is relevant, though not key. Somewhat lower mechanical properties can be compensated by increasing material thickness (see section 5.2.1 and Annex 3). In principle, particle board strength class P2 is suitable for furniture applications (section 5.1.1.3), meaning that next to wood a couple of feedstocks discussed in section 5.1.2.2.2 are potentially suitable, e.g. hemp shives, cereal straw, reed and the stems from some plants.

More important for furniture is the visual quality of the products. Board materials are often covered with a layer of veneer or plastic sheet, eventually with a print on top. Sawn wood requires grade A or B (see section 5.1.1.2), which may contain a small amount of knots only and no (coloured) core wood.

5.3 Textiles

As discussed in section 2.1.2, constructing a fabric involves several steps. The properties of the selected fibres, yarns, and fabric structure significantly impact the final product's performance characteristics. Figure 16 presents an overview of:

1. Fibre feedstocks, intermediate materials and final products;
2. General and specific conversion processes;
3. Processing parameters;
4. Material properties;
5. Link to product requirements, throughout the textile construction process, from fibres to fabric.

In the following paragraphs, these terms and processes will be explained, detailing how fibres are transformed into fabric and how this transformation is linked to the final product requirements. This will provide a comprehensive understanding of how each stage in the process contributes to the overall properties of the final textile product.

The properties of the fabrics depend on the fibres and yarn properties, spinning type, fabric structure and processing parameters. Some of the most important fabric properties include fabric strength, fabric density, weight, abrasion and pilling resistance, and comfort. The following paragraphs elaborate further on fabric strength, weight and density. Other important fabric properties include abrasion, pilling and comfort

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93 https://www.compositepanel.org/wp-content/uploads/Technical-Bulletin-Particleboard-MDF-for-Shelving.pdf

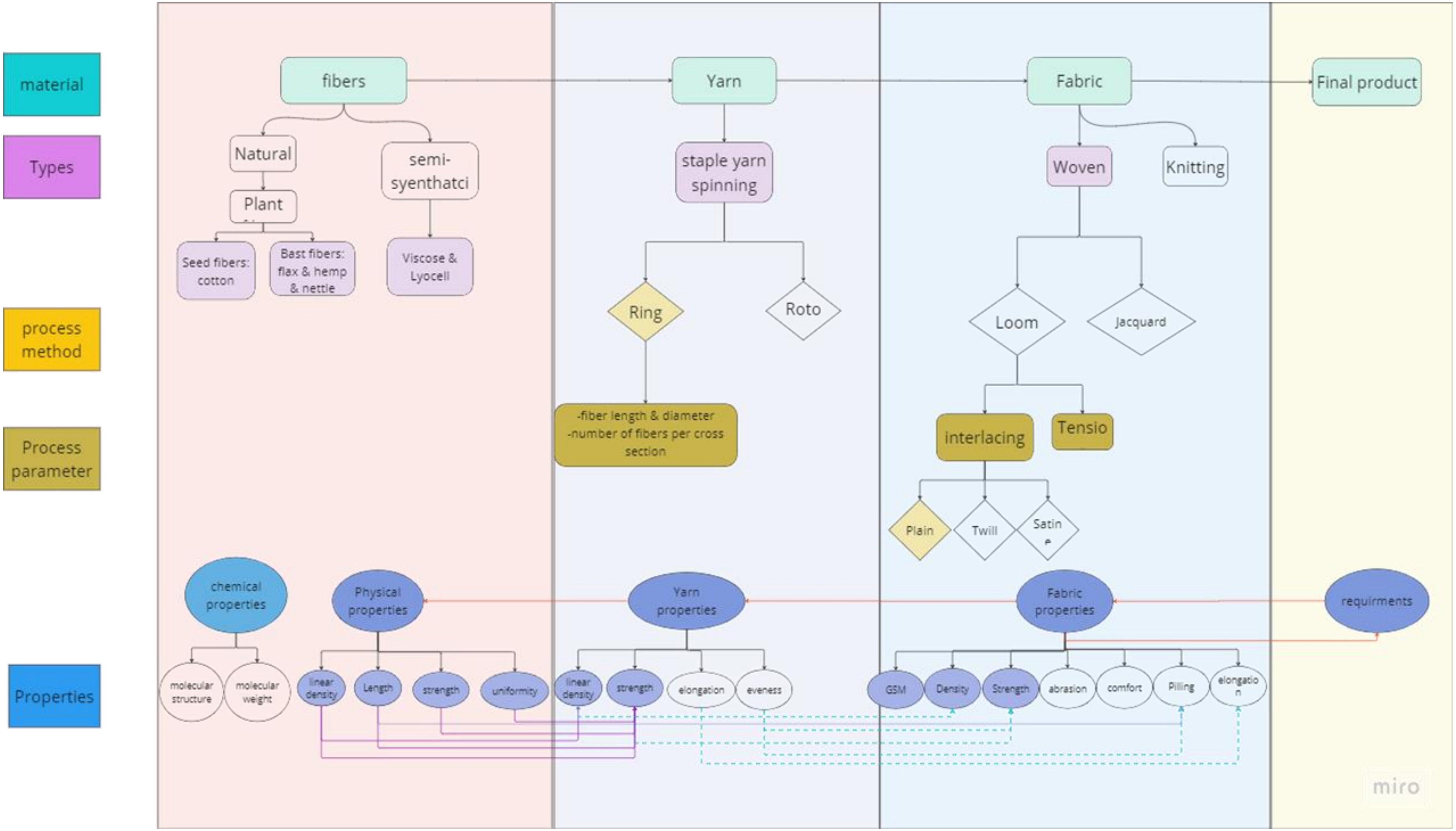

Figure 16   Scheme for conversion of fibres into textile products; indicating most relevant processes and material properties.

5.3.1 Textile quality requirements

5.3.1.1 Fabric strength, general

When it comes to the application of the fabric, either for clothing or any other application, strength is considered as a first property to evaluate. The relevant strength of the fabric can be tensile or bursting strength, depending on the type of the fabric and final application. For woven fabric tensile strength and tear strength are usually measured to determine the fabric strength. Usually, fabric tensile strength is measured according to standard ISO 13934-1 or ISO 13934-2[94].

Fabric strength depends on many factors starting from the used type of fibres (mono fibre or fibre blends), fibre quality, spinning system, number of twists applied to the yarns, twist direction, yarn bending behaviour and yarn count. Also, fabric strength is affected by weaving structure, weaving density, and fabric geometry[95]. Due to these complex relationships, it is challenging to determine the fabric strength theoretically, although it was studied by many researchers[96]. More information about fabric strength and empirical correlation with yarns and fibre properties is provided in Annexes 4 and 5.

5.3.1.2 Fabric weight and density, general

Other important fabric properties are weight and density. Those two properties relate to each other and influence the durability, performance and potential applications of the produced fabric[97]. Fabric weight refers to the mass per unit area. Fabric weight is considered as a key parameter in the market of woven fabric, with light weight being appointed to tops such as blouses and shirts and heavy fabric to bottoms such as trousers and skirts. Usually, textile fabric weight is expressed in grams per square meter. The fabric can be categorised based on its weight into light fabric in the range of 100-170 GSM, medium weight fabric in the rang 170- 340 GSM and heavy fabric in the range of 340-400 GSM and higher[98].

Fabric density is measured by number of yarns per inch or cm. It is well known that the denser the fabric the more durable and resistant to abrasion it will be. On the other hand, less dense fabric or open fabric has better breathability properties. Materials and processing choices such as fibre type, yarn construction and fabric structure, affect the fabric weight and density properties[99]. Annex 5 illustrates the formulas used to calculate fabric weight and fabric density from yarn and fibre properties and processes used.

5.3.1.3 Specific key textile product requirements

For a fabric to be suitable for a specific application it should meet specific requirements. Those requirements relate to the physical properties of the fabric: e.g. weight, strength, elongation[100]. Those physical properties are usually determined by standard tests such as ISO or ASTM which are dedicated to fabrics.

Some properties and requirements are more important for a certain fabric application than others. For example, having a good abrasion resistance for furniture is a crucial requirement however for curtain is it not important. Curtains require high light resistance compared to other home textiles. Further, elongation is not a desired property for furniture (sofa and chair covers), but it is an important property for clothing. Fabric strength is an important property and requirement for all textile products. In the tables below some of the most important physical requirements for clothing textile (Table 23), and for home textile (Table 24) are presented.

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94 Fan, J., & Hunter, L. (2009). Engineering apparel fabrics and garments. Elsevier. P.180
95 Malik, Z. A., Hussain, T., Malik, M. H., & Tanwari, A. (2011). Selection of yarn for the predefined tensile strength of cotton woven fabrics. Fibers and Polymers, 12, 281-287.
96 Pan, N. (1993). Development of a constitutive theory for short fiber yarns part II: mechanics of staple yarn with slippage effect. Textile research journal, 63(9), 504-514.
97 Gandhi, K., & Sondhelm, W S. (2016, January 1). Technical fabric structures – 1. Woven fabrics. Elsevier BV, 63-106. https://doi.org/10.1016/b978-1-78242-458-1.00004-2
98 Understanding Fabric Weights – Core Fabrics (corefabricstore.com)
99 Elmogahzy, Y. (2019). Engineering textiles: Integrating the design and manufacture of textile products. Woodhead Publishing.
100 ecodesign_criteria_for_consumer_textiles.pdf (europa.eu)

Table 23 Minimum requirements for clothing textile fabrics: weight, tensile force and elongation.

Product categories	Fabric weight (gsm)	Tensile Force[101] (N)	Elongation (%)
Jackets	250 - 300[102]	> 200	12.5 - 55
Trousers/ suits	136 - 305[103]	> 250	12.5 - 55
Shirts	100 - 200	> 180	12.5 - 40
Jeans	150 - 370[104]	> 250	12.5 - 55
Dresses	100 - 230	> 180	12.5 - 40
Skirts	100 - 230	> 250	
Swimwear*	180 - 200[105]	> 220	12.5 - 40
Sportswear*	150 - 250[106]	> 250	12.5 - 55
Sleepwear	100 - 350[107]	> 180	12.5 - 40

* Tensile force is the force needed to break the fabric having 50 mm width into 2 pieces, according to ISO 13934-1; the force is expressed in N (Newton). Stress is the force per cross section.
* Important properties of swimwear include to be waterproof, dry fast, and have a high elongation at break (stretch).
* Sportswear should have high elongation at break (stretch).

Table 24 Minimum requirements for home textile fabrics: weight and tensile force.

Product categories	Fabric weight (gsm)	Tensile Force (N)
Curtains*	>150 - 350<[108]	>160
Sheets and pillow covers	>200 - 400<[109]	>180
Blankets	>150 - 600<[110]	>120
Towel	>300 - 900<[111]	>140
Table linen	>75 – 150<[112]	>180
Carpets*	>600[113]	>50
Fabric for sofas and chairs *	>250 – 1000<[114]	>50

* One of the most important properties for a curtain is to have high colour/light fastness.
* Carpets have a complex structure. Their requirements depend on the type of carpet and the material used. This table provides the minimum requirements considering the carpet is made from natural fibres.
* For upholstery fabric (sofas and chairs), other important requirements include flame retardancy and dirt repellence.

[101] ecodesign_criteria_for_consumer_textiles.pdf (europa.eu)
[102] https://www.onlineclothingstudy.com/2018/09/what-is-gsm-in-fabric.html
[103] https://www.fabricsight.com/blogs/posts/suiting-fabrics-top-10-fabrics-for-your-suit-complete-guide and https://www.fabricsight.com/blogs/posts/fabrics-for-trousers-top-10-fabrics-for-your-trousers-complete-guide
[104] Annapoorani, S. G. (2017). Introduction to denim. In *Sustainability in denim* (pp. 1-26). Woodhead Publishing.
[105] High quality printed swimwear fabric choices: What to choose for swimsuit fabrics | maake
[106] What is GSM in Fabric? Sportswear Material Weight Guide (sphere-sports.com)
[107] 7 Common Sleepwear Fabrics: Pros & Cons (jingsourcing.com)
[108] Understanding Fabric Weight in Order to Choose the Right Fabric - Fabric Blog (fabricuk.com)
[109] What Is GSM of Fabric? [Complete Guide] (silverbobbin.com)
[110] Understanding GSM in Bedding: What to Look for When Choosing Quality B (arthcrafted.com)
[111] Understanding GSM in Towels: Your Guide to Buying the Best Bath Towel (flandb.com)
[112] Fabric Weight Guide - Everything You Need to Know (ctnbee.com)
[113] Selecting the Right Carpet - The Carpet and Rug Institute (carpet-rug.org)
[114] GSM is not a quality but the weight | Cotton Monk

5.3.2 Analysis of quality requirements for local biobased textiles

5.3.2.1 From fibre to fabric

Fibre is the essential component to produce textile items. The fibres suited for textile have a length of about 100 times their diameter. Normally, the length of the staple fibres for textile is between 2 – 46 cm (more information about staple fibres in Annex 4 paragraph 4.1). The minimum strength of the fibres that is suitable for textile application is about 6 cN/tex (84 MPa at a density of 1.4 g/cm^3).[115] Fibres for textile can be classified into three categories: natural fibres, regenerated fibres (semi-synthetic) and synthetic fibres. Each category can be further subdivided (Annex 4, paragraph 4.1).

The fibre properties strongly correlate to the properties of the produced fabric. Fibre strength links directly to the molecular weight and orientation of the polymers in the fibre. For example, cotton and flax have a similar degree of polymerization yet flax has higher crystallinity and higher molecular orientation which results in a stronger and stiffer fibre[116]. Fibre diameter has a direct effect of the fabric properties: The larger the fibre diameter, the stiffer the fabric will be; hence the feel of the fabric will be harsher and crisper[117]. Longer fibre may result in a stronger yarn due to the corresponding higher surface friction between the fibres which holds the fibres together[118]. Also, finer fibres will result in a stronger fabric.[119] The table below shows the most important properties of the bast fibres (flax, hemp and nettle), cotton and regenerated fibres (viscose and lyocell).

Table 25 Properties of bast fibres (flax, hemp, nettle), cotton, and regenerated cellulose fibres (viscose and lyocell).

Property	Flax	Hemp	nettle	Cotton	Viscose	Lyocell
Fibre length (mm)	6 - 65[120]	15	48 - 52	9 - 60	40*	40*
Fineness (µm)	~20	~20	30 - 35	10 - 20	10 - 20	10 - 20
Specific gravity (g/cm^3)	1.5	1.5	1.3	1.5	1.5	1.5[121]
Tenacity (cN/tex)	~55	53 - 62	24 - 62	25 - 40	25 - 30	36
Elongation at break (%)	1.8	1.5	2.3 - 2.6	5 - 10	15	14

* Viscose and Lyocell are man-made cellulosic fibres; their length is adaptable, depending on the process and request.

Yarns for textile can be processed either from 'endless fibre' (so called 'filament') or from fibres with a finite length (so called 'staple fibres'). Staple fibres can be given a specific length and diameter by nature such as cotton or wool. Also, staple fibres can be obtained from (cellulosic or synthetic) filaments by cutting to a specific length, and which can be processed into staple yarn. Staple yarns are made by aligning the staple fibres in longitude direction and giving a twist to create a strong yarn that can be applied in a fabric.[122] Yarn properties are affected by the fibre properties and the type of the spinning process. There are different techniques of producing yarns from staple fibres such as ring spinning, rotor spinning, air-jet spinning and friction spinning. Ring spinning is the most common spinning technique with global production share of 70% of staple yarn

[115] https://www.vigotex.com/blogs/fiber-length/fiber-strength-and-fiber-elongation
[116] Elmogahzy, Y. (2019). *Engineering textiles: Integrating the design and manufacture of textile products*. Woodhead Publishing. P. 212.
[117] Fan, J., & Hunter, L. (2009). *Engineering apparel fabrics and garments*. Elsevier.
[118] Sinha, S. K., & Chattopadhyay, R. (2007). A study on spinning limits and yarn properties with progressive change in yarn count in friction spinning. AUTEX Research Journal, 7(1), 1-8.
[119] Zupin, Z., & Dimitrovski, K. (2010). Mechanical properties of fabrics from cotton and biodegradable yarns bamboo, SPF, PLA in weft. *Woven fabric engineering*, 25-46.
[120] Mather, R. R., Wardman, R. H., & Rana, S. (2023). *The chemistry of textile fibres*. Royal Society of chemistry.
[121] Zhang, D. (Ed.). (2014). *Advances in filament yarn spinning of textiles and polymers*. Elsevier.
[122] Wilson, J. (2001). Handbook of Textile Design. Principles, Processes and Practice. Institute of textile Technology. North America.

spinning.[123] Each spinning process has its own specifications and produces yarns with different properties. More information is provided in Annex 4, paragraph 4.2. There is a linear relation between the yarn diameter (so called 'yarn count') and the end application: The thicker the yarn, the stiffer the fabric will be. The figure below shows the relationship between the yarn count and the final application. For each type of application there is a specific range of yarn count that is required to meet the final application requirements.[124]

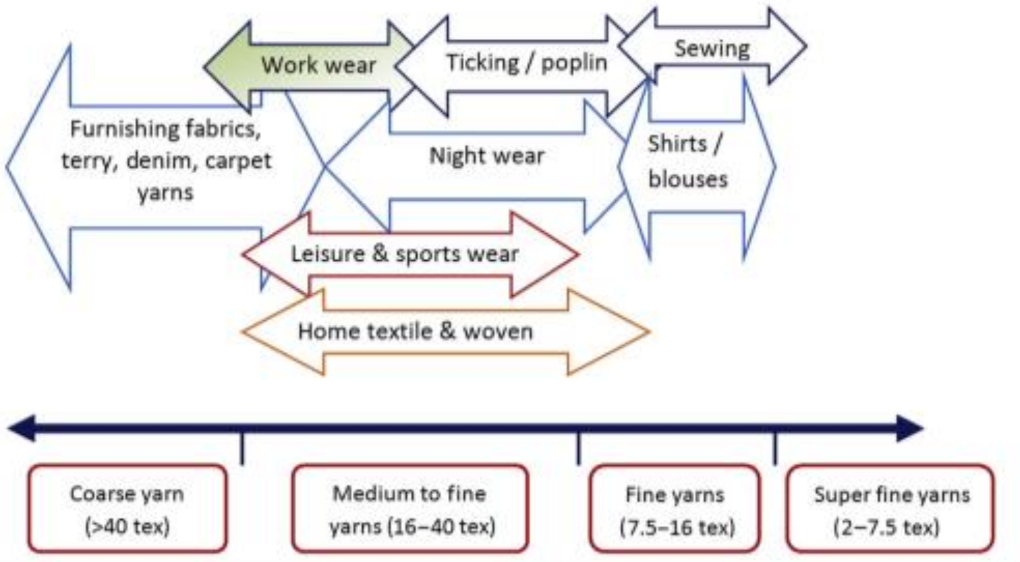

Figure 17 Types of application versus staple spun yarn diameter (copied from Sinclair).[124]

Yarn count and yarn strength is explained is depth in annex 4, paragraph 4.2.1. These properties are directly connected to the specific characteristics of the fibres and can be modelled through theoretical and empirical equations.

Woven fabric is produced by interlacing of two yarns in longitudinal direction (warp) and widthway direction (weft) on a loom machine. Different interlacing in woven fabric results in different weave structures. The three main woven fabric structures are plain, twill and satin[125]. More information about woven fabric structure properties can be found in Annex 4, paragraph 4.3.

The properties of fibres and yarns are intrinsically linked and hence impact fabric properties as well as the final textile products. This goes both ways: The final textile product has specific requirements that should be considered throughout the processing chain: starting from fibre selection, yarn type and spinning process, fabric type, structure and weight, etc.

5.3.2.2 Model for predicting fabric weight and strength

As mentioned previously, to ensure the product requirements are met, many tests should be held on the fibres, yarns and fabric throughout the production process. As the textile processing is complex, including many steps and variations, it is difficult to predict the resulting fabric properties and characteristics. Many researchers tried to predict the fabric outcome starting by using specific fibres, yarns and fabric structure by applying theoretical equations or empirical modelling equations that link fibre properties with ring spun yarn and plain weaved fabric properties.

The models used in this study are based on theoretical (weight) and empirical (strength) equations that were developed for cotton fibres. The equations illustrate the relations between fibres, ring spun yarn properties

[123] Jabbar, A., Palacios-Marín, A. V., Ghanbarzadeh, A., Yang, D., & Tausif, M. (2023). Impact of conventional and modified ring-spun yarn structures on the generation and release of fragmented fibers (microfibers) during abrasive wear and laundering. *Textile research journal*, *93*(5-6), 1099-1112.
[124] Sinclair, R. (Ed.). (2014). Textiles and fashion: materials, design and technology. Elsevier.
[125] Karaduman, N. S., Karaduman, Y., Ozdemir, H., & Ozdemir, G. (2017). Textile reinforced structural composites for advanced applications. *Textiles for advanced applications*, *87*.

and woven plain fabric density, weight, and strength. The theoretical model for weight is described in Annex 5, section 5.1. The empirical equations for strength are derived for cotton and are applied for flax yarns in order to obtain a first estimation of the correlation between such fibres and plain woven fabric.

Fabric weight is calculated by the sum of warp weight and weft weight, equation 12 in appendix 5. To calculate the warp weight and weft, the yarn diameter needs to be known. Yarn diameters determine how many yarns can fit per length unit of fabric weight (equation 10 & 11, appendix 5). The yarn contains fibres in its diameter, the minimum number of fibres in the yarn diameter being 80 for ring spun yarn. Once the fibre count (diameter) is known (equation 7 in appendix 5), the yarn count can be calculated (equation 9 in appendix 5). Knowing the minimum yarn count based on fibres count is important because it shows the range of the possible yarns that can be made from this type of fibre. This determines for which application this yarn can be used. For instance, yarn count above 40 tex is not suitable to make blouses because the fabric will be too stiff to give the required flexibility.

Fabric and yarn strength is more difficult to predict theoretically, as many variations and parameters in the process can affect the strength of the fabric and yarn. Therefore, some empirical formulas were developed based on cotton fibres. To predict the fabric strength in warp and weft direction (equations 16 and 17 in appendix 5), yarn strength in both warp and weft direction needs to be estimated. As in this exercise the same yarn for warp and weft is used, the yarn strength can be calculated based on equation 13 in appendix 5. To estimate the yarn strength, information about fibre strength, fibre diameter and fibre uniformity ratio, bundle elongation and twist factor are required. All fibre properties are measurable using fibre analysing equipment.

Example calculations have been presented for flax fibres to illustrate the models. The same correlations were applied on the following fibres: hemp, cotton, viscose and lyocell, in order to give an indication about the limitations and possibilities of using each fibre for certain application. The table in section 5.4 in Annex 5 shows the link between the properties of fibres, yarns and the fabric based on the adopted equations. In this context, it is important to note the following:

- The calculation is based on 100% mono-fibre. That is not always the case when making a fabric. It is possible to blend different fibre types and to use different percentage to reach the desired fabric properties.
- In this study, the fibres with diameter 35 μm and above are referred to as flax and hemp, and the fibres with lower diameter are referred to as cottonized hemp and cottonized flax. In order to produce a higher yarn count, either coarser fibres or a larger number of fine fibres may be used.
- Yarn count is used the same for warp and weft to construct the fabric. That is not always the case when a fabric is built. It is possible to use different yarn types and different yarn count for warp and weft.
- Fabric density: number of yarns in weft and warp is the same. Also, in both directions (warp and weft) the maximum number of the yarns are assumed, resulting in a dense fabric. It is possible to reduce the number of wrap or weft yarns, or both, which means that a more open and lighter fabric will be obtained, depending on the requirements of the final applications. Further it is also possible to use knitting, which delivers a more open fabric structure compared to weaving.
- The model can be used starting from the fibre, which means that if the properties of the fibres are known, then it is possible to estimate the yarn count and strength and fabric weight and strength.
- The model can also be used reversely: Starting from the fabric weight, it is possible to calculate the minimum yarn count and fibre count. Also, it is possible to calculate the max number of yarns per inch in warp (EPI) and in weft (PPI,) and the weight of warp and weft yarns.

5.3.2.3 Evaluation of suitability of local biobased fibres for textile applications

In the previous section, the correlation between the properties of textile fibres, yarns and fabric has been discussed. In this paragraph, the suitability of different biobased fibres for specific textile applications will be explored. Based on target fabric weight, the minimum yarn counts and subsequently the fibre count are estimated based on the adopted model. The fibre diameter (micron) can then link to suitable biobased fibres: flax, hemp, cottonized flax and hemp, cotton, viscose and Lyocell. In the table below, the following parameters have been listed, from the left to the right:

- Applications columns refer to the type of end-textile (clothing and house) application e.g. shirt, curtains etc.
- Fabric GSM is the minimum fabric weight. In the traditional woven fabric market, fabric weight plays a crucial role as a key parameter, to such extent that fabric weight is a most key requirement. Based on GSM, the target yarn count can be determined based on the equations. Using the model in reverse can be found in Annex 5, section 5.1.
- Minimum yarn count refers to minimum count of the yarn required to produce the specified minimum fabric weight. Once the fabric weight is known, it is possible to determine the minimum yarn count based on the equation 12 in Annex 5. Once the yarn count is known, it is possible to calculate the fibre count.
- Fibre count refers to the diameter of the fibres (micron) required to produce the minimum yarn count. First, fibre count is calculated from the yarn count using equation 9 in Annex 5, considering that the minimum number of the fibres in a yarn should be 80 fibres. Once the fibre count is known, it is possible to calculate the fibre diameter in micron based on equation 7. Alternatively, in order to produce a minimum yarn count, also a larger number of finer fibres may be used.
- Suitable local fibre to meet required GSM refers to the biobased fibres considered in this report which match the calculated fibre count based on the fabric weight. This column highlights the suitable fibres which can be locally produced (flax, hemp, cottonized flax and hemp, viscose and lyocell). Fibre properties can be found in the table in section 5.4 of Annex 5.
- Options for local fibres optimal processing and properties refers to the possible blend options. In textiles, blends of fibres are often essential as each fibre type has unique properties that may contribute to help balance quality and price.

Table 26 Deducting the yarn count, fibre count and fibre type from fabric weight (GSM): Aligning clothing textile requirements with local biobased fibre types.

Applications	Fabric GSM requirement	Minimum yarn count (tex)	Fibre count calculated * (micron)	Suitable biobased fibre to meet required GSM	Options for local fibres – Optimal processing and properties
Shirt- blouses	100	15.2	12.7	Viscose* Lyocell*	Blends of viscose/lyocell Blends of cottonized flax or hemp (~20%) with viscose or lyocell (~80%)
Shirt- blouses	150	34	19	Viscose Lyocell	blends with (~20-30%) cottonized flax &hemp
Night wear, jackets, suits, jeans, Dresses, skirts	200	60	25	Cottonized hemp Cottonized flax Viscose Lyocell	(50/50) Blends of cottonized hemp/cottonized flax/viscose/lyocell 80%Blend of cottonized hemp/cottonized flax/viscose/lyocell with ~20% of flax and hemp
Jackets, Trousers, suits, jeans	250	95	32	Cottonized hemp Cottonized flax Viscose Lyocell	(50/50) Blends of cottonized hemp/cottonized flax/viscose/lyocell 70-80% of cottonized hemp/cottonized flax/viscose/lyocell with 20-30% of flax and hemp
Jacket, suits, jeans	300	136	38	Cottonized hemp, Cottonized flax Flax Hemp Viscose Lyocell	Mono fibre suffices; Any blend with different percentages

* Based on indicated fabric weight (gsm) and 80 fibres per yarn cross section. The same yarn count may be achieved by using larger number of finer fibres as well.

Table 27 Deducting the yarn count, fibre count and fibre type from fabric weight (GSM): Aligning home textile requirements with local biobased fibre types.

Applications	Fabric GSM	Mini yarn count (tex)	Fibre count calculated * (micron)	Suitable fibre from the studied local fibre	Options for local fibres – Optimal processing and properties

table linen	100	15.2	12.7	Viscose* Lyocell*	80% Blends of viscose/lyocell with 20% cottonized flax or hemp
table linen	150	34	19	Viscose Lyocell	70-80% Blends viscose or lyocell with ~20-30% cottonized flax &hemp
Curtains, sheets and pillow cover	200	60	25	Cottonized hemp Cottonized flax Viscose Lyocell	(50/50) Blends of cottonized hemp/cottonized flax/viscose/lyocell; 80% blends of cottonized hemp/cottonized flax/viscose/lyocell ~20% of flax and hemp
Curtains, sheets and pillow cover	250	95	32	Cottonized hemp Cottonized flax Viscose Lyocell	(50/50) Blends of cottonized hemp/cottonized flax/viscose/lyocell; 70-80% of cottonized hemp/cottonized flax/ viscose/lyocell with 20-30% of flax and hemp
Curtains, sheets and pillow cover, towel	300	136	38	Cottonized hemp Cottonized flax Flax Hemp Viscose Lyocell	Mono fibre suffices; Any blend with different percentages
Curtains, blanket, towel	350	185	44	Cottonized hemp, Cottonized flax Flax Hemp Viscose Lyocell	Mono fibre suffices; Any blend with different percentages
Towel, fabric for sofa or chair	400	242	51	Cottonized hemp, Cottonized flax Flax Hemp Viscose Lyocell	Mono fibre suffices; Any blend with different percentages

* Based on indicated fabric weight (gsm) and 80 fibres per yarn cross section. The same yarn count may be achieved by using larger number of finer fibres as well.

Looking at the weight of different clothing products and the indicative fibre count calculated in this study, the following may be concluded:

T-shirt, shirts, blouses, dresses and skirts are considered as light-medium weight clothing items. Of the (semi)natural fibres, fine fibres such as cotton, lyocell and viscose are most commonly used for these applications[126]. Hemp and flax are more stiff naturally, and as such are less suitable for these applications. By doing some chemical treatments, through a so-called cottonization process, those fibres will become more like cotton fibres. Cottonization of bast fibres facilitates blend yarn processing and which allows to improve the fabric handle and feel quality compared to non-cottonized fibres[127]. The diameter (Micronaire) of cottonized hemp fibres is between 13-16 μm[128], which is in the same range of cotton diameter. Therefore, it is possible to partly (~20-30%) replace cotton fibres with cottonized hemp and flax for the mentioned clothing types. The main drawback of cottonized hemp and flax remains that it is still stiffer than cotton fibres. Yarns with diameters ranging from 11 to 74 tex[129] (from fine to coarse) can be produced using cottonized hemp and flax, depending on the blend ratio. This versatility makes them suitable for a wide range of fabrics, from lightweight materials like blouses to medium-weight fabrics such as jeans.

Jackets, suits and jeans are considered a medium-heavy clothing item. All fibre types are suitable to make jackets and jeans (denim). Cotton is normally used as a raw material to make denim by ring or open-end spinning and twill weaving.[130] Blends of cottonized hemp and flax are also an option to be used in jeans. It is also suggested that cotton/flax blend provides a good combination to be used in denim (jeans) due to the desired properties of both fibres such as cooling, strength etc. Much effort has been done to develop flax and hemp fibres to make them more desired in textile clothing[131]. It is possible to blend flax and hemp with cottonized flax/hemp, viscose and lyocell to produce fabric that can be applied for clothing and home textiles. For example, a ring spun yarn of flax/viscose/cotton is produced with count of 31 tex, strength 10 cN/tex and

126 https://www.gentelle.com/what-is-gsm-in-fabrics
127 Kozłowski, R., & Mackiewicz-Talarczyk, M. (Eds.). (2012). *Handbook of natural fibers* (pp. 11-23). Woodhead Pub. P.153-154.
128 https://marmarahemp.com ; https://dnfi.org/flax-fibers
129 https://en.procotex.com/cottonized-flax
130 Annapoorani, S. G. (2017). Introduction to denim. In *Sustainability in denim* (pp. 1-26). Woodhead Publishing.
131 Elmogahzy, Y. (2019). Engineering textiles: Integrating the design and manufacture of textile products. Woodhead Publishing. P.323-328.

elongation 5%[132]. Such properties are ideal for a variety of applications such as jeans, jackets, curtains, etc. Further, fabric from hemp with weights of 270-540 gsm have been produced[133]. For clothing this means it can be applied for medium-heavy weight fabric such as jackets and jeans. Therefore, based on the estimations, it is possible to fully (100%) replace cotton with cottonized flax, cottonized hemp, flax and hemp fibres for the mentioned clothing type. Nonetheless, the stiffness and comfort should also be tested. In general, clothing can be made from light or heavy fabric, depending on the many factors such as the exact end-use, comfort, etc.

Looking at home textiles, it is also possible to use all type of the fibres covered in this study. However, certain properties should be taken into account. For example, towel should be soft on the skin, curtains should have colour stability and fabric for chairs should have high strength and abrasion resistance. Further, for home textiles, it is possible to use (cottonized and non-cottonized) flax and hemp intensively for light to heavy fabric as those fibres can provide the required strength as well. For all the studied home textile, it is possible to fully (100%) replace cotton with cottonized flax, cottonized hemp, flax, hemp, regenerated cellulose and their blends.

In home textiles synthetic fibres play an important role. To show the potential of replacing synthetic fibres for more local biobased fibres, many studies covered this topic. For example, a group of researchers developed a blend of cotton/hemp to be used in upholstery to shift toward ecofriendly materials. The researchers developed three different fabric structures and studied their properties. The results show that the cotton/hemp fabrics are suitable to be used in upholstery because their breaking strength (22.6 kg) matches the fabric standard given by ASTM. Further, the fabric shows a good abrasion resistance[134].

Since textile processing involves numerous steps and machinery, actually constructing the fabric is essential to evaluate its true characteristics. By exploring various factors such as yarn count, yarn strength, fabric density, fabric strength, and comfort, one can determine the most suitable fabric for a specific application.

5.3.2.4 The potential of local biobased fibres for textile applications

Based on the outcomes described above, it is possible to draw some general conclusions regarding the potential for local biobased fibres as an alternative to non-local biobased fibres (cotton) and fossil fibres (e.g. polyester). Market shares mentioned below are based on Textile Exchange [135].

Flax fibres can be used as mono fibre or blends for both clothing and home textiles. 100% flax results in a heavy fabric which is suitable for home textiles such as covers for chair/sofa or heavy clothing such as jackets. To produce medium to light weight fabric, flax should be cottonized and blended with other fibres or use open fabric structure such us open weaving or knitting. Open fabric allows using lower number of yarns per cm, hence lighter fabric for specific yarn count. Flax is used currently in textile industry in different application such as bed linen, trousers, composite etc with a world market share in fibres of 0.3%.

Hemp can be somewhat compared to flax and can be used as mono fibre or blend in clothing and home textiles. Similar to flax, 100% hemp fabric is a heavy and stiff fabric, which is suitable for applications such as furniture, curtains or jackets. To produced medium to light weight fabric, a blend with other fibres is required or hemp is to be cottonized. The market share of hemp fibre is 0.2%. To expand the market share of flax and hemp, it is essential to implement various developments in processing hemp fibres to obtain the desired properties and invest in developing machines to process hemp fibres more efficiently and foster collaboration among stakeholders.

Cotton is used for clothing and home textiles. Cotton is easily processed, has the desired comfort and physical properties. Cotton is the mostly used natural fibre and the second mostly used fibres in textile after polyester. The market share of cotton fibre in textile industry is 24,7%. As shown in this study, on fabric weight basis it is possible to obtain a local alternative for cotton (which is not locally available in Western Europe) with viscose, lyocell and partly with cottonized hemp and flax for light-medium fabric weight such as shirts, blouses and pillow covers. Further, it is possible to obtain a local alternative to cotton with other biobased fibres and their blends for medium-heavy fabric as shown in the previous two tables, right two columns. However, fully

[132] Kozlowski, R. M., & Mackiewicz-Talarczyk, M. (Eds.). (2020). Handbook of natural fibers: volume 1: types, properties and factors affecting breeding and cultivation. Woodhead Publishing. P.82-92.
[133] Kozłowski, R., & Mackiewicz-Talarczyk, M. (Eds.). (2012). *Handbook of natural fibers* (pp. 11-23). Woodhead Pub.. P.153.
[134] Singh, A., Gahlot, M., & Negi, M. (2016). A sustainable and potential alternative to commercial household upholstery: hemp–cotton union fabric. *Eco Env Cons*, 22, 373-378.
[135] Textile Exchange, Materials Market Report, September 2024

replacing cotton with viscose, lyocell, cottonized flax or hemp, flax and hemp will alter the fabric's mechanical properties, such as elongation, as well as its comfort properties like feel and softness. Therefore, it is crucial to test the developed fabric to accurately determine its actual properties.

Viscose and lyocell both are regenerated cellulosic fibres. Both fibres can be applied as mono fibre or blends in clothing and home textiles. Both have good physical and comfort properties, and therefore they are desired to be used for clothing such as blouses, dresses, suits. The world market share of viscose fibres is 6,3% and lyocell fibre is 0.4%. Both can be applied more in textile application and – in order to come to textiles based on locally available fibres - can replace the cotton on fabric weight basis. Nonetheless, fibre the durability of viscose and lyocell fabric is lower than cotton fabric hence the viscose fabric will have a shorter life span compared to cotton fabric.

As discussed, (ligno)cellulosic fibres can be used in many textile applications. However, various household and personal items may be less feasible to be made with (ligno)cellulosic fibres. For instance, swimwear or carpets require good water and dirt repellence, which is typically a property of more hydrophobic fibres such as polyester (fossil-based fibres)[136,137]. However, it must be noted that also Lyocell is applied in swimwear currently. When it comes to creating water and dirt repellent fabrics, the use of synthetic fibres is a common approach. These synthetic materials can be engineered to have hydrophobic properties, allowing them to effectively repel water and resist the absorption of dirt and other contaminants[138,139].

To shift from using those synthetic fossil-based fibres such as polyester, many researchers worked on developing biobased alternatives fibre which have similar properties in terms of hydrophobicity, durability and controlling the fibres diameter. An example is biobased polyesters which could be applied in different type of garments instead of the conventional fossil-based polyester[140]. The adoption of bio-based polyester in the textile industry has been slow, with only 1% of all synthetic fibres. This is due in part to the additional cost and technical challenges associated with the production and processing of bio-based polyester.

5.4 Summary

In this chapter, the qualitative performance of biobased building, textile and furniture materials has been evaluated against existing performance requirements.

Wood is an existing biobased material with a long history of application in construction and furniture. Softwood (light, fast-growing, visually less attractive) is most commonly used for construction and there are several species (which are common as a constructive building material in TFC or CLT-construction. Spruce, but also Scots pine, larch and Douglas fir are all common species to deliver C18 or C24 strength class needed to be applied in TFC or CLT construction. At the same time it should be mentioned that trees in the Netherlands often are not grown for production, while management for production of solid wood products is required to make them suitable for construction purposes. Hardwood (heavier, slow growing, visually attractive) is most common for furniture production. Visual quality is more important than strength in furniture, since any shortcomings in the strength can be solved in the design (e.g. thicker planks).

For board production, in principle, all strength classes (P1-P7) can be attained using a broad variety of wood species. For boards made from fibre crops or side-streams, many of the boards currently meet only P2- or P3 quality. This is mainly due because of thickness swelling, which is (considerably) higher than the standard in almost all cases, and most probably the result of not using moisture repelling agents in the scientific studies.

[136] Pellis, A., Acero, E H., Gardossi, L., Ferrario, V., & Guebitz, G M. (2016, February 24). Renewable building blocks for sustainable polyesters: new biotechnological routes for greener plastics. Wiley, 65(8), 861-871. https://doi.org/10.1002/pi.5087
[137] Perin, D., Rigotti, D., Fredi, G., Papageorgiou, G Z., Bikiaris, D N., & Dorigato, A. (2021, May 7). Innovative Bio-based Poly(Lactic Acid)/Poly(Alkylene Furanoate)s Fiber Blends for Sustainable Textile Applications. Springer Science+Business Media, 29(12), 3948-3963. https://doi.org/10.1007/s10924-021-02161-y
[138] Loghin, C., Ciobanu, L., Ionesi, S D., Loghin, E., & Cristian, I. (2018, January 1). Introduction to waterproof and water repellent textiles. Elsevier BV, 3-24. https://doi.org/10.1016/b978-0-08-101212-3.00001-0
[139] Davies, A J. (2018, January 1). Performance evaluation and testing of water repellent textiles. Elsevier BV, 347-366. https://doi.org/10.1016/b978-0-08-101212-3.00012-5
[140] Jönsson, C., Wei, R., Biundo, A., Landberg, J., Bour, L S., Pezzotti, F., Toca, A., Jacques, L M., Bornscheuer, U T., & Syrén, P. (2021, February 12). Biocatalysis in the Recycling Landscape for Synthetic Polymers and Plastics towards Circular Textiles. Wiley, 14(19), 4028-4040. https://doi.org/10.1002/cssc.202002666

Compared to fossil references, biobased insulation blankets of a variety of fibre types show a thermal conductivity very similar to glass wool and rockwool, even though their average density is higher than glass wool and lower than rock wool. Most of the insulation panels show a higher conductivity, whereas for blow-in cellulose, sheep wool and wood fibre perform similar to glass wool and rock wool. EPS and especially PIR-PUR have a significantly lower conductivity.

For textiles, it was more challenging to validate the performance of mixtures of local fibres (mainly: bast fibres from flax and hemp and viscose/Lyocell). Empirical equations were used to describe the correlation between fibre properties and the final fabric characteristics. Based on this modelling and literature references, it was found that regarding fabric weight and strength, viscose/lyocell and bast fibres can in principle be sufficient to produce well-performing textiles. Particularly the cottonization of hemp and flax fibre promise to play an important role in expanding the potential properties of local fibres and mimic the properties of cotton (which is not a locally available fibre). For specific properties like hydrophobicity and durability some synthetic (biobased) fibres may still be required.

6 Land use of local biobased materials

This chapter presents calculations for the land use footprint required to meet the basic material needs of a household with locally available biobased feedstock for building materials, furniture and textiles.

6.1 Building materials

In section 2.2.1.3, the volumes of building materials required for 'average' Dutch housing have been presented. Based on the conversion yield factors for the conversion of biomass into products (ton product/ton biomass) in chapter 4 (4.1 for wood based products; 4.2.1 for hemp insulation), and based on the crop/tree production yields (ton/ha.a) in sections 3.1.1 for spruce and 3.2.3 for hemp, the land-use per material can be calculated. These values are presented in the table below. The following assumptions apply to the table:

- Sawn wood, CLT and Glulam are produced using coniferous tree species using the average annual growth rate for the selected coniferous species in this study (described in chapter 5). This means that the number of hectares mentioned in the table is not the number of hectares which should be fully harvested to obtain the required amount of material. It is rather the number of hectares of standing forest of which the annual additional growth produces the required amount of material. In practice, only 80% of this additional growth is harvested to make sure that the forest's biomass keeps growing. This percentage is also applied in the land-use calculations.
- The chips which become available as a side-stream during production of sawn wood, CLT and Glulam are sufficient to cover the OSB and particle board use in these buildings. In these cases, a value of zero hectares of additional land use is assumed, compared to the land which is already used for the sawn wood/CLT/Glulam production.
- Insulation is produced with hemp bast fibres and the hectares presented in the table therefore refer to the number of hectares of hemp grown to produce the required amount of bast fibres for the insulation.

Table 28 Material and land use results and assumptions for an 'average newly built house in NL'.

Type of building	Unit	Sawn wood	CLT	Glulam	OSB	Particle board	Insulation
Material use per average newly built building in NL (based on table 7)	m^3	8.42	9.06	2.27	2.05	1.96	46.4
Average yield biomass source	m^3/ha	8.5 (average yield selected softwood species)					8 (hemp)
Conversion factor from harvested feedstock to product		40%*	33%*	33%*	26%*	26%*	21%**
Harvest factor of annual growth (forest) or annual yield (hemp)		80%	80%	80%	80%	80%	100%
Land use footprint of average newly built building in NL	ha	3.1	3.9	1.0	0***	0***	1.5

*Based on chapter 4.1. It is assumed that OSB is produced with saw residues (chips) and not by shredding the whole log.
**Based on combined conversion factors from biomass to insulation mat (90%*100%*25%*95%) figure 10 in chapter 4. Specific density insulation mat of 0.055 ton/m^3.
*** the 8 ha of wood production required to supply sawn wood, CLT and Glulam, produces 8 ha * 8.5 m^3/ha * 80% harvest factor * 26% conversion factor = 14.1 m^3 of particle board/OSB compared to the 4 m^3 which is required for the average building.

By applying the same calculation approach, the land use footprints for various types of buildings can be calculated. These results are presented in table 29 below.

Table 29 Land use per material for main biobased building materials and types of buildings.

Type of building	Sawn wood (ha)	CLT (ha)	Glulam (ha)	OSB (ha)	Particle board (ha)	Insulation (ha)	Total (ha/house)
Apartment flat > 30 m	-	21.8	-	0*	-	0.6	22.4
Apartment flat < 30 m	0.9	-	5.4	0*	0*	0.8	7.2
Ground level houses (terraced and 2/1 roof)	4.6	-	-	0*	0*	1.9	6.5
Average of newly built buildings in NL	3.1	3.9	1.0	0*	0*	1.5	9.5

* No additional land-use. Strands/chips/particles can be obtained as a side-stream from the same surface area of forest from which the sawn wood/CLT production have been obtained.

From the table above, the following can be concluded:

- High-rise buildings are built using a lot of CLT in order to provide sufficient strength and stability. This is because these buildings require at least a so-called core which is built out of massive wood in order to replace concrete. In addition, it is also common practice to use CLT in (bearing) walls and floors in wooden high-rise buildings. Because of the high amount of CLT applied, the land-use for high-rise buildings beyond 30 meters is also relatively high (22.4 hectares).
- Ground-level houses are the most land-use efficient houses (6.5 hectares), because they can be built using wood-efficient timber frame constructions and require little additional wood compared to high-rise buildings beyond 30 meters.
- The relatively high wood intensity of the average newly built houses – particularly caused by high CLT use in high-rise buildings beyond 30 m – results in a excess amount of wood chips (14 m^3) which are enough to cover the OSB and particle board (combined 4 m^3). Potentially it could even cover part of the insulation, but due to compression (14 m^3 of chips will result in a lower volume of board) when pressing the boards it is assumed that it only covers the board material.

Currently, there are 8.4 million households (houses) in the Netherlands[141]. In practice (see section 2.2.1.1), approximately 60,000 houses a year are built in the Netherlands. In addition, between 6,000 and 16,000 houses are demolished and replaced[142], which corresponds to an annual average 11,000 houses. So, the total amount of houses which are built in the Netherlands corresponds to about 70,000 houses a year. To produce these houses with biobased materials, this would require (70,000 houses * 9.5 ha/house) 665,000 hectares of forest and hemp (31% of Dutch agricultural land and forest area combined).

It is possible to lower this footprint, if the 70,000 houses/year could be built only in low-rise buildings, the required surface area would be (70,000 houses * 6.5 ha/house) 455,000 hectares of forest and hemp (approx. 21% of Dutch agricultural and forest area). Further, if the amount of 70,000 houses would be built in compact material-efficient terraced houses only, then 300,000 hectares of forest and hemp (1/7th of Dutch agricultural and forest area) may be possible. It must be noted however that there is a certain trade-off between the space needed to build the buildings (which for high-rise building is obviously low) and the space required to grow the biomass for the building materials applied in the building.

6.2 Textiles

For textiles, the annual textile consumption has been presented in section 2.2.2 and amounts to 15 kg per person. For the Dutch situation (2.1 person per household), this would amount to 31.5 kg of textiles per year per household and to 264 kton for all 8.4 million Dutch households.

It is not possible to determine an exact fibre composition for the textile products. In section 5.3.2.3, it was shown that with (cottonized) hemp, flax and viscose/Lyocell it is possible to produce a broad range of textile

141 https://www.cbs.nl/nl-nl/visualisaties/dashboard-bevolking/woonsituatie/huishoudens-nu
142 https://aedes.nl/media/document/handreiking-renoveren-sloop-oplegger-aedes-oktober-2023#:~:text=Sinds%202001%20zijn%20jaarlijks%20tussen%20de%206.000%20en%2016.000%20woningen%20gesloopt.

products for clothing and home textiles when only considering these fibres on the potential GSM they could deliver in the fabric. As such, in order to calculate the footprint of Dutch textile demand using local fibres, it is assumed that half of it is produced using hemp or flax and the other half is produced using regenerated fibre (viscose/lyocell). Hemp or flax will have a similar land footprint. The slightly higher yield for hemp will be offset by a higher share of long fibres in flax.

Table 30 Land use for the 31.5 kg average biobased textile use per household per year, assuming that all fibres can be biobased, and an equal distribution over regenerated cellulose fibre and hemp/flax fibre.

Allocation over local fibres available	Biomass yield	Conversion factor	Footprint of respective share (ha)
15.75 kg Regenerated cellulose from hardwood	7.6 m^3/ha* 5 ton/ha*	14%**	0.015
15.75 kg Hemp or flax	8 ton/ha	13.1%***	0.018
Total land use footprint for textiles per household			0.033

* Average productivity hardwood species selected in chapter 3.
** Based on figure 14, cellulose content of 45% and conversion factors: 80% cellulose yield, 80% dissolution yield, 50% fibre to fabric conversion. A harvest factor of 80% is applied to ensure that the forest net growth is maintained.
*** Based on figure 11 and an average conversion factor from fibre to product of 68%. Low and middle tex conversion efficiency: 2* (90%*100%*11%* 38%*68%)=5.1%. High tex conversion efficiency of 90%*100%*13%*68%=8%. Total: 5.1 + 8% = 13.1%. For each fraction, the percentages apply to retting, baling, scutching, hackling and spinning, respectively.

Taking into account the respective footprints of the different fibre categories, an average footprint of 0.033 ha per household per year is calculated. Based on this footprint, the total textile demand by 8.4 million households in the Netherlands would require 280,000 hectares (about 13% of combined Dutch agricultural and forest area).

Wool is also an obvious candidate for locally sourced fibres, even though the quality of Dutch wool is not optimized anymore (too course) for textile production, in principle sheep with good textile wool may flourish in the Netherlands. Even though wool is not in scope of this study, it is valuable to put the productivity of wool in perspective to that of bast fibre crops and wood. Taking an average density of 10-15 sheep per hectare[143] and an annual productivity of 3 kg of wool per sheep[144] results in up to 45 kg of wool per hectare. This is a factor of 100 till 160 less than the productivity of hardwood and hemp respectively. This effectively positions wool not as a main fibre for locally produced textiles; nevertheless due to its unique properties (insulation, breathability, moisture wicking, odour resistance and durability) wool is a very important fibre for applications which require these properties (e.g. thermo sports wear) or to add these properties to fabrics made of other fibres.

143 https://edepot.wur.nl/545887
144 Handboek Schapenhouderij (2002), ISSN 0169-3689

6.3 Furniture

For furniture, the main material needs are for upholstery (textile), sawn wood (mostly hardwoods) and board material (MDF, particle board, hardboard). Based on the material use presented in section 2.2.2 and the conversion efficiencies presented in chapter 4, the associated footprints can be calculated.

Table 31 Land use for the average biobased furniture use per household, assuming an equal distribution over regenerated cellulose fibre and hemp/flax fibre for upholstery.

Furniture material use per household (based on table 8)	Sawn wood	Board	Upholstery	Total
Average material use (m^3)	1.02	1.56	8.26 (kg)	10.81
Average yield hardwood (m^3/ha)	7.6	7.6		
Conversion factor from harvested hardwood to product	37%	19%/62%*	13.5%**	
Harvest factor of annual growth (forest) or annual yield (hemp)	80%	80%		
Land use footprint of furniture in NL	0.455	0.357	0.009	0.82

* Production of board first from side-stream of sawn wood (chips, conversion efficiency 19% from harvested hardwood) and the rest from dedicated trees for board production (conversion efficiency 62%)
** Assuming a 50/50 blend of regenerated cellulose and hemp, and considering a land use intensity of 0.033 ha for 31.5 kg of textiles per household, 8.26/31.5 * 0.033 results in 0.009 ha for upholstery per household.

Considering a 10 years lifetime for furniture, 10% of the 8.4 million Dutch households renew their furniture each year. This means that about 840,000 households x 0.82 ha/household = 690,000 hectares are needed. This is the equivalent of about 32% of the combined Dutch agricultural and forest area.

6.4 Opportunities to reduce land footprint through re-use and recycling

Given the high land-use footprints of local biobased production as estimated in the previous section, it is interesting to assess what re-use and recycling could contribute to the feasibility of local biobased production.

6.4.1 Building materials

For building materials, re-use or recycling of materials after demolition is already taking place. In a recent study for the Netherlands[145], new end-of-life values for building materials have been determined based on an assessment of current demolition practices. It was found that most building materials (beams, planks, frames, doors, boards) are re-used, recycled or re-manufactured for about 40 – 50%. This rate is only expected to increase for new buildings, as demountability of structures becomes increasingly important in (biobased) construction and is part of recent guidelines on sustainable construction, like for example 'het nieuwe normaal'[146], and confirmed by already much higher actual reuse/recycling rates achieved by circular demolition contractors.[145] Taking into account the land footprint of 455,000 ha (of which 2/3 is allocated to wood production) for the annual construction of 70,000 low-rise buildings, a recycling rate of 50% for timber based building demolition materials would reduce the land footprint to 300,000 ha.

[145] van den Oever, M., Weterings, H., & de Munck, E. (2024). Bio-based building products in the Dutch Environmental Database (NMD): Part 2: Proposal for updated end-of-life lump-sum values for wood based products. (Rapport /Wageningen Food & Biobased Research; No. 2582). Wageningen Food & Biobased Research. https://doi.org/10.18174/672247
[146] https://www.hetnieuwenormaal.nl/leidraden/infra/standaard/losmaakbaarheid/

6.4.2 Furniture

For furniture, recycling rates are low. According to European Federation of Furniture Manufacturers statistics, 80% to 90% of the EU furniture ends as waste in MSW and is incinerated or sent to landfill, while ~10% is recycled[147]. This may relate to the diverse nature of wood types and design forms used in furniture. To increase recycling rates for furniture, material passports and quick scanning technologies may be developed. In the Netherlands, there is increasing attention for circular furniture. For wood, the WoodLoop value chain collaboration was set up, which mainly focuses on recycling wood during furniture production, which is the equivalent of 20% of the wood used in furniture production[148]. Such a recycling rate could potentially decrease the land footprint for furniture from 690,000 to 550,000 ha.

6.4.3 Textiles

Currently, an important barrier to textile recycling is the diverse composition of textiles. Particularly the large scale blending of cotton with polyester or Elastane fibres makes it difficult to separate cotton (or another natural fibre like flax or hemp in a future local system) for recycling. An attractive garment for cotton recycling are jeans, which are made almost entirely out of cotton. A frontrunner in jeans recycling – Mud Jeans – currently uses 40% post-consumer recycled cotton in its jeans, which is one of the highest percentages in the industry[149]. Their long-term goal is 100%, however, this can never apply to the entire sector as (cotton) fibres degrade during subsequent processing and use stages. Cotton from jeans are also the model feedstock for Metisse in the production of biobased insulation[150]. In this way, there are two potential recycling loops in the textile system:

- First, recycling as a garment for at least 40%, based on Mud Jeans practice as the new standard. This route is only possible to garments which mainly consist of cotton. Assuming 1/3rd of the textiles would have the right composition and be recycled for 40%, this would reduce the land footprint for textiles (280,000 ha*1/3*40%) with 37,000 ha to 243,000 ha. An alternative for mechanical recycling would be the SaXcell process which would result in a regenerated cellulose fibre.
- Secondly, recycling of discarded garments towards insulation. In the Netherlands, 305,000 tons of household textiles are discarded every year[151], which is in the same order of magnitude as our calculation of 264 kton of textile consumption in 6.2. The vast majority of these discarded textiles are currently incinerated (with energy recovery). Especially (long) cotton fibres, but in principle also other natural textile fibres, are very suitable and applied at small scale for producing insulation blankets. This route is in principle suitable for cotton-polyester blends as it is the polyester which is used as a binder in the insulation mat, even though the average share of polyester in textile waste is 50% and insulation mats only require 10-20%[152]. If we assume that 50% of the discarded textile volume is in fact suitable for making insulation, this would result in (305,000 ton * 50% suitable * 40% recycling rate) / 70,000 houses is 871 kg or 15 m^3 of insulation per house. This could reduce the land footprint for hemp by 0.9 ha (50%) or the total land footprint for low-rise buildings by 16%.

6.5 Summary and perspective for local biobased production

In this chapter, the material needs for biobased building materials, textiles and furniture have been recalculated into land use footprints per house and household, and for the Dutch society as a whole. The total land use footprints are presented in the table below.

147 CIRCULAR ECONOMY OPPORTUNITIES IN THE FURNITURE SECTOR, European Environmental Bureau, Brussels, 2017
148 https://www.wood-loop.nl/
149 https://mudjeans.com/nl/pages/duurzame-materialen-mud-jeans?srsltid=AfmBOooJBd155oQ1pXGXavshPOhDGsvIg1eCaK2MJso95FX3Xv_7DHoy
150 https://www.fibers-foams.nl/producten/metisse-katoen-isolatie
151 https://recyclingnederland.nl/artikelen/textielrecycling-in-nederland/
152 WFBR expert estimate

Table 32 ***Overview of land footprints for the production of biobased building material, textile and furniture for the Dutch situation, including recycling.***

	Building	Textiles	Furniture	Total
Area required, no recycling (ha)	455,000	280,000	690,000	1,425,000
Saving by recycling within sector (ha)	155,000	37,000	140,000	332,000
Saving by intersectoral recycling (textile – building) (ha)	73,000			73,000
Area required, incl recycling (ha)	227,000	243,000	550,000	1,020,000

Without recycling, the total required land footprint for material self-sufficiency amounts to 1.4 Mha, which corresponds to 66% of the combined Dutch agricultural and forest area. It would not be realistic to assume that current food production would be replaced entirely by forests and fibre crops in order for the Netherlands to become self-sufficient in housing, textile and furniture production. Besides the required land area, another challenge is the fact that the forests required to produce the biomass are currently not present in the Netherlands and take at least 60-80 years to grow. A long term perspective would be needed in order to grow a forest which could provide a critical value of wood biomass needed to attain some degree of local biobased material production for the construction of houses and household items, excluding paper, boxes, pallets, etc.

Due to this long horizon, it is safe to assume that in this period more circular practices will become available in each of the sectors studied. The impact of recycling on land use can be significant as is shown by the table above and can reduce land-use by 405,000 ha to 1 Mha in total for all material needs, which corresponds to 47% of the combined Dutch agricultural and forest area. This is still significant and challenging for large-scale implementation in the Netherlands as a whole. The perspective for local biobased production lies in making deliberate choices which sectors should transition to local resources as their main feedstock.

Building materials and textiles have a lower land footprint than furniture, which makes them a more logical candidate for biobased production in The Netherlands. In addition, for biobased building materials there is already strong policy support for the local production of biobased materials (NABB), which makes the opportunities for more local biobased production more likely. However, current policy focuses mainly on fibre crops, whereas the wood is assumed to be sourced internationally. The above shows that also for wood there is a perspective for local production as long as a more long-term horizon is applied. At the same time, the eco-system services provided by forests (see chapter 3) could provide a key rationale for increasing the amount of productive forest in the Netherlands.

Also for textiles, the land-use footprint allows for some perspective of local biobased production. Flax is already an existing textile crop in The Netherlands, but its processing currently takes place abroad (France or even China). A first flax spinning facility would be a priority if local Dutch textile production is to be stimulated. Also for wool – an available high-quality fibre – bringing back a spinning facility to make yarns is a priority in order to enable local textile production. The increase of hemp as a fibre crop is already promoted in the Netherlands and 50,000 ha of fibre crops should be reached in 2030 according to the Dutch NABB initiative. Hemp varieties for textiles should become a part of this. The first initiative to make textiles from hemp is already launched by MVO Nederland and another company Hemptex is producing flags from hemp. Truly local production of viscose or lyocell from wood will be challenging in the Netherlands as it requires a large pulping and spinning facility which also requires a certain abundance and homogeneity of biomass which is not present in the Netherlands. As an alternative, discarded textiles could be a feedstock source for which SaXcell is planning to set up a factory at scale.

Finally, the argument that our food production requires all the available agricultural land in the Netherlands should taken for granted too easily. If self-sufficiency for basic need materials would become a main driver for Dutch land use, this would probably go hand in hand with self-sufficiency in food production. In this regard, it should be noted that our current agricultural system for food production is not designed for self-sufficiency. The meat and dairy sector plays a dominant role and uses 64% (grass land and feed crops)[153] of the Dutch

[153] https://www.cbs.nl/nl-nl/cijfers/detail/81302ned

agricultural area (1.15 Mha). Overall, 60% of the revenues earned with meat come from export[154]. For dairy, this is 65%[155] and also for eggs the Netherlands are a an important exporter. This implies that if the principle of self-sufficiency would be applied to meat and dairy production in the Netherlands approximately (60% export * 1.15 Mha) would free up 639.000 ha for other agricultural activities. This area could then be used for other types of food production needed to attain some form of food self-sufficiency, but also by forests and fibre crops to attain some degree of self-sufficiency in building materials, textiles and furniture production. In the next chapter, we will go further into the land footprint of food in order to come to an overall comparison and land allocation rule for food and material production.

[154] https://www.cbs.nl/nl-nl/nieuws/2021/25/nederland-grootste-vleesexporteur-van-de-eu
[155] https://zuivelonline.nl/handel-en-economie/#:~:text=Ongeveer%20twee%20derde%20van%20alle,Midden%2DOosten%20en%20de%20VS.

7 Towards biobased, self-sufficient landscapes

The different value chains which are relevant for local biobased production of buildings, furniture and textiles have been described and quantified in chapter 4. The feedstock qualities have been described in chapter 5. Required feedstock volumes have been quantified in chapter 6. This paves the way for taking the final step and apply this knowledge in the design of biobased landscapes for primary household material needs. For these landscapes, a land use allocation rule will be defined which allocates land to food, textiles, building materials and furniture based on the principle of self-sufficiency. Then, the land allocation rule will be applied to a landscape: the sandy soils of the Achterhoek (near Hengelo – Gelderland).

7.1 Development of allocation rule for self-sufficient landscapes

To design landscapes which are self-sufficient, the land footprint for each product type (building materials, furniture, textiles) which has been calculated in chapter 6 can be used as a starting point in order to determine how many households could be supported per unit area. However, if local self-sufficiency is used as a design rule for landscapes, the topic of food production cannot be ignored. Local self-sufficiency in food production will for many regions or countries probably be a priority over self-sufficiency in material production and both should therefore be considered in the design of self-sufficient landscapes.

In order to take food production into account, a couple of indicators for food production are relevant here:

- The global agricultural land use per capita amounts to 0.6 hectares[156]. Agricultural land is defined as the land area that is either arable, under permanent crops, or under permanent pastures. Arable land includes land under temporary crops such as cereals, temporary meadows for mowing or for pasture, land under market or kitchen gardens, and land temporarily fallow.
- For the calculations in this report, arable land will be taken as a reference. For arable land, the average food productivity equals 0.17 hectares per person based on current diets[157]. A study looking particularly into the Dutch situation estimated a land footprint of 0.2 ha per person[158]. For our calculations, the land use of 0.17 ha will be used, which is the equivalent of approximately 3 Dutch households per hectare.
- A (future) vegan diet could reduce this footprint to 0.12 hectares per person. The so-called 'circularity diet' requires even less agricultural land. In this circular agriculture, farm animals are fed on natural grasslands and residual streams, converting otherwise inedible biomass into animal proteins. In this way, a diet with less meat and a lot of vegetable protein is possible and only requires between 0.08 and 0.11 hectares of agricultural land per person[159].

Now that we have indicators for land use intensity of food production, we can calculate the average ‘composition’ of a landscape which is self-sufficient for both food and biobased materials. In order to do so, we can use the land footprints which have been calculated for building materials, textiles and furniture in chapter 6. In order to account for differences in product lifetime and differences in the way the annual material demands have been calculated, they are all converted into an annual material demand:

- The land footprint for building materials (see table 29) applies to a whole house and therefore should be divided by its lifetime (75 years) to obtain an annual material demand per household. For landscape design in rural areas, the land footprint of ground-level houses will be used for the calculations.
- The textile demand per household has already been calculated based on annual demand and therefore the number calculated in chapter 6 (table 30) can be used.

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[156] FAO. 2021. Land use statistics and indicators statistics. Global, regional and country trends 1990–2019. FAOSTAT Analytical Brief Series No 28. Rome
[157] Circularity in animal production requires a change in the EAT-Lancet diet in Europe, Van Zanten et. Al, Nature Food 2022
[158] https://www.clo.nl/indicatoren/nl007511-landvoetafdruk-1990-2021
[159] https://www.wur.nl/en/newsarticle/the-world-can-be-fed-with-only-plant-based-food.htm

- Furniture land footprint in chapter 6 (table 31) was also calculated based on the furniture which is available in a household. In order to translate this into an annual demand, a lifetime of 10 years will be assumed for furniture.

The table below shows that food is by far the most land-intensive basic need and requires 68% of the productive landscape. Building materials comes second (15%), followed by furniture (10%) and textiles (7%). For the materials, the share of different types of vegetation can be calculated:

- Coniferous (softwood) species make up 13% of the landscape
- Hardwood also makes up 13% of the landscape
- Hemp (or flax) accounts for 6%.
- Food accounts for 68%. This is not a vegetation type, but a share which has been calculated using the average land footprint explained in the section before. In practice, this land consists of arable farming and livestock farming.

Table 33 Absolute and relative land footprint per year for building materials, textile and furniture (recycling not included).

	Softwood for building materials	Remarks softwood	Hardwood for furniture and viscose	Remarks hardwood	Hemp/flax for textiles and insulation	Remarks hemp/flax	Food	Total	
Unit	Hectares of softwood per hh per year		Hectares of hardwood per hh per year		Hectares of hemp/flax per household per year		Hectares of food per household per year	Total ha per year per household	Relative land footprint per basic need
Building materials (ground level houses)	0.061*	Also covers board demand by excess chips			0.013	Additional acreage of hemp for insulation***.		0.074	15%
Textiles	-		0.018	Softwood for viscose production	0.015	Long fibre for textiles, short fibre to insulation, shives to board		0.033	7%
Furniture	-		0.046**	Board demand (P2) can be achieved with excess chips and shives****	0.0005	Half of upholstery assumed to be produced with hemp/flax		0.0475	10%
Food							0.33	0.33	68%
Total	0.061		0.064		0.0285		0.33	0.484	
Share in landscape	13%		13%		6%		68%		
Number of inhabitants provided: -households/ha -inhabitants/km²								2.1 434	

*Based on table 29, sawn wood land footprint of 4.6 ha/household, divided by 75 years of lifetime of a biobased house.

**Based on table 31, 0.46 hectares of hardwood for sawn wood and chips for board and half of the upholstery land use per household 0.01/2=0.005 ha (0,0005 over lifetime of 10 years. Over lifetime of 10 years: (0.46/10 + 0.0005)/10=0.046. Without other sectors which can provide excess feedstocks, an additional 0.36 ha would be needed to supply additional chips. Instead, board demand from furniture (P2) can be covered with excess chips from softwood and shives from hemp (for textile production) in a 50/50 mix.

*** Short fibre coming from hemp/flax textile production already covers half of building insulation demand.

**** Chips obtained from softwood sawmill during production of saw wood and excess shives from hemp.

The average population density which can be provided for on one productive hectare by a self-sufficient landscape design based on the above allocation rule corresponds to 434 inhabitants per km^2 of land. This does not yet include (unproductive) nature areas and buildings and infrastructure. Two future developments could improve the land footprint:

- In case of a circularity diet (see earlier this section), the shares of food, building materials, furniture and textiles would become 57%, 21%, 13%, 9% respectively and it would provide for 593 inhabitants per km^2.
- When more circular value chains for materials are included (see 6.5, table 32, reduction of land footprint for materials by 30%), this figure could even rise to 700 inhabitants/km^2 provided for by the landscape.

In order to account for buildings and infrastructure which are needed to accommodate this number of inhabitants, an average land use of 15%[160] (which corresponds to the Dutch average) is used. Another important land use element are nature protection areas, which have a share of 20% in Dutch land use[161]. The population density numbers calculated earlier (434/593/700) have been corrected for building and infrastructure surface and nature surface area in the table below.

Table 34 Overview of population densities for self-sufficiency, taking into account the Dutch share of built environment and nature protection areas in the landscape.

Diet and circularity assumptions (see text above)	Inhabitants supported (including 15% buildings/infrastructure) Inh/km^2	Inhabitants supported (including 15% buildings/infrastructure + 20% nature) Inh/km^2
Current diet, No additional circularity for materials	369	282
Circularity diet, No additional circularity for materials	504	385
Circularity diet, Additional circularity for materials	595	455

The average population density for the Netherlands is 529 inhabitants per km^2.[162] A circularity diet without additional circularity measures for materials would bring the Netherlands close to food and material self-sufficiency (504 inhabitants/km^2) in case the land is fully used productively (no nature protection areas). With additional circularity measures, material and food self-sufficiency seems possible (595 inh/km^2) in case of a fully productive land-use. When the current share of nature protection areas is taken into account (right column), self-sufficiency in the Netherlands does not seem possible (max 455 inh/km^2 provided for).

By optimizing between nature land use and self-sufficiency, a nature protection area of 10% of total land use combined with circular diet and circular materials results a population density which corresponds virtually to the current population density can be provided for (529 inh/km^2). This would lower nature protection areas compared to the current situation (10% instead of 20% nature protection). However, at the same time it would create another 20% of production forests which also have a fairly high value for supporting nature and the provision of eco-system services and would bring the combination of nature protection and (productive) forest to 30%. This is effectively 10% higher than the current nature protection area share in the landscape. This challenges our perception of nature conservation areas and to which extent they can have some productive purpose. Particularly if harvest takes place below the annual additional growth of the forest (in this study we assumed 80% of the annual additional growth was harvested), the forest biomass also after harvest still experiences a net increase. In addition, when the productive forests also consists of multiple species (polyculture), then the eco-system services may come close to forests which are not used for production.
Since the Netherlands is a densely populated country for which the challenge to become self-sufficient in both food as well as indicated material production is obvious, it is interesting to see how these results relate to surrounding Western-European countries - which could grow the same types of wood and fibre crops – have a

[160] Compendium voor de Leefomgeving, Kaart Bodemgebruik van Nederland, 2017
[161] https://www.clo.nl/indicatoren/nl142505-aandeel-beschermde-natuurgebieden-in-nederland-2022#:~:text=Het%20beschermd%20natuurgebied%20op%20land,en%20mariene%20wateren%2031%20procent.
[162] CBS (2023). StatLine: Regionale kerncijfers Nederland. CBS, Den Haag/Heerlen.

lower population density[163] and could potentially achieve self-sufficiency *without additional circularity measures* based on the footprint calculated in table 34 (282 inhabitants/km^2):

- Germany (236 inhabitants per km^2)
- France (107 inhabitants per km^2)
- The United Kingdom[164](279 inhabitants per km^2) all

Belgium has a population of 383 inhabitants per km^2 which could be provided for when a circularity diet is applied (see table 34).

Germany, France and the UK have the perspective to become self-sufficient in food and indicated materials, including a 20% nature protection area and without additional circularity measures in diet or materials. This implies that from a population density point of view, there is a certain perspective for self-sufficiency in Western Europe for food and biobased materials. Nevertheless, the real potential for self-sufficiency can only be assessed when taking into account the local level, which is greatly affected by the soil fertility and suitability for food production. Self-sufficiency for food and materials may not be automatically applicable on the scale of the Netherlands. Nevertheless, as will be clear from the following paragraph, self-sufficiency may be an interesting perspective on a local scale for specific areas in our country. At the same time, the outcomes of the case imply that biobased production of materials may be an interesting perspective as part of the overall agricultural transition.

7.2 A self-sufficient landscape for food and materials in De Achterhoek region

The above allocation rule in combination with insight into the growth conditions of the specific tree and fibre crop species on specific soil types, enable the potential re-design of a potential self-sufficient landscape (for food and bio-based materials in households). In this design, we also considered more room for water and biodiversity, following the soil-and-water guiding approach that has been propagated by the Dutch national government[165]. This means that local soil and water conditions determine the type of activities that can take place in that specific area. De Achterhoek was selected because there are a lot of activities related to biobased crops and materials. In addition, the sandy soils make up the majority of Dutch landscapes, thus the Achterhoek region may be representative for several/many other regions. An area around De Marke (agricultural test Station Wageningen UR) served as a pilot area for this first design study. The area includes 2,000 hectares in total, including arable land and part of the village of Hengelo (Gelderland). This area is characterised by the typical elements of the Dutch sandy landscapes:

- ‘Essen’ areas: fertile sandy soils that have been enriched in a centuries long process of adding organic material. These are the best productive soils in the area, and have been used for agriculture, mostly since Medieval times.
- Stream valleys: originally moist to – very – wet soils, located in the lowest parts of the area. Most of the streams have been straightened and normalised over the last century. The soils are drained to enhance agricultural use. By doing this ecological values deteriorated severely.
- Reclaimed heather soils: mostly poor, sandy soils that were reclaimed for agriculture over the last century. Through reclamation and drainage, agricultural use intensified, creating ecological losses and droughts.
- Windblown soils: very poor, dry, elevated soils with deep groundwater tables. Groundwater is pumped to accommodate drinking water production.

In the figure below, the pilot area for De Achterhoek region and its geographic location is presented.

[163] Eurostat population data: https://ec.europa.eu/eurostat/databrowser/view/tps00001/default/table?lang=en
[164] "Mid-Year Population Estimates, UK, June 2022". Office for National Statistics. 26 March 2024. Retrieved 3 May 2024.
[165] Kamerbrief Water en Bodem sturend; Ministerie van Verkeer en Waterstaat, november 2022. Den Haag.

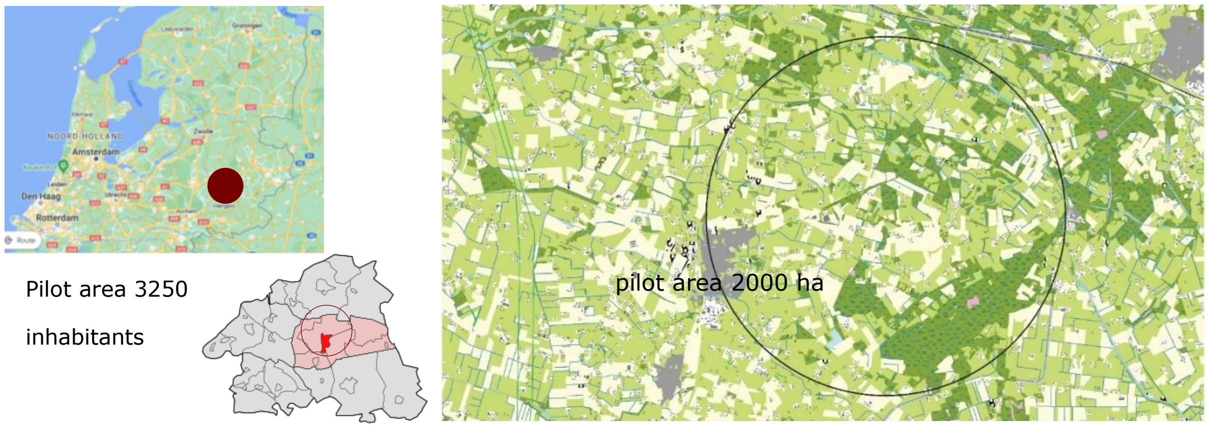

Figure 18 Pilot area geography.

The next figure shows how the pilot area for De Achterhoek region has been translated into a representative cross-section of the area. This cross-section shows the various landscape elements of the Dutch sandy landscapes and combines them into a representative configuration of the landscape which allows for further extrapolation towards other areas in De Achterhoek.

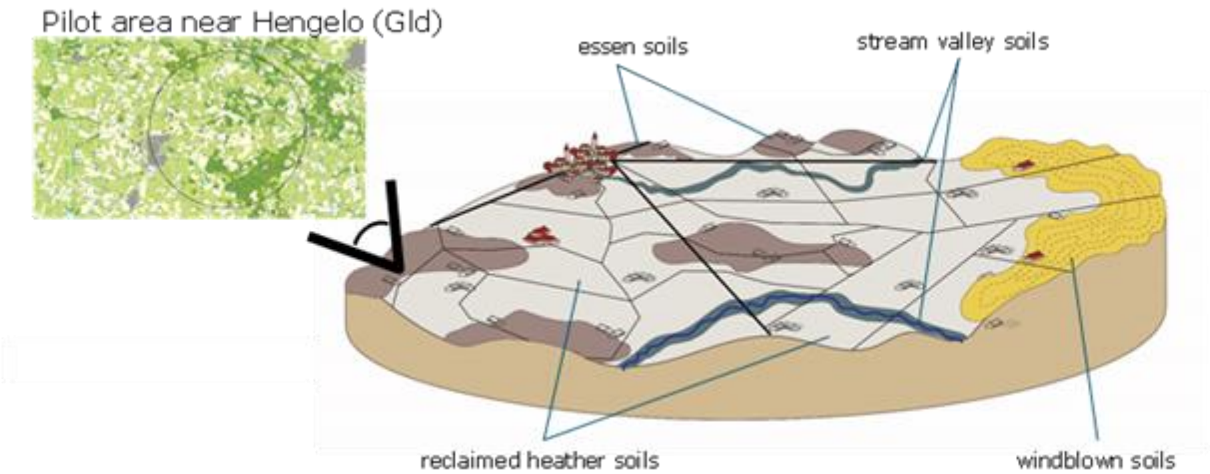

Figure 19 Pilot area and main landscape types for De Achterhoek.

The 'soil-and-water' approach asks for restoring hydrological conditions, thus adapting to climate change and (re)developing biodiversity. Stream valleys will be used for water conservation and water storage. By doing this, inundation of the best agricultural lands may be prevented. And at the same time, the retained water could be used for overcoming dry periods. In parts of the higher wind-blown sandy soils, evapotranspiration will decrease by developing natural dry vegetation. We assumed that about 20 % of the area may be necessary to meet these hydrological and ecological objectives. Furthermore, the different soil (and water) conditions within the area offer different perspectives for biobased and food production, matching the cultivation requirements of different food or fibre crops or tree and forest types. This resulted in the following choices:

- Essen soils are the most fertile areas and will be mainly used for food production. A minor part of this landscape type is used for hemp production and deciduous trees. We suggest developing 'strip-cropping' cultivation, that includes, apart from the crops, hedgerows, tree lines and food forests or different forms of agro-forestry, with for example chestnut and nut or fruit trees.
- Reclaimed heather soils are less fertile than Essen soils but still suited for food production. Here, over 50% of the area is assigned to food production whereas the rest is divided over:
  - Coniferous species, like Grand fir, Japanese Larch, Norway Spruce, Black pine and Douglas fir are known to grow on sandy soils (see table 9).
  - Deciduous trees, like Field maple, Birch, Oak and potentially Black Locust could grow on these soils (see table 10)
  - Hemp production, again in strip farming cultivation.
- Windblown soils are less fertile and feature coniferous (e.g. Scots pine) and deciduous trees (e.g. birch) for wood production and most of the remainder is assigned as nature protection zone not

used for productive purposes. Also some of the other Grand fir, Japanese Larch, Norway Spruce, Black pine and Douglas fir are known to grow on sandy soils (see table 9).

- Stream valleys are mainly used for water retention and nature restoration. Part of more natural woodlands may be combined with productive wet-tolerant deciduous tree production (e.g. alder, oak, willow or populus nigra or fast-growing populus alba, see table 10).
- Furthermore, road verges, urban green lands, yards and gardens will be used for planting deciduous trees. These do not only add up to biobased production, but also have positive effects on micro-climate, such as reducing heating up in hot periods.
- 20% of the landscape has been assigned as natural areas with no productive purposes. This corresponds to the current share of protected nature areas on land in the Netherlands[166].

Following the choices as mentioned before, the allocation of the land uses across the different sub-landscapes is presented in figure 20. Based on this allocation, a sketch of the landscape is presented in figure 21. The diagram illustrates that conversion to food and biobased production may be used to develop the area based on the differentiation of soil and hydrological conditions.

[166] https://www.clo.nl/indicatoren/nl142505-aandeel-beschermde-natuurgebieden-in-nederland-2022#:~:text=Het%20beschermd%20natuurgebied%20op%20land,en%20mariene%20wateren%2031%20procent.

Inhabitants living in the area	**3250**					
Total acreage (ha)	**2000**					
Total productive acreaage (ha)	**1449**					
Inhabitants that can be provided for based on land allocation key	**6392**					
Essen soils (ha)	**580**					
Main use	**Food**		**Biobased**		**Other**	
Type of application	**Conventional diet**	**Hardwood**	**Softwood**	**Hemp**	**Infra**	**Nature**
Share in landscape	83%	5%	0%	5%	7%	0%
Number of ha	481	29	0	29	41	0
Wind blown soils (ha)	235					
Main use	**Food**		**Biobased**		**Other**	
Type of application	**Conventional diet**	**Hardwood**	**Softwood**	**Hemp**	**Infra**	**Nature**
Share in landscape	0%	35%	19%	0%	6%	40%
Number of ha	0	82	45	0	14	94
Stream valley (ha)	**171**					
Main use	**Food**		**Biobased**		**Other**	
Type of application	**Conventional diet**	**Hardwood**	**Softwood**	**Hemp**	**Infra**	**Nature**
Share in landscape	0%	31%	0%	0%	9%	60%
Number of ha	0	53	0	0	15	103
Reclaimed heather soils (ha)	**1016**					
Main use	**Food**		**Biobased**		**Other**	
Type of application	**Conventional diet**	**Hardwood**	**Softwood**	**Hemp**	**Infra**	**Nature**
Share in landscape	50%	2%	14%	6%	7%	21%
Number of ha	508	20	142	61	71	213
Total ha per application	**989**	**185**	**187**	**90**	**141**	**410**
% total	49%	9%	9%	4%	7%	20%
% productive	68%	13%	13%	6%		

Figure 20 ***Soil and water guiding landscape design while at the same time allocating forest, hemp and food production over different soil types in a typical landscape in De Achterhoek, matching the demand-ratio for food and biobased materials for buidlings, furniture and textiles.***

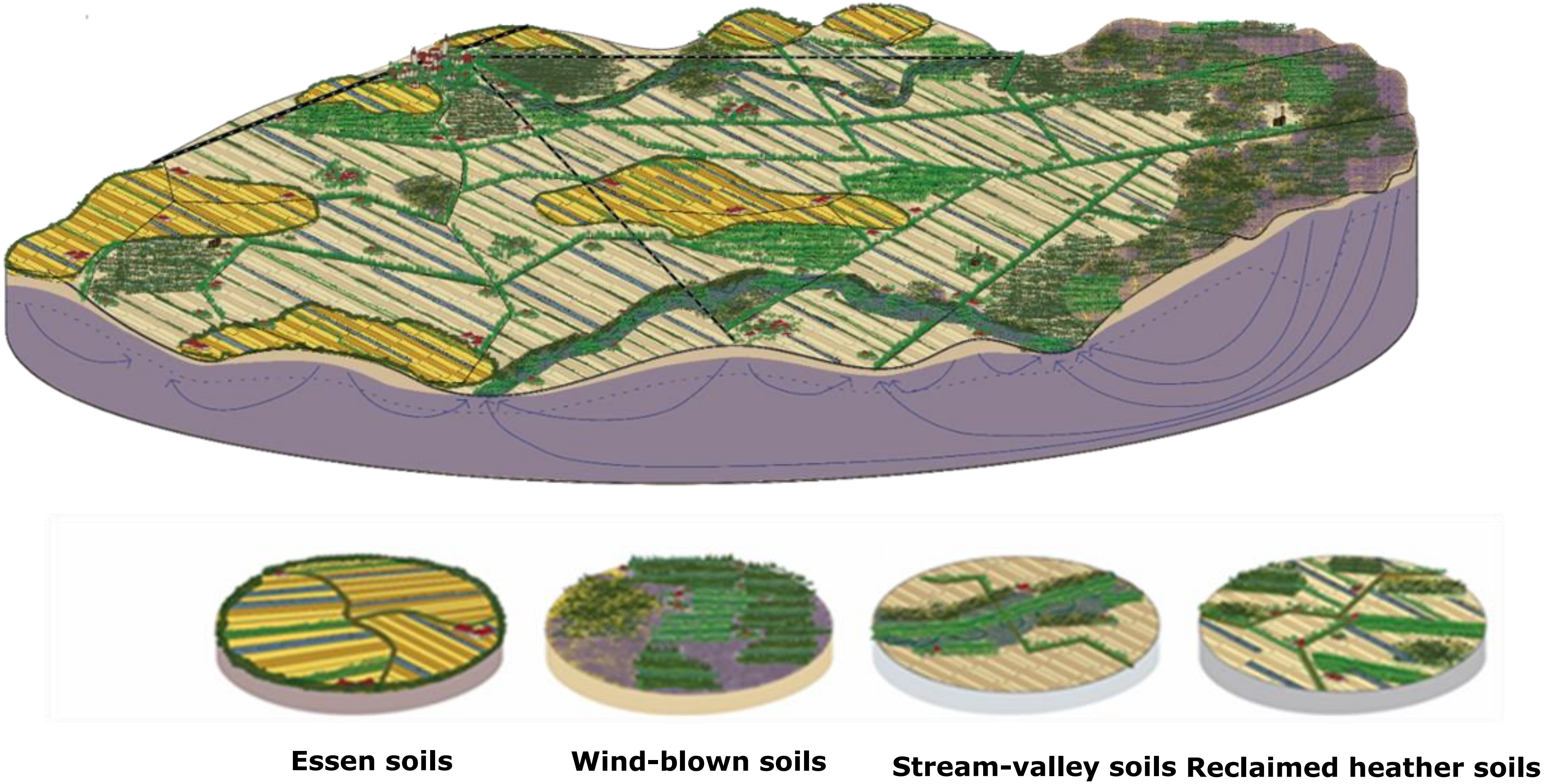

Figure 21 The overall design illustrating a potential self-sufficient landscape in De Achterhoek area.

Using the area as reflected in the overall design, may restore main features of the traditional cultural landscape as it takes the natural conditions in the area (soil, water) as a starting point rather than adapt areas recklessly to human needs without further consideration. It also offers ample space to restore hydrological conditions to overcome droughts and inundations by increasing the water retention capacity of the landscape. As figure 21 shows, water flows from the higher (essen and wind-blown) soils to the lower stream valley areas. The higher share of forest in all areas ensures that more water is captured in the upper soils layers, while surplus water infiltrates and flows towards the stream valley areas which have been designed to capture and store more water by using water-tolerant tree species (e.g. alder, willow).

In addition, the landscape is designed to maximize biodiversity and eco-system services by a network of small production forests, which are connected through forest belts and hedgerows. Given an average nature protection area (non-productive) of 20%, the coniferous and deciduous production forests add another 18% (see figure 20, 9% of softwood and 9% of hardwood productive forest) of forest to the area, resulting in a total forest coverage of 38%. These forest belts and hedgerows are primary habitats to a range of animals and are then connected through fields of fibre crops (hemp) in order to create an additional green network which provides shelter and habitat to a variety of animals. The food crop fields create open spaces within this network. This high share of nature protection in combination with self-sufficiency is possible given the fairly low population density in the area compared to the average Dutch population density (see section 7.1).

8 Summary and Conclusions

In the previous chapters, we have explored the opportunities for local and biobased production of basic household material needs in building, textiles and furniture. We mainly looked at (ligno)cellulosic materials, since the bulk of household materials can be made out of this type of biomass. Local was defined as self-sufficiency and processing of biomass at a national level for the Netherlands or at a regional level when possible. The first question to be answered was to which extent biomass could be made available in sufficient quantities to meet demand and at which scale (regional/national) this demand could be met, taking into account also the scale of the production processes. Secondly, an assessment was made whether these materials meet current quality requirements and can be(come) a viable alternative to conventional materials. Thirdly, a sketch of a productive self-sufficient and soil-water guided landscape was made at regional level.

8.1 Quantitative assessment of local material production and demand

For the quantitative assessment, data were gathered on the whole value chain: from wood and fibre crop cultivation to conversion processes up till the final demand for building, furniture and textile materials. This allowed for the calculation of land footprints required to meet Dutch demand for these materials. Jointly, these land footprints amount to 1.4 million ha, which 65% of the combined Dutch agricultural and forest area. It was shown the land footprint required to enable for local production was as follows:

- For **building materials**, 455,000 ha of coniferous forest and hemp is needed to supply building materials to meet the current Dutch demand of 70,000 houses per year in ground-level houses which are less wood-intensive.
- For **textiles,** 280,000 ha of deciduous trees (for viscose/lyocell textile fibres) and hemp/flax (bast textile fibres) are needed.
- For **furniture,** 690,000 ha of 93% deciduous trees (saw wood, board and viscose/lyocell) and 7% flax/hemp (textiles for upholstery) are needed to replace indicative amount of furniture for all Dutch households in 1 year.

This land footprint could be further reduced to 1 million ha by the adoption of more circular (re-use/recycling) practices. Particularly in the building sector, demountability, re-use and recycling is gaining traction and this will lower the land required for virgin bioresources. In addition, there are opportunities between sectors, like for example textile waste which could be recycled, but could also be used as insulation material in the building sector.

Even though the production of basic need materials at local or national level would require considerable surface areas which in the first place seem difficult to accommodate in the Netherlands, it should be noted that a fair comparison with current land-use can only be made if self-sufficiency would be the rule for Dutch agricultural land use for food production as well, because current Dutch food production is exported for about 50%. If for example the cattle and dairy farming sector would produce only for domestic demand, this could make available 639,000 ha which could be used for other forms of food production but also for fibre crops and forestry. Hemp, flax, straw and Miscanthus were shown to be the most economically viable crops, while at the same time contributing a range of eco-system services: biodiversity, soil organic matter and soil life, ground and surface water quality, to mention a few. Production forests deliver more eco-system service than crops, but also require a longer period (60-80 years) before harvest can take place.

With regard to scale, for most of the conversion processes discussed in this chapter, either regionally oriented or nationally oriented production facilities could be set up. In principle, processes which include chemical conversion steps are large scale and would require biomass supply at national scale in order to convert it into a product in an economically viable way. Examples of these processes are the production of dissolving pulp (extraction of cellulose) and spinning of dissolving pulp into viscose/lyocell. Other examples include CLT production and board production. However, for board production also more regionally oriented small scale initiatives have been set up.

8.2 Local biobased material quality assessment

Can locally produced biobased materials meet the quality requirements to become an alternative to conventional materials? The answers differs per material category.

For **building materials**, wood has been around as a building material since early human history. In modern construction, wood building techniques like Cross-laminated Timber (CLT), Glulam and Timber Frame Construction (TFC), complemented with other biobased materials like fibre boards and insulation, are increasingly becoming common practice.

For CLT, the strength class required is usually C24. For Glulam, this is GL24 and for TFC usually C18 strength class is used. There are many tree species which are also common to the Netherlands which can provide the quality required to apply wood as a building material. Even though Norway spruce (Picea abies, not very common in the Netherlands) is currently the main and most fast growing tree species for the building material industry, delivering strength class up to C24 and higher. Many other species are possible for CLT, Glulam and sawn wood, like Scots pine (most common coniferous species in Dutch forests), larch, Douglas fir and other spruces, and oak can be used. Even experiments are being conducted with the use of recycled wood for use in CLT , also in the Netherlands. The market is geared towards coniferous wood species, however, also hardwood species may be used, having higher density, typically higher strength, and higher prices.

Wood is the current reference feedstock for the production of different types of particle board and is made from residue streams from the (sawn) wood processing sector, but also from construction demolition. In principle, all strength classes (P1-P7) can be attained using a broad variety of wood species. Many other biobased fibre crops and fibrous residues meet the strength and stiffness requirements of P3-P5 strength classes, but fall short on the thickness swelling. This is probably the result of not using moisture repelling agents in the scientific studies and may be resolved in the longer term by adding paraffin or the like, which is already industrial practice for wood based board production.

Compared to fossil references, biobased insulation blankets of a variety of fibre types show a very similar thermal conductivity to glass wool and rockwool (approx. 0.036-0.040 W/m.K), even though their average density is higher than glass wool and lower than rock wool. Most of the insulation panels show a higher conductivity, whereas for blow-in insulation cellulose, sheep wool and wood fibre perform similar to glass wool and rock wool. EPS and PIR-PUR have a significantly lower conductivity of 0.033 and 0.025, respectively.

For **furniture**, mechanical (strength) performance is relevant, though not key. Somewhat lower mechanical properties can be compensated by increasing material thickness. In principle, particle board strength class P2 is suitable for furniture applications, meaning that next to wood also hemp shives, cereal straw, reed and the stems from some plants can be used. More important for furniture is the visual quality of the products. Board materials are often covered with a layer of veneer or plastic sheet, eventually with a print on top. Sawn wood requires grade A or B (see section 5.2), which may contain a small amount of knots only and no (coloured) core wood.

For **textiles**, it was more challenging to make a statement about the suitability of local biobased fibres, since current textiles are mainly composed of cotton and/or polyester (and a range of other fibres). Natural (ligno)cellulosic fibres from local feedstocks can only be sourced from bast fibre crops (hemp/flax, currently 1% of textiles market) and regenerated fibres (viscose/lyocell, 5% of textiles market). Based on a very basic evaluation of GSM and fabric strength, it could be derived that it is possible to use (ligno)cellulosic fibres in all home and clothing textile applications.

However, in order to come up with a local biobased alternative for the most common natural (but not locally available) textile fibre cotton, a range of other properties also need to be attained. Cotton is easily processed, has the desired comfort and physical properties. Cotton (textile market share 25%) is the mostly used natural fibre and the second mostly used fibre in textile after polyester. Fully replacing cotton with viscose, lyocell and (cottonized) flax or hemp will alter the fabric's mechanical properties, such as elongation, as well as its comfort properties like feel ad softness. These properties can hardly be predicted with a model and need to be tested in practice. Cottonization of hemp/flax fibres (refining and shortening) and a higher share of viscose/lyocell can contribute to mimic some cotton properties in the fabric, but this comes at a prices (chemicals used and more expensive fabric). Obviously, also recycled cotton could play a role here.

However, various other household and personal items may be less feasible to be made with (ligno)cellulosic fibres. For instance, swimwear, sportswear or carpets require good water and dirt repellence, which is typically a property of more hydrophobic fibres such as polyester (fossil-based fibres), even though also Lyocell swimwear is available. Polyester also has good abrasion resistance which is an important property for upholstery as well. Here, biobased polyesters (e.g. PEF) may play a role but these have not been the scope of this study.

8.3 From value chain to landscape

The data obtained on biobased material demand, conversion ratios and biomass production, allowed to assess the potential for biobased self-sufficient landscapes, which was done on national level and regional level (de Achterhoek). For this, a landscape allocation rule was established based on land footprint for materials and food relative to the amount of inhabitants per hectare of arable land. This resulted in 68% of arable land use required for food and 32% for indicated materials: buildings, furniture, textiles. It also looked at the impacts of more land-efficient diets (circularity diet) and additional circularity of biobased materials. The highly explorative character of these calculations should be emphasized, but they serve to sketch the potential of local production of biobased materials, which can only be done by also looking at (self-sufficient) food production and land use as a whole.

The average population density for the Netherlands is currently 529 inhabitants per km^2. The average population density which can be provided for by a self-sufficient landscape design based on the above allocation rule *at current practice* corresponds to 282 inhabitants per km^2 of land, taking into account current shares of (non-productive) buildings and infrastructure and nature in the Netherlands. When applying a circularity diet and circularity of materials, up to 455 inhabitants per km^2 can be provided for. Only by reducing the share of nature protection areas from 20% to 10%, the current Dutch population density's food and material demand could be provided for. On the one hand this may seem a questionable step; on the other hand this study has shown that in return production forests make up a higher share of the landscape, resulting in a combined nature and production forest area of over 30%, a net increase of 10%. This raises the question whether nature conservation areas can be productive to some extent and shows the potential benefit of productive landscapes for food **and** materials. It should be emphasized that the required forest areas are annually harvested at 80% of their annual additional growth, which means that, despite the production forest character, the forest biomass still increases and ensures that there is continuous forest coverage on the forestry acreage. Looking at population densities of surrounding countries, Germany, France and the UK have the perspective to become self-sufficient in food and indicated materials, including a 20% nature protection area and without additional circularity measures in diet or materials. In practice, the real potential for self-sufficiency can only be assessed when taking into account the local level, which is greatly affected by the soil fertility.

The same approach was applied on regional level for De Achterhoek. The development of self-sufficient landscapes starts in the region by taking into account the specific characteristics of a region and optimally align with soil and water conditions (soil-water guiding principle). The soil and water conditions in De Achterhoek area provided ample opportunities for food and material cultivation. Here, a self-sufficient landscape for food and materials production was designed. The design showed that – assuming a non-productive natural forest cover of 20% – the addition of productive forest could increase forest coverage by 18% to a total of 38%, while at the same time sustaining the local population in food as well as building, furniture and textile materials. The landscape is designed to maximize biodiversity and eco-system services by a network of small production forests, which are connected through forest belts and hedgerows. These belts are then connected through fields of fibre crops (hemp) in order to maintain a green network which provides shelter and habitat to a variety of animals. The food crop fields form open spaces within this network. In this way, it was shown how food crops, fibre crops and trees can complement each other and result in a mixed forested/open landscape which creates many types of habitats for a range of animals.

8.4 Opportunities for implementation and follow-up research

As mentioned earlier, the land footprint required to become fully self-sufficient in basic materials for the Netherlands is too big to be actually implemented on the short term and would require an area of 1.4 Mha, or 1.0 Mha considering potential re-use/recycling options. This means that striving for self-sufficiency in all these materials may be challenging. However, based on the characteristics and developments in these sectors, it is possible to make smart choices here.

A potential priority sector for local self-sufficiency would be the construction sector, for a number of reasons:

- There is a serious perspective for self-sufficiency for this sector. When circular practices are applied in the building industry, already with an additional forest area of 227,000 ha (Scots pine, Douglas, Spruce), an annual need of 70,000 houses per year could be met for ground-level houses.
- There is already an existing policy which focuses on local production of biobased building materials (NABB), mainly insulation and particle board from hemp, flax, Miscanthus and straw. A long-term policy for production forests could complement the current NABB policy.
- There is an existing sector which can process the wood (large number of saw mills) and many builders have TFC or CLT construction knowledge and facilities.
- Building materials are applied for at least 75 years and therefore store carbon in buildings. Setting up production forests for the construction sector would in this way also contribute to climate change mitigation.

In order to ensure resilience against plagues/diseases and to create diversity in the proposed 227,000 ha production forest for the construction sector, adding an additional 100,000 ha of deciduous production forests could be considered. The harvests could be used for local furniture production. Also here, the existing infrastructure of saw mills and the presence of furniture companies makes it possible to accommodate and process this wood. The coniferous and deciduous forest areas may be smartly integrated in the landscape in such a way that they are in line with local soil-water conditions, create (bio)diverse elements in the agricultural landscape and connect Natura 2000 areas. In this way, the forest complements food production and creates (bio)diverse landscapes.

For textiles, the perspective for local production is more challenging as there is a lack of industry (particularly in the spinning step) which could work with local fibres. Key priority here is to first re-create this industry:

- Flax is an existing textile crop in the Netherlands, but its processing currently takes place abroad (France or even China). A first flax spinning facility would be a priority if local Dutch textile production is to be stimulated. Also for wool – an available high-quality fibre – bringing back a spinning facility to make yarns would be needed in order to enable local textile production, in addition to dedicated sheep for wool production (e.g. Merino).
- The increase of hemp as a fibre crop is already promoted in the Netherlands and 50,000 ha of fibre crops should be reached in 2030 according to the Dutch NABB initiative. Hemp varieties for textiles should become increasingly a part of this. The first initiative to make textiles from hemp is already launched by MVO Nederland.
- Truly local production of viscose or lyocell from wood will be challenging in the Netherlands as it requires a large pulping and spinning facility which also requires a certain abundance and homogeneity of biomass which is not present in the Netherlands. As an alternative, discarded textiles could be a feedstock source for which SaXcell is planning to set up a factory at scale. If half of the Dutch textile consumption could be met with recycled textiles (instead of viscose/lyocell) and the other half with (cottonized) hemp, then only 135,000 ha of hemp would be needed. In addition, there may be potential for Miscanthus (e.g. via Miscancell) to become a feedstock source for regenerated cellulose fibre.

In addition to the strategy per sector, several follow-up research topics are suggested which generally support the transition to local biobased production of basic material needs:

- To perform trials with locally available fibres to validate performance requirements for each textile application. In which applications are wool, regenerated cellulose and bast fibres a good fit?
- To perform a study into additional opportunities for circularity between construction, textiles and furniture sector as circularity is key to further reducing the land footprint of local biobased material production. Cascading of biomass is key to attain this. Key opportunities here:
  - Re-use of demolition wood in construction timber or in furniture (building on initiatives by TNO).
  - Recycling of demolition wood into board material.
  - The utilisation of fibre crop (residues) into board material.
  - The application of used textiles as a feedstock for insulation (building on experience by Metisse) or as a source for regenerated cellulose fibre (building on experience by SaXcell).
- To fully develop a region for self-sufficiency according to the land allocation rule and to connect and set up local industries.

Complementary to the above sectoral strategies, an intersectoral approach to landscape development could be developed in which food and material production go hand-in-hand. After all, besides the advantages of local biobased materials, a key driver to local biobased production is the integrated design of robust, sustainable, (bio)diverse productive landscapes for food and materials. This has been illustrated by the landscapes developed in this study. The initiative to introduce more productive forestry in The Netherlands could be taken by current forest management organisations like Staatsbosbeheer and provinces, but potentially also through community owned land management organisations like Land van Ons.

A perspective for local biobased material production for The Netherlands is certainly not straightforward and may, also after reading this report, be difficult to imagine. It requires a **long-term perspective and strategy**, which embraces the fact that setting up significant areas of forestry (key for all three sectors considered in this study) may take at least 60-80 years, but enables future generations to be self-sufficient in material production and benefit from the eco-system services delivered by these forests, provided that they are harvested below annual growth (which has been the main assumption throughout this study). Productive forestry is positioned between agriculture and nature conservation and requires a long-term perspective. Particularly in the Netherlands, where current intensive land-use puts a high burden on soil, air, water quality and biodiversity, the actual value of these eco-system services should be duly appreciated.

Annex 1 Estimates for amounts of biobased household items

In subsections below, the amounts of materials are estimated for a household acquiring biobased household items. For each item, assumptions and data considered are indicated. In section 2.2.2 of the main report an overview of the data is presented.

1.1 Amounts of textile household items which may be biobased

1.1.1 Fabric for curtains

Considerations and assumptions:
- The average window area of a Dutch house is 20 m^2.[167]
- 75% of the window area of a house is covered with curtains.
- On average single pleat curtains are used; most common types of pleat are: half, single, double.
- To make these curtains fabric size of twice the window area is required.[168]
- The weight of biobased fabric for curtains is 500 g/m^2.[169]
- 20% cutting losses.

Then the amount of fabric required for a household sourcing biobased curtains is: 18.75 kg/household.

1.1.2 Fabric for clothes

Considerations and assumptions:
- 248,000 ton of consumer clothing was marketed in Netherlands in 2018.[170]
- 8.1 million households in the Netherlands early 2022.[171]
- 20% cutting losses.

Then the amount of fabric required for a household sourcing clothes is: 38.27 kg/household.

1.1.3 Fabric for bed linen and towels

Considerations and assumptions:
- 67,000 ton ton/a fabric for bed linen, towels and curtains sourced in Netherlands in 2018.[172]
- 15,188 ton/a of fabric sourced for curtains (see section 1.1.1, and assuming replacement every 10 years).
- 8.1 million households in the Netherlands early 2022.[171]
- 0% cutting losses.

The amount of biobased fabric required for household sourcing bed linen and towels is: 6.40 kg/household.

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[167] https://www.glas.nl/nieuws/nederlanders-verspillen-elk-jaar-bijna-half-miljard-euro#:~:text=Van%20de%20ongeveer%207.300.000,over%2020%20m%C2%B2%20aan%20ramen
[168] https://www.budgetstoffen.nl/blog/stofhoeveelheid-gordijnen/
[169] https://www.ecotex.nl/contents/nl/p52581_Meubelstof-of-gordijnstof-van-hennep.html
[170] https://open.overheid.nl/documenten/ronl-9a6b4b22-eefa-4875-a83f-e03404de4e63/pdf
[171] https://www.cbs.nl/nl-nl/visualisaties/dashboard-bevolking/woonsituatie/huishoudens-nu https://opendata.cbs.nl/statline/#/CBS/nl/dataset/82550NED/table?dl=4297C
[172] https://open.overheid.nl/documenten/ronl-9a6b4b22-eefa-4875-a83f-e03404de4e63/pdf

1.2 Amounts of furniture household items which may be biobased

1.2.1 Upholstery for sofas

Considerations and assumptions:

- Household has a 2 seat and a 3 seat sofa.
- The weight of fabric for sofas is 500 g/m^2.[169]
- 20% cutting losses.

The amount of biobased fabric required for household sourcing a 2 and a 3 seats sofa is: 8.26 kg/household.

1.2.2 Construction for sofas

Considerations and assumptions:

- Household has a 2 seat and a 3 seat sofa.
- Volumes of wood based material is estimated from an example.

The amount of material for a 2 seat and 3 seat sofa is: 0.052 m^3 of sawn wood and 0.093 m^3 of PB/MDF.

1.2.3 Kitchen and coffee table

Considerations and assumptions:

- Household has solid wooden kitchen and coffee tables.
- Volumes of wood based material is estimated from an example.

The amount of material for tables is: 0.097 and 0.058 m^3 of sawn wood for kitchen and coffee table, respectively.

1.2.4 Kitchen chairs

Considerations and assumptions:

- Household has 5 sawn wood based kitchen chairs.
- Volumes of wood based material is estimated from an example.

The amount of material for chairs is: 0.050 m^3 of sawn wood.

1.2.5 Kitchen cabinets

Considerations and assumptions:

- Volumes of wood based material is estimated from an example.

The amount of material for kitchen cabinets is: 0.266 m^3 of PB/MDF and 0.015 m^3 of hardboard.

1.2.6 Cabinet & bookcase

Considerations and assumptions:

- Household has a stand alone cabinet partly closed with doors for household items and a bookcase for books, board games, etc. Both about 2 m wide.
- Volumes of wood based material is estimated from an example.

The amount of material for cabinet and bookcase is: 0.152 m^3 of PB/MDF and 0.014 m^3 of hardboard.

1.2.7 Wardrobes

Considerations and assumptions:
- Household has a 2 wardrobes with hanging space, one 2 m wide and one 1 m wide. And 2 smaller cabinets, about 0.6 m wide.
- Volumes of wood based material is estimated from an example.

The amount of material for wardrobes is: 0.035 m^3 of sawn wood, 0.348 m^3 of PB/MDF and 0.031 m^3 of hardboard.

1.2.8 Beds

Considerations and assumptions:
- Household has one double bed and 2 single beds.
- Volumes of wood based material is estimated from an example.

The amount of material for beds is: 0.177 m^3 of sawn wood and 0.086 m^3 of PB/MDF.

1.2.9 Flooring

Considerations and assumptions:
- Gross used floor area is 181, 133, 110, 110 and 92 m^2 for detached, 2/1 roof, corner, terraced houses and apartment flats, respectively.[173]
- It is assumed that detached houses apply parquet flooring on ground floor and laminate on storey floors. Other houses apply MDF based laminate. This is translated into 50 and 90 m^2 of detached houses floor is covered with parquet and laminate, respectively. And 100, 80, 80 and 65 m^2 of floor of 2/1 roof, corner, terraced houses and apartment flats, respectively, is covered with laminate.

The amount of material for flooring is:
- Detached house: 0.4 m^3 of sawn wood and 0.72 m^3 of MDF
- 2/1 roof house: 0.80 m^3 of MDF
- Corner and terraced house: 0.64 m^3 of MDF
- Apartment flat: 0.52 m^3 of MDF

1.2.10 Fences

Considerations and assumptions:
- 80 m^2 is average backyard.[174]
- 8.94 m is smallest length of the corresponding rectangle (a square).
- 26.8 m is the sum of 3 sides, however, part of the length will be 'covered' with walls of annexes.
- Fences are typically shared by 2 neighbours.
- 10 m of fence is assumed per house.
- Volumes of wood based material is estimated from an example.

The amount of material for fencing is: 0.495 m^3 of sawn wood per house.

[173] https://www.rvo.nl/sites/default/files/2017/02/Referentiegebouwen%20BENG.pdf
[174] https://vastgoedactueel.nl/tuinoppervlak-bij-rijtjeshuis-wordt-steeds-kleiner

Annex 2 Emission data for crops

2.1 Straw of Barley, Wheat, Oats and Rye

For cereal crops, an important note is that the data covers the entire crop. There is no breakdown by main product (grain) and by-product (straw). As a reference for energy and greenhouse gas emissions, an average per hectare is included in the text above. The cereals are below this average per hectare.

Sustainability aspects of straw of Barley, Wheat, Oats and Rye.

Sustainability aspects	Unit	Barley	Wheat	Oats	Rye
Nitrogen efficiency	%	88%	113%	92%	68%
Nitrogen (removal)	Kg N/ha	105	181	110	89
Nitrogen (supply)	Kg N/ha	120	160	120	130
Energy input	MJ/ha	15,600	18,819	17,087	17,971
GHG-emission	Kg CO_2-eq./ha	1,372	1,644	1,440	1,479
Crop protection	Applied	Yes	Yes	Yes	Yes
MBP-water life	Score per ha	493	320	257	11,929
MBP-soil life	Score per ha	130	160	134	195
MBP-ground water	Score per ha	151	138	1,133	1,918
Soil org. Matter	Kg OM/ha	1,570	1,640	1,570	1,500

2.2 Straw of Grain maize, Rapeseed and Triticale

For grain maize, rapeseed and triticale, an important note is that the data covers the entire crop. There is no breakdown by main product (grain/seed) and by-product (straw). The environmental aspects of maize, rapeseed and triticale are similar to cereals. In an inter-comparison, there are no major differences.

Sustainability aspects of straw of Grain maize, Rapeseed and Triticale.

Sustainability aspects	Unit	Grain maize	Rapeseed	Triticale
Nitrogen efficiency	%	81%	78%	76%
Nitrogen (removal)	Kg N/ha	150	140	107
Nitrogen (supply)	Kg N/ha	185	180	140
Energy input	MJ/ha	22,647	16,286	18,070
GHG-emission	Kg CO_2-eq./ha	1,659	1,343	1,506
Crop protection	Applied	Yes	Yes	Yes
MBP-water life	Score per ha	291	867	301
MBP-soil life	Score per ha	236	567	191
MBP-ground water	Score per ha	79	1,442	1,918
Soil org. Matter	Kg OM/ha	900	975	1,570

2.3 Roadside grass, Cup plant and Sorghum

Roadside grass has not been calculated as an agricultural crop. As a result, no values have been included. This does not mean that the crop has no energy input or greenhouse gas emissions. There is insufficient data known for this assessment. Cup plant and Sorghum have been included as a biomass crop. For these crops no by-product was taken into account. For both these crops, the literature used is mainly foreign literature. Cultivation in the Netherlands might therefore differ in practice. Cup plant and sorghum are equal or slightly lower than that of the cereals in terms of energy and greenhouse gas emissions. However, Cup plant is higher compared to other perennial crops in this research.

Sustainability aspects of Roadside grass, Cup plant and Sorghum.

Sustainability aspects	Unit	Grass	Cup plant	Sorghum
Nitrogen efficiency	%	N/a	101%	289%
Nitrogen (removal)	Kg N/ha	N/a	122	260
Nitrogen (supply)	Kg N/ha	N/a	120	90
Energy input	MJ/ha	n.b.	16,912	10,598
GHG-emission	Kg CO_2-eq./ha	n.b.	1,350	939
Crop protection	Applied	No	Yes (snails)	No
MBP-water life	Score per ha	N/a	0	N/a
MBP-soil life	Score per ha	N/a	0	N/a
MBP-ground water	Score per ha	N/a	0	N/a
Soil organic Matter	Kg OM/ha	n.b.	n.b.	n.b.

2.4 Sustainability aspects of Miscanthus, Reed, Cattail, Willow and Switchgrass.

The perennial crops listed in the table below have been assessed with 10 years cultivation period. As a result, the effects of e.g. planting material relative to annual crops are lower. This affects the entire crop. This is especially visible in the energy content and greenhouse gas emissions per hectare. Tillage, planting or sowing, for example, are cultivation operations that are carried out only once every 10 years. All this explains the lower results in this regard for perennial crops. For Miscanthus and Switchgrass, chemical weed control is included for the first year. It is possible to replace this with mechanical weed control. This eliminates the need for crop protection.

Sustainability aspects of Miscanthus, Reed, Cattail, Willow and Switchgrass.

Sustainability aspects	Unit	Miscanthus	Reed	Cattail	Willow	Switchgrass
Nitrogen efficiency	%	167%	87%	60%	n.b.	80%
Nitrogen (removal)	Kg N/ha	50	130	90	n.b.	60
Nitrogen (supply)	Kg N/ha	30	150	150	80	75
Energy input	MJ/ha	4,846	8,767	8,767	5,774	5,950
GHG-emission	Kg CO_2-eq./ha	356	726	726	472	446
Crop protection	Applied	Yes	No	No	No	Yes
MBP-water life	Score per ha	1	N/a	N/a	N/a	14
MBP-soil life	Score per ha	11	N/a	N/a	N/a	36
MBP-ground water	Score per ha	20	N/a	N/a	N/a	14
Soil organic Matter	Kg OM/ha	n.b.	n.b.	n.b.	n.b	n.b.

2.5 Flax, Hemp and Common Nettle

Flax is mainly grown conventionally which means the use of plant protection products is common. In the sustainability analysis the lower score for aquatic life is caused by insecticide use. For soil life, this concerns insecticides and fungicides. An alternative is to opt for organic flax cultivation. Organic cultivation of flax can reduce yields. Hemp and Common nettle are less susceptible to diseases and pests, so no crop protection is needed for cultivation. Flax and hemp also have a processing industry in the Netherlands, making them the most promising crops in regard to cultivation practise and gross margin.

The low energy and greenhouse gas emissions of flax and hemp are largely due to the fact that harvesting is done on a contract basis. This is common practise in the cultivation of flax and hemp. For cereals, harvesting is part of the field operations by a farmer. This somewhat distorts the results of the comparison. Common nettle cultivation is a perennial crop. As a result, nettle scores lower as annual crops.

Sustainability aspects of Flax, Hemp and Common nettle.

Sustainability aspects	Unit	Flax	Hemp	Nettle
Nitrogen efficiency	%	180%	90%	187%
Nitrogen (removal)	Kg N/ha	63	72	140
Nitrogen (supply)	Kg N/ha	35	80	75
Energy input	MJ/ha	8,283	10,116	6,951
GHG-emission	Kg CO_2-eq./ha	535	801	550
Crop protection	Applied	Yes	No	No
MBP-water life	Score per ha	1,102	N/a	N/a
MBP-soil life	Score per ha	93.2	N/a	N/a
MBP-ground water	Score per ha	479	N/a	N/a
Soil organic Matter	Kg OM/ha	100	n.b.	n.b.

2.6 Nitrogen emissions of fertilization and soil operations

Nitrogen emissions from livestock manure in the Netherlands are determined with the National Emission Model for Agriculture (NEMA). Estimated emissions from manure application in agriculture in 2020 according to WOT technical report 224 (2022) are given in Table 30.
The amount of agricultural land (arable + grassland) is about 1.8 million ha. The average emissions per type of nitrogen emission per ha that can be calculated with this is also shown in Table 30.
It should be noted that the uncertainties in the emissions are relatively large (CDM, 2020); however, these uncertainties are the same and work in the same direction for the different crops.

The amount of animal manure applied to agricultural land in the Netherlands in 2020 is 334.7 million kg N. Taking into account the share of N in NH_3, N_2O and NO, the proportion of N emitted in the applied manure can be calculated from the above data (Table 30). Cumulatively, 9.5 w/w% of N applied to land emits as NH_3, N_2O and NO. These emissions precipitate on natural areas, among others, and contribute to the nitrogen crisis. It is assumed that emissions are proportional to application; so a crop requiring less manure will be able to be produced with less nitrogen emissions.

For comparison, emissions from tillage were also estimated. NOx emissions for heavy tillage (ploughing) are higher than for lighter tillage. Data are reported by Janulevicius et al. (2017).[175] Deep tillage simultaneously takes more time: about 1 ha per hour for ploughing versus 2.5 ha for shallower methods of tillage. Conversion to emissions per ha of tillage is also given in Table 30. This shows that N_2O and NO emissions for heavy tillage are ca 1.1% and 15% of emissions due to fertilisation with animal manure; and 0.27% and 4.0% for light tillage, respectively.

[175] Janulevicius, 2017. https://doi.org/10.1016/j.biosystemseng.2017.06.022

Nitrogen emissions from to the (pasture)land applied animal manure in the Netherlands according NEMA, and conversions to emissions per ha for manure and soil operations.

	Emission (million kg)	**Emission (kg/ha)**	**Share emission relative to applied (w/w.%)**	**Emission soil operations *[175] (kg/h)**		**Emission soil operations *[176] (kg/ha)**	
				Deep	Light	Deep	Light
NH_3	32.0	17.8	7.6%				
N_2O	3.9	2.2	0.7%	0.024	0.015	0.024	0.006
NO	8.1	4.5	1.1%	0.67	0.45	0.67	0.18

For reference, NH_3 emissions from barns and storage are about 82% higher than from manure applied to (pasture) land; for N_2O and NO, those percentages are 64% and 77% lower, respectively. Emissions of methane (CH_4) occur mainly from stables (the animals themselves) and manure storage/treatment.

[176] Akkerwijzer, 2010. https://www.akkerwijzer.nl/artikel/85856-eigen-proefveld-niet-kerende-grondbewerking-aanleggen/

Annex 3 Furniture performance calculation

The maximum deflection, δ_{max}, in a shelf (beam) with uniform load supported at both ends is:

$$\delta_{max} = \frac{5*q*L^4}{384*E*I} \qquad \text{(equation 3)}$$

Where:
q = uniform load per length unit of shelf (N/m)
L = length of shelf (m)
E = modulus of elasticity (N/m^2)
I = moment of inertia = (h^3 * b)/12 (m^4)
h = thickness of shelf (m)
b = width ('depth') of shelf (m)

Example

Considering a typical shelf having 85 cm span, 30 cm depth, 19 mm thickness, and assuming a deflection limit of span/240 (= 3.5 mm in this case), the required board performance (modulus of elasticity, E) for different loading situations can be calculated. 3 Situations are considered:

- Clothing: E.g. 7 jeans, 7 sweaters, 10 shirts; 10 kg maximum.
- Crockery: 8 Diner plates à 650 g, 8 soup plates à 470 g, 8 breakfast plates à 460 g
- Books: Full length of the shelf covered with on average 20 x 25 cm size books
    - The force in N is calculated by multiplying the weight in kg by 9.81 m/s^2.

The required performance for the modulus of elasticity, E, and the corresponding particle board grade (par. 5.1.1.3) are presented in Table 35. At given panel thickness (19 mm = 3/4 inch), P3 grade PB is required for crockery, whereas for a heavy load of books, even P7 would not meet the defined deflection limit.
In order to meet the deflection limit, a thicker panel can be used. Results for a 25 mm (1 inch) panel are also presented in Table 35.
Alternatively, a shorter shelf span could be used: at 70 cm span instead of 85 cm, the modulus would have to be 2274 MPa (P4); at 65 cm span the modulus would need to be 1821 MPa (P3), and at 60 cm span a modulus of 1432 MPa (P1) can deliver the performance.

Table 35 Required modulus of elasticity, E, and the corresponding particle board grade for shelves of 85 x 30 x 1.9 cm³ for different loading situations.

				Thickness = 19 mm		Thickness = 25 mm	
Type of load	**Weight (kg)**	**Force (N)**	**Force per length (N/m)**	**Modulus, E (MPa)**	**Minimum Grade**	**Modulus, E (MPa)**	**Minimum Grade**
Clothes	10	98.1	115.41	1292	P1		
Crockery	12.64	124.0	145.88	1633	P3	717	P1
Books	31.52	309.2	363.81	4072	>P7	1787	P3

When staying withing the indicated deflection limit of span/240, the stress in the shelf usually remains within the safe range for typical PB and MDF board grades. When developing board materials based on new feedstock, the ratio of stiffness (relevant for deflection) and strength may change. Then it is important to evaluate the maximum stress in a shelf at given conditions relative to panel strength. The maximum stress, σ_{max}, in a uniformly loaded shelf can be calculated as follows:

$$\sigma_{max} = \frac{y_{max}*q*L^2}{8*I} \qquad \text{(equation 4)}$$

Where:
y_{max} = half the thickness of the shelf (m)

Annex 4 Textile background information

This appendix provides background information about the textiles.

4.1 Fibres for textiles

Fibres that are used in textile processing have specific lengths. Normally, short staple fibres refer to fibres that have a length of up to 60 mm. For example, cotton is considered as a short staple fibre with lengths of 25-45 mm. On the other hand, long staple fibre are the fibres which have a length of more than 60mm. For instance, wool fibres are considered as a long staple fibre with lengths between 60–460 mm[177].

Three different types of fibres in textiles can be distinguished. 1) Natural fibres could come from plants or animals. Plant fibres could be extracted from plant seeds such as cotton or from plant's bast such as flax, hemp, nettle. In general, bast fibre is stronger and coarser than cotton and more durable. 2) Semi-synthetic fibre or regenerated fibre such as viscose and lyocell could be generated from cellulosic sources after chemical extraction and solution spinning process. 3) Synthetic fibres are usually fossil-based plastic fibres such as polyester and nylon[178].

The global production of textile fibres reached 116 Mt in 2022. The two main fibres which are dominant are polyester and cotton with a share of 54% and 22%, respectively. Regarding bast fibre, it has a small share of around 6% of the total fibre produced for textiles worldwide[179]. Flax is the most important bast fibre in textiles[180,181] and it is used for many textile applications in clothing (e.g. coats, hats, dresses, etc.) and furniture (e.g., upholstery and curtains)[182].

The mechanical properties of natural fibres are influenced by a range of factors, including their physical, chemical, and structural characteristics, along with conditions during growth, timing of harvest, methods of extraction, treatment processes, and how they are stored[183,184]. To give an example, Pickering et al (2007)[185] observed that hemp fibres experienced a 15% decrease in strength over a period of five days following the optimal harvest time, which was identified as 114 days after sowing, showing an average tensile strength of 857 MPa.

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[178] Harmsen, P., & Bos, H. (2020). *Textiles for circular fashion: Part 1: Fibre resources and recycling options*. Wageningen Food & Biobased Research.

[179] Materials Market Report 2023, https://textileexchange.org/materials-market-report-2023

[180] Materials Market Report 2023.

[181] Ahmad, S., Ullah, T., & Ziauddin. (2020). *Fibers for technical textiles* (pp. 21-47). Springer International Publishing. P.25

[182] Kozlowski, R. M., & Mackiewicz-Talarczyk, M. (Eds.). (2020). *Handbook of natural fibres: Volume 2: Processing and applications*. Woodhead Publishing. P.147-166

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[184] Schumacher, A. G. D., Pequito, S., & Pazour, J. (2020). Industrial hemp fiber: A sustainable and economical alternative to cotton. *Journal of Cleaner Production*, *268*, 122180.

[185] Pickering, K. L., Beckermann, G. W., Alam, S. N., & Foreman, N. J. (2007). Optimising industrial hemp fibre for composites. *Composites Part A: Applied Science and Manufacturing*, *38*(2), 461-468.

4.2 Yarns for textiles

Yarns that are produced by ring-spinning are the strongest and finest yarns. Ring spinning produces yarn with a wide range of count and twist (see Figure below). Those yarns can be used for a variety of knitted and woven fabric. Rotor spinning produces yarn that is thicker and less strong (by almost 20%) than ring spun yarn[186].

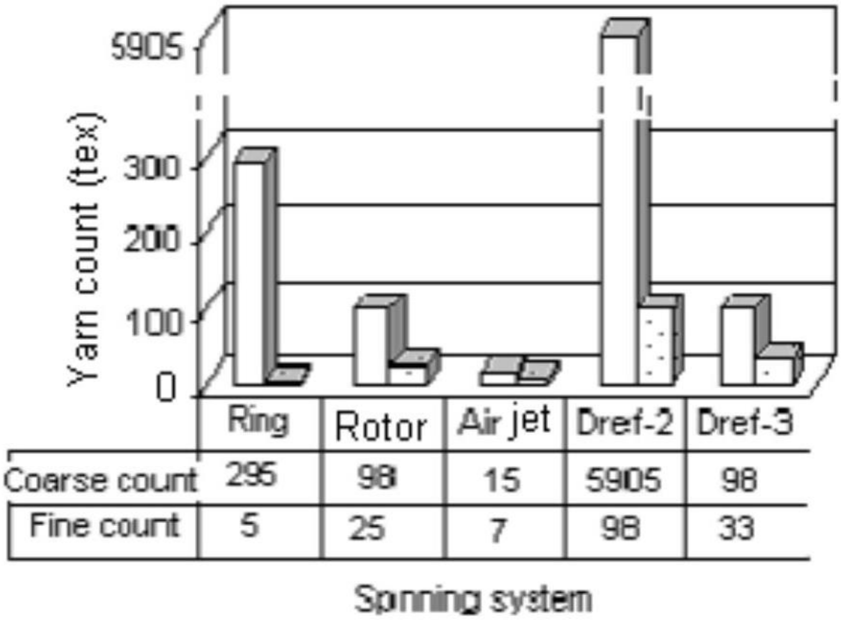

Figure 22 Economic count ranges of different spinning systems. (copied from Sinha).[187]

The length of wool fibres can be varying between 250–300 mm (10–12 inches)[188] and the diameter between 8- 60 microns[189].

4.2.1 Yarn strength

When it comes to evaluating the quality of the yarn, strength would be the most important property. The stronger the yarn used to construct the fabric, the stronger the fabric will be[190]. Yarn strength is usually determined according to ISO testing. Normally, for textile products the requirement of the yarn strength is in the range 10 - 30 cN/tex.[191]

It is important to note that there are two ways for the yarn to fail: fibre breakage and fibre slippage.

4.2.2 Yarn fineness (count)

Yarn fineness is an important property affect fabric's weight and bending rigidity. To produce a fine yarn, fine fibres are required. Using coarse fibres would result in a thick yarn. Fine yarn from coarse fibre might be produced, however, the yarn would be irregular and weak. Having coarser yarn will affect the bending rigidity of the fabric. The fabric made from coarse yarn will be stiff and less drapeable[192].

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[186] Elmogahzy, Y. (2019). Engineering textiles: Integrating the design and manufacture of textile products. Woodhead Publishing.
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[188] Hearle, J. W., & Morton, W. E. (2008). Physical properties of textile fibres. Elsevier.
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[190] Begum, M. S., & Milašius, R. (2022). Factors of weave estimation and the effect of weave structure on fabric properties: A review. Fibers, 10(9), 74.
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The finest yarns can be produced from viscose and lyocell because the finesses of the fibres are controlled during the production. From cotton can also be produced fine yarn. The fineness and strength of the yarn spun from cotton are influenced by the length of its fibres. Generally, longer fibres result in finer and stronger yarns[193]. With other properties being equal, finer yarns can generally be spun from longer fibres. As mentioned previously, the finer the fibre, the finer the yarn that can be produced. However, it is important to take into account the strength of the yarn when producing fine yarn. An example, a ring spun yarn cotton/polyester should have 18 cN/tex strength for weaving.[194]

Flax and hemp have naturally a thicker fibre diameter than cotton, which makes the spinning process more challenging. Looking into flax, fine and regular long fibres can be spun into textile clothing. Flax fabric is suitable for summer clothing because it provides cooling next to UV protection. The challenge related to flax spinning is the elongation (1.5-3%) which leads to breaks on the spinning machine. Hemp is similar to flax with its properties. Nonetheless, hemp have thicker diameter compared to flax which make spinning of fine yarn impossible. The range of hemp yarn finesses is between 18 - 380 tex. Fabric hemp weight can be varied between 270-540 gsm. Hemp could be processed on a flax production line. In general, the difficulties related to hemp and flax spinning require lower spinning speed, which makes the process more costly.[195]

Many developments have been carried on conttonizing hemp fibres. China succussed to cottonize hemp fibres and produced on industrial scale. Those cottonized hemp fibres are mainly blended with cotton or wool for clothing. From the shives of hemp is possible to produce hemp viscose which is ideal for clothing.[196]

Ring spun yarn of hemp/cotton blends show 15-20% increase of strength compared to pure cotton.[197] A flax/viscose/cotton ring-spun yarns show possibilities to be processes with the following properties yarn count 31 tex, strength 10 cN/tex and elongation 5%.[198] This make it possible to be applied in jeans or suits.

4.3 Fabric for textiles

The three main woven fabric structures are plain, twill and satin (figure below).[199] The difference between those three different weave structures is the way of production on the loom and the type of interlacing which gives different properties. Plain fabric is the strongest weave structure due to the maximum number of interlacing. Also, plain fabrics are stiffer compared to twill and satin weave with the same yarn and fabric density.[200]
Next to the weave structure, the properties of the fabric are affected by warp preparation, loom speed, warp and weft tension and densities, weave density, etc. The fabric that comes out of the loom undergoes post-treatment prior to finishing. Those treatments also affect the mechanical properties of the final product.

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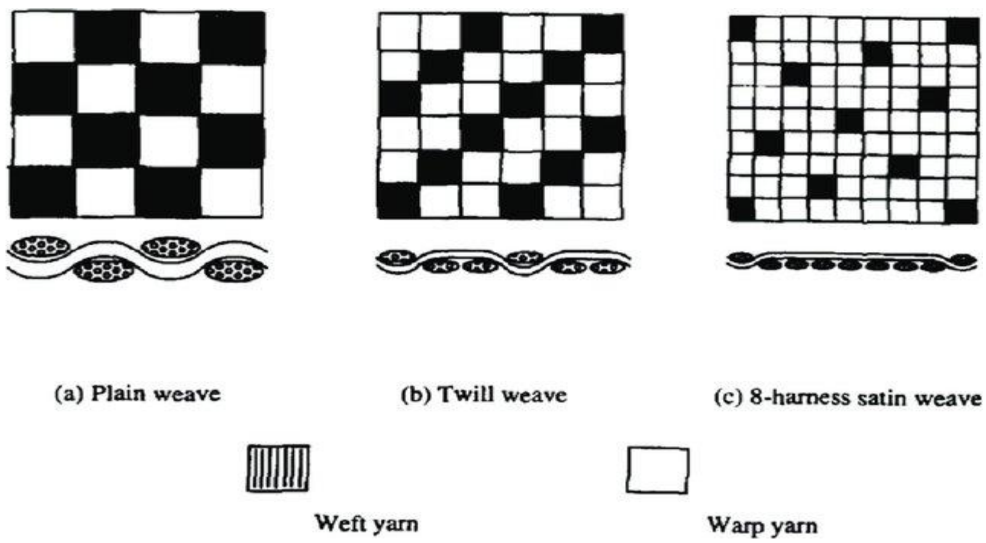

Figure 23 Different weave structures, from left to right: plain, twill and satin, acquired from Karaduman, 2017.[199]

4.3.1 Fabric strength

Research reveals that there is a linear correlation between yarn strength and fabric tensile strength. This means the stronger the yarn, the stronger the fabric that will be produced. Experience shows that for the same so called 'cover factor' (i.e., the fractions of area covered by warp and weft in fabric), plain weave has higher tensile strength than twill and satin due to the higher number of interlacings and the shorter float length (i.e., the number of warp or weft threads the yarn passes over) in plain structure. Further, fabrics with higher mass per unit area have higher tensile strength.[201] Weave structure also affects other properties such as fabric stiffness and tear strength.[202]

4.3.2 Fabric density and weight

Besides fabric strength, final application of the fabric relates to the fabric weight and density. It is well known that the denser the fabric, the more durable and apron to abrasion it will be.[203]

The fabric can be categorised based on its weight into light fabric 100-170 GSM, medium weight fabric 170-340 GSM and heavy fabric 340-400 GSM.[204] Light woven fabric is typically used for top clothing such as blouses, while heavier fabrics are used for bottom clothing such as pants. It is possible to adjust or control fabric weight by focusing on four main factors: fibre type, yarn count, fabric construction and fabric count (i.e., number of yarns per length unit). Additionally, mechanical and chemical treatments applied after weaving can further alter the fabric's weight.[205]

Fabric weight can be calculated by combining the weight of the warp and weft yarn per fabric surface area. Knowing the fabric weight will help later to match the final products requirements with the fibre properties. Warp and weft weight can be calculated after knowing the number of warp yarns per inch and number of weft yarns per inch.

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[201] Fan, J., & Hunter, L. (2009). *Engineering apparel fabrics and garments*. Elsevier. P.180
[202] Begum, M. S., & Milašius, R. (2022). Factors of weave estimation and the effect of weave structure on fabric properties: A review. *Fibers*, *10*(9), 74.
[203] El Mogahzy, Y. E. (2009). Integrating the Design and Manufacture of Textile Products. P 255-256
[204] Understanding Fabric Weights – Core Fabrics (corefabricstore.com)
[205] El Mogahzy, Y. E. (2009). Integrating the Design and Manufacture of Textile Products. P 257-258

4.4 Abrasion

Abrasion refers to the fabric wear or tear as a result of friction and rubbing against another fabric which could be the same or another material. Abrasion is considered as a fabric default and one of the criteria which determine fabric quality. Less cohesion yarns usually resulted in a weak fabric that prone quickly to abrasion. Further, the fabric structure affects the degree of resistance to abrasion. For instance, fabric with short float length has a higher resistance to abrasion then fabric with short float length. Plain woven structure usually has higher abrasion resistance then twill and satin. Abrasion is determined by ISO 12947-1, -2, -3 and -4. When the fabric reaches a specific number of broken yarns then the test is finished, and the quality of the fabric is determined.[206]

4.5 Pilling

When the fibres are removed party from the yarn and entangled to form a ball-like clusters on the fabric surface it is called then pill. Pilling is considered one of the import quality fabric properties. This phenomenon is a significant concern in both clothing and home textiles, serving as an indicator of material integrity besides less aesthetic appearance. Pilling testing is determined by ISO 12945-2 (Modified Martindale method). In this test the fabric surface is subjected to rubbing against another fabric which could be the same fabric or a different material. The evaluation is based on a specific number of rotations or cycles, resulting in a graded assessment ranging from the highest to the lowest quality according to 5 grades specified in the mentioned ISO.[207]

Pilling is highly connected to the fibre's length used. The longer the fibre the less baron to pilling the fabric will be. Fabric with low density and high float length is more likely to face pilling issues. For example, satin is less resistance to pilling than plain fabric.[208]

4.6 Comfort

One of the basic functions of the clothing is to be comfortable during wearing or using phase. Comfort for clothing can be classified into physiological and psychological comfort. Physiological comfort involves maintaining bodily functions, while psychological comfort relates to mental well-being. Factors influencing comfort include thermal insulation, moisture permeability, tactile sensations, and garment fit. Tactile comfort, for example, is influenced by fabric surface characteristics and sensory receptors in the skin, while thermal comfort depends on factors like fabric thickness, insulation, and moisture transmission properties. Garment design plays a crucial role in thermal insulation and moisture management. Ultimately, achieving optimal comfort in clothing involves balancing various factors to meet the diverse needs of users.[209]

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Annex 5 Modelling indicative textile strength and weight

This appendix provides an indicative textile modelling exercise on fibre-yarn-fabric correlations in order to assess the potential suitability of locally available fibres for a range of applications.

5.1 Fabric density and weight

Fabric weight consists of the combined weight of the warp and weft yarn per fabric surface area. In this exercise, a fabric surface area of 1 m^2 is selected. However, the calculation exercise starts with the fibres in the yarn.
The volume, V, of a fibre can be determined as follows:

$$V = \frac{\pi * d^2 * L}{4} \quad \text{(Equation 5)}$$

Where:
d = fibre diameter (m)
L = fibre length (m)

Using the equation that correlates mass, volume and density: m = V * ρ, the following equation can be written:

$$\frac{m}{L} = \frac{\pi * d^2 * \rho}{4} \quad \text{(Equation 6)}$$

Where:
m = fibre mass (kg)
ρ = fibre specific density (kg/m^3)

The linear fibre density of the fibre, FC, expressed in tex (= g/1000 m) then is as follows:

$$FC = \frac{\pi * d^2 * \rho * 0.001}{4} \quad \text{(Equation 7)}$$

With:
d = fibre diameter (micron)
ρ = fibre specific density (g/cm^3)

Assuming the minimum number of 80 fibres per yarn cross section, the diameter of the yarn, d (micron), then can be calculated from yarn count, YC (tex), using the 'inverse' of equation 7, and including the yarn packing factor, θ:

$$d = \sqrt{\frac{YC * 4}{\pi * \rho * 0.001 * \theta}} \quad \text{(Equation 8)}$$

Where:
YC = FC * 80 (tex) (Equation 9)

The number of yarns per m in warp direction, EPM, is:

$$EPM = \frac{L * Of}{d} \quad \text{(Equation 10)}$$

Where:
L = fabric length in warp direction (mm)

Of = warp occupation factor (-)
d = warp yarn diameter (mm)

The number of yarns per m in weft direction, PPM, is:

$$PPM = \frac{L*Of}{d} \quad \text{(Equation 11)}$$

Where:
L = fabric length in warp direction (mm)
Of = weft occupation factor (-)
d = weft yarn diameter (mm)

The weight, W (gsm), of a plain weave fabric with the same yarn used for both warp and weft direction, and considering crimp then is:

$$W = YC * \left(\left(EPM * L * (1 + cra) \right) + \left(PPM * W * (1 + cre) \right) \right) * 0.001 \quad \text{(Equation 12)}$$

Where:
L = fabric length in warp direction (m)
W = fabric length in weft direction (m)
cra = crimp in warp direction (%)
cre = crimp in weft direction (%)

<u>Example calculation:</u>
Using equation 7, and assuming a fibre of 20 micron diameter and 1.5 g/cm^3 specific density, the linear fibre density or fibre count, FC (g/1000 m) is:

$$FC = \frac{\pi*20^2*1.5*0.001}{4} = 0.47 \text{ tex}$$

Using equation 8, and assuming a yarn packing factor, θ, of 0.6, the yarn diameter, d (micron), is:

$$d = \sqrt{\frac{0.47*80*4}{\pi*1.5*0.001*0.6}} = 231 \text{ micron} = 0.23 \text{ mm}$$

Using equation 10, and assuming a warp occupation factor, Of, of 0.48, the number of yarns per m in warp direction, EPM (yarns/m), is:

$$EPM = \frac{1000*0.48}{0.23} = 2078 \text{ yarns/m}$$

Using equation 11, and assuming a weft occupation factor, Of, of 0.45, the number of yarns per m in weft direction, PPM (yarns/m), is:

The number of yarns per m in weft direction, PPM, is:

$$EPM = \frac{1000*0.45}{0.23} = 1949 \text{ yarns/m}$$

Using equation 12, and assuming crip factors of 3% and 5% in warp and weft direction, respectively, the weight, W (gsm), of 1 m^2 of plain weave fabric is:

$$W = 0.47 * 80 * \left(\left(2078 * 1 * (1 + 3\%) \right) + \left(1949 * 1 * (1 + 5\%) \right) \right) * 0.001 = 158 \text{ gsm}$$

5.2 Yarn strength

Many researchers have worked on yarn strength modelling, often resulting in equations that include parameters that are difficult to measure. One of the easier to use correlations is a regression equation mentioned by Ghosh (2005),[210] estimating ring spun yarn tenacity, RYT (cN/tex), based on the cotton bundle strength:

RYT = 0.31 * UR + 0.80 * BT – 1.1 * BE – 0.73 * Mc + 0.062 * YC + 0.35 * TF – 21.8 (equation 13)

Where:
UR = uniformity ratio (%). This is measure for the variation in fibre length, being 40-50% for cotton, 45% on average.[211]
BT = fibre bundle tenacity (cN/tex)
BE = bundle elongation (%)
Mc = micronaire. This is a measure of the air permeability of compressed cotton fibres, used as an indication of fibre fineness and maturity.[212]
YC = yarn count (tex). See equation 14.
TF = twist factor. This is the relative value that indicates the degree of twisting of the yarn in combination with the linear density.[213] See equation 15.

Yarn count (tex) can be determined as follows:
YC = FC * N (equation 14)

Where:
FC = fibre count (tex). See equation 15.
N = number of fibres in yarn cross section. For ring spun yarns, the minimum number of fibres in the cross section would be 80.[214]

The fibre count, FC (tex), can be determined according to equation 7 in section 5.1
The twist factor, TF, relates to the twist, T (turns per cm), and the yarn count, YC (tex):[215]

$$TF = T * \sqrt{\frac{JC}{1000}}$$ equation 15)

The twist is typically about 40 twists per inch (15.75 twists per cm).

<u>Example calculation</u>
Whereas it may be noted that equation 13 has been derived for cotton, it has been used to obtain an impression of how flax fibre properties affect flax ring spun yarn strength. The following may be considered:
UR = 45 %
BT = 55 cN/tex
BE = 1.8%
Mc = d = 20 micron
N = 80

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ρ = 1.5 g/cm^3
YC = 38 tex (calculated using equations 7 and 14)
TF = 3.1 (calculated using equation 15)

Thus, from equation 13, the estimated tenacity of flax ring spun yarn is:
RYT = 0.31 * 45 + 0.80 * 55 – 1.1 * 1.8 – 0.73 * 20 + 0.062 * 38 + 0.35 * 3.1 – 21.8 = 25 cN/tex

5.3 Fabric strength

Malik et al, (2011) developed a linear regression equation for the tensile strength of 100% cotton fabric in warp and weft direction.[216] The equations for fabric strength in warp direction, FTSwp (N), and weft direction, FTSwt (N), are:

FTSwp = YSwp * (0.025 * E – 0.5) + 0.06 * YSwt – 1.85 * E + 0.88 * P – 13.8 * F + 55.01 (equation 16)

FTSwt = YSwt * (0.023 * P – 0.38) + 0.03 * YSwp + 0.72 * E – 1.64 * P – 13.5 * F + 37.1 (equation 17)

Where:
YSwp = warp yarn breaking force (cN). See equation 13.
YSwt = weft yarn breaking force (cN). See equation 13.
E = number yarns per 25 mm in warp direction. See equation 10.
P = number of yarns per 25 mm in weft direction. See equation 11.
F = float length (e.g. 1 for plain weave)

YS (cN) can calculated by multiplying yarn tenacity, YT (cN/tex), and linear density or yarn count, YC (tex), both described in section 5.2:

YS = YT * YC (equation 18)

<u>Example calculation:</u>
The same flax yarns are used in warp and weft direction, so the breaking force, YS, is the same. The following parameters have been determined in sections 5.1 and 5.2:
YT = 25 cN/tex
YC = 38 tex
YS = 950 cN (calculated using equation 18)
E = 53 yarns/inch (2078 yarns/m *25.4 mm/inch / 1000 mm/m)
P = 50 yarns per inch (1949 yarns/m *25.4 mm/inch / 1000 mm/m)
F = 1

Thus, from equations 16 and 17, the estimated fabric strength in warp and weft direction is as follows:

FTSwp = 950 * (0.025 * 53 – 0.5) + 0.06 * 950 – 1.85 * 53+ 0.88 * 50 – 13.8 * 1 + 55.01 = 804 N

FTSwt = 950 * (0.023 * 50 – 0.38) + 0.03 * 950 + 0.72 * 53 – 1.64 * 50 – 13.5 * 1 + 37.1 = 713 N

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5.4 Textile correlations from fibre to fabric

The correlations presented in the previous sections were applied on the following fibres: flax, hemp, cotton, viscose and lyocell, in order to give an indication about the limitations and possibilities of using each fibre for certain application. The table below presents how the physical properties of each fibre are linked to ring spun yarns and finally plain-woven fabric, according to the equations presented in the previous sections. This provides a rough indication of to which extent the fibres are suitable to match products requirements.

Table 36 Estimation of ring spun yarn and plain weave fabric weight and strength based on theoretical and empirical equations for cotton (sections A5.1 – A5.3).

	Fibre				Yarn						Fabric						
	fibre count	fibre count	Bundle tenacity	Bundle elongation	yarn count	Twist factor	Uniformity ratio	Yarn strength	yarn breaking force	yarn diameter	EPM (warp)	PPM (weft)	Warp weight	Weft weight	Fabric weight	Fabric tensile strength (warp)	Fabric tensile strength (weft)
	micron	dtex	cN/tex	%	tex	-	%	cN/tex	cN	mm	yarns per m	yarns per m	GSM	GSM	GSM	N	N
flax	20	4.71	55	0.018	37.7	3.1	45	24.9	940	0.23	2078	1949	80.7	77.1	158	796	705
hemp	20	4.71	58	0.015	37.7	3.1	45	27.3	1031	0.23	2078	1949	80.7	77.1	158	873	775
Nettle	30	10.6	40	0.025	84.8	4.6	45	9.1	771	0.35	1386	1299	121.1	115.7	237	334	301
Cotton	15	2.65	30	0.05	21.2	2.3	47.8	8.1	172	0.17	2771	2598	60.5	57.8	118	193	164
viscose	10	1.18	30	0.015	9.4	1.5	51	11.8	111	0.12	4157	3897	40.4	38.6	79	175	149
Lyocell	10	1.18	36	0.014	9.4	1.5	51	16.6	157	0.12	4157	3897	40.4	38.6	79	273	235

Assumptions: Fibre specific density is 1.5 g/cm^3; yarn packing factor is 0.6; loom reduction factor is 48/50 and 45/50 for warp and weft direction, respectively; crimp is 3% and 5% for warp and weft direction, respectively; float length is 1 for all fabrics. Strength is per 25 mm fabric width.

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Annex 7 Qualitative justification of eco-system service scores

7.1 Justification scores biodiversity

Flax
"Both flax and hemp form good territories for various farmland birds. This is because of the shelter that the crop provides, and leftover seeds that can serve as a food source in winter. Partly for this reason, flax is also regularly included in the prescribed mixtures for the management package for winter food fields. Interesting for birds such as meadow pipit, tree sparrow, goldfinch and skylark. (CLM report) Flax cultivation provides a habitat for insects, which serve as 'pollinators'. A number of rare animals find flax fields a pleasant habitat, such as the partridge or the flax finch. (Coninx et al., 2014)"

Hemp
"Both flax and hemp form good territories for various farmland birds. This is because of the shelter that the crop provides, and leftover seeds that can serve as a food source in winter. Partly for this reason, flax is also regularly included in the prescribed mixtures for the management package for winter food fields. Interesting for birds such as meadow pipit, tree sparrow, goldfinch and skylark. (CLM report) Hemp has a slightly positive effect on the number of yellow wagtails and a strong positive effect on the skylark. Wiersma et al. expect that hemp can form a suitable breeding crop for the skylark, especially at the beginning of the breeding season, when the crop is still low and open. (CLM report)" "(…) it offers an attractive environment for hares and partridges.

Miscanthus
(WUR) Compared to maize or other annual crops, Miscanthus has more biodiversity. The crop mainly functions (in winter) as a shelter, for hares, mice and insects, among other fauna. Because Miscanthus does not flower, it does not provide nectar; Insects such as bees and bumblebees therefore find no food there. A flowering field edge around it does provide food. Organic cultivation produces a more open crop with more weeds than conventional cultivation and may therefore contain more biodiversity. (Louis Bolk)

Reed
The banks, reed edges and strips form a biotope for reed birds and insects. (this source is about all forms of reed cultivation) (Korevaar & van der Werf) in "wet agriculture", the effects on biodiversity and meadow birds are more difficult to estimate. Crops such as reeds and cattails will not be beneficial for meadow birds because they form a relatively high, closed production vegetation. A complete development of an area with wet crops is therefore not desirable from the point of view of meadow birds. (Louis Bolk 4)

Cattail
It turns out that for butterflies, dragonflies and amphibians, the diversity is highest in the cattail areas based on the occurrence of numbers/diversity. Literature studies show that moths, reptiles (grass snake), mammals (bats and dwarf mice) and macrofauna these species use reeds and cattails to shelter and forage (HAS) Important habitat for dragonflies and aquatic fauna (Factsheet Cattail).

Willow
Shelter, foraging or resting place for animals (Factsheet Willow). Flowering willows provide pollen and/or nectar for bees early in spring. (Feeder trees).

Cupplant
Also for wild bees (Bee plants) The long flowering season and the abundance of flowers provide a rich source for the bees and the cultivation of honey (Biobased crops). The leaves retain rainwater and thus form drinking troughs for insects and birds. Small game can also hide there. (Agricultural Life)

Nettle
Stinging nettles are great wildlife attractors: caterpillars of the small tortoiseshell and peacock butterflies use them as foodplants; ladybirds feast on the aphids that shelter among them; and seed-eating birds enjoy their autumn spoils. (Wildlifetrust)

Verge grass
Positive under the following conditions: sowing verges with local flower meadow mixtures that are attractive to bees and other insects. (Value Wenders)

Straw (rapeseed)
Rapeseed is a flowering crop that attracts bees, for example. The presence of bees stimulates biodiversity. Bees provide 80% of the flower pollination. (Prospects rapeseed) "Rapeseed attracts many insects and is a shelter crop for many mammals (e.g. deer and hares), so it promotes biodiversity." (LTO Noord 2)

7.2 Justification scores soil organic matter

Flax
Limited; provides an effective organic matter input of 100 kg/ha per crop to the soil. Fibre flax itself hardly supplies any input of organic material to the soil via crop residues: the entire crop is harvested (De Bont et al., 2008). When a green manure is grown after flax or when flax serves as a cover crop for grass seed cultivation, there is input. It is precisely the short growth period of flax that offers excellent opportunities for sowing green manures that contribute to organic matter in the soil CLM report)

Hemp
Limited; The input of effective organic matter from hemp is 660 kg/ha per crop, including stubble (organic matter balance NMI & SMK). As has already been noted, crop residues from hemp remain (Grow2Build 2015; Rana et al., 2014; CLM report).

Miscanthus
Miscanthus has a more favourable influence on a number of soil properties than annual crops: higher organic matter content (Louis Bolk).

Reed
The risk on decline of soil organic matter is limited in reed fields, as reed is a perennial plant of which at least the roots and stubbles remain in the soil. Late harvesting in winter is in this case beneficial for soil organic matter, as the leaf biomass will remain on the field. (WUR 7)

Cattail
No literature found, probably comparable to reed.

Straw (rapeseed)
Because the organic matter of the rapeseed remains on the bed and is not removed, the soil is enriched with humus. This improves soil fertility and promotes soil life. Along with the remaining parts of the plant, the rapeseed also brings nutrients into the soil - especially sulphur, nitrogen and potassium. Finally, the cultivation of rapeseed as green manure also ensures that the soil is covered. This protects the soil from drying out and erosion. (Jardin Planet)

Straw (barley)
Grains differ in the amount of effective organic matter they leave with the root and stubble residues. Winter and spring wheat supply the highest amount, followed by oats and winter barley. Rye and spring barley have the lowest supply of effective organic matter. (Seven crops)

Straw (wheat)
Grains differ in the amount of effective organic matter they leave with the root and stubble residues. Winter and spring wheat supply the highest amount, followed by oats and winter barley. Rye and spring barley have the lowest supply of effective organic matter. (Seven crops)

Straw (oats)
Oats are not only grateful for a good organic matter content, but also ensure their maintenance through a large production of roots and stubble. (WUR 4)

Straw (rye)
Grains differ in the amount of effective organic matter they leave with the root and stubble residues. Winter and spring wheat supply the highest amount, followed by oats and winter barley. Rye and spring barley have the lowest supply of effective organic matter. (Seven crops)

Straw (triticale)
As a cereal crop, triticale fits perfectly in a crop rotation with root crops. By supplying organic matter in the form of roots, stubble and shredded straw and its suitability as a cereal crop for the sowing of a green manure, triticale contributes to a good soil structure. As a monocot, triticale has a suppressive effect on various pathogens, such as fungal diseases, free-living nematodes and cyst nematodes. In a cropping plan with many root crops, triticale, like the other types of grain, is considered a healthy crop. (WUR 6)

Straw (more)
Maize is bad for soil structure, soil organic matter and soil biodiversity. (Forage trees)

Straw (sorghum)
No convincing evidence has yet been found in the Netherlands for a more positive organic matter balance under (starch) sorghum compared to maize. As far as structural sorghum is concerned, slight indications have been found for a higher root mass (supply of organic matter) compared to maize, but the differences are limited. (Louis Bolk)

7.3 Justification scores other effects soil

Flax
It is striking that both flax and hemp can be used for the remediation of soils contaminated with heavy metals, because these crops absorb heavy metals (Ahmed et al., 2015; Kozlowski et al. 2004; Piotrowski & Carus, 2001). In the Netherlands, flax and hemp are not used for this purpose. (CLM report)

Hemp
It is striking that both flax and hemp can be used for the remediation of soils contaminated with heavy metals, because these crops absorb heavy metals (Ahmed et al., 2015; Kozlowski et al. 2004 in Piotrowski & Carus, 2001). In the Netherlands, flax and hemp are not used for this purpose. (CLM report)

Miscanthus
"Miscanthus has a more favourable influence on a number of soil properties than annual crops. Better soil structure, higher aggregate stability, lower penetration resistance, deeper growing roots. Because of its beneficial effects on the soil, miscanthus can play a role in restoring soil structure and eliminating soil compaction in deeper layers. (Louis Bolk)"

Reeds/Cattails
Because of the similarity between reed and cattail you would expect a similar assessment effect in halting land subsidence (Factsheet Cattail)

Willow
Inhibits soil subsidence at high groundwater levels (Factsheet Willow). The willow is deep-rooted and has a positive effect on soil quality. (Forage trees)

Cup plant
"Cup plant improves Soil through humus build-up (Silphie). During autumn, sun and increasing heavy rainfall increase the risk of soil erosion. Due to the rapid regrowth of the Silphie plant after harvest, this prevents erosion by water. In addition, the deep root system of Silphie increases its absorption capacity. This prevents soil silting and crusting. That is why Silphie is very suitable for cultivation on slopes, as there is a lot of soil erosion there. (Silphie 2)"

Straw (Barley)
Because it breaks down quickly, fields where barley was planted require less tillage. This reduces disturbance of the soil structure, which is also good for soil health. (Skagit Valley Malting)

Straw (Oats)
Oats play a beneficial role in soil fertility and soil health because it reduces various soil-borne pathogens. (WUR) Beyond those general benefits, oats are a particularly good crop for soil health and water quality, according to Larson. (Greenbiz)

Straw (rye)
As a deep-rooted green manure, (Japanese) oats, winter rye, are beneficial for restoring soil quality. (Agrarisch waterbeheer) Cereal rye roots does not contribute much to reduce soil compaction but it certainly improves soil tilth. Water infiltration is improved as well (IA State)

Stro (Maize)
Maize is bad for soil structure, soil organic matter and soil biodiversity. (Forage trees)

Sorghum
Keeping soil structure intact Less soil compaction (Louis Bolk 2)

7.4 Justification scores water infiltration

Flax/Hemp
Water drains well in wet periods/ Fibre flax and fibre hemp contribute to a good soil structure due to their deep rooting. (CLM report) Water drains well in wet periods. Fibre flax and fibre hemp contribute to a good soil structure due to their deep rooting. (CLM report)

Miscanthus
Promotes infiltration through deeper growing roots. (Louis Bolk)

Reed
Reed is the most popular because it grows quickly, has many and deep roots, is strong and sturdy, easy to grow and can withstand peak loads due to acids and salts, among other things. With its hollow rhizomes, it also transports oxygen to the soil. (Ypres plant)

Cattail
With its rhizome, it will spread underground. (Ecopedia)

Willow
Because the willow grows quickly and has deep strong roots, it is often planted to prevent erosion on the banks of rivers. (Green of course)

Cup plant
Deep root system, 2 meters deep (Silphie) & It has a very deep fine-meshed taproot and is therefore good for the soil. (LTO Noord)

Nettle
Maximum root depth up to ±1.5m (Cultivation manual Nettles)

Straw (rapeseed)
Cereals and grasses have intensive and deep roots (Agricultural water management). Growing rapeseed as a green manure has many advantages: the deep taproots of rapeseed loosen the soil and prevent compaction. In addition, the good rooting of the plant improves the soil structure and thus also the water retention capacity and aeration of the soil (Jardin Planet).

Straw (barley)
These barley grains are grown in a biodynamic way. Biodynamic goes a step further than organic. (…) Grain is a favourite crop in crop rotation: the deep root system makes the soil nice and airy. (Ekoplaza)

Straw (wheat)
Wheat has a fibrous root structure and, because it is a grass, its roots go deep into the soil profile, helping to develop soil structure and improve water infiltration. (Soilhealthpartnership)

Straw (oats, rye)
As deep-rooted green manure, (Japanese) oats, winter rye, English and Italian ryegrass or tall fescue are beneficial for restoring soil quality. (Agricultural water management)

Stro (triticale)
Triticale has a deep and fibrous root system (Biotill).

Straw (Maize)
The traditional cultivation method of maize has advantages as well as disadvantages: nitrate leaching, deterioration of general soil quality (including water infiltration and moisture retention capacity) (WUR 3).

Sorghum
As an alternative to and/or in rotation with maize, sorghum contributes to strengthening resistance to diseases and pests (especially soil-borne diseases and also the maize rootworm and maize stalk borer) and can eliminate soil compaction with deeper rooting (WUR 2).

To explore the potential of nature to improve the quality of life

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