



# **ARTIFICIAL INTELLIGENCE SOLUTIONS FOR THE RECYCLING AND UTILIZATION OF BIOMATERIALS FOR INDUSTRIAL APPLICATIONS**

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The escalating threat of global warming, primarily driven by the emission of greenhouse gases and the combustion of fossil fuels, underscores the urgency for adopting more sustainable practices. In response to this need and to reduce dependence on fossil fuels, biomaterials are increasingly recognized as a viable and sustainable alternative to conventional, unsustainable materials. Concurrently, rapid advancements in technology, particularly in artificial intelligence (AI), are presenting new opportunities for innovation and offering potential solutions to address the challenges posed by climate change. The commissioner for this thesis was Vaasa University of Applied Sciences Design Center MUOVA who wanted to gain insights of the industrial applications of biomaterials and explore the potential opportunities AI could offer in this field. Given the topicality and the specific research needs identified by Muova, the research questions were formulated to investigate the utilization of biomaterials in industrial settings, their recyclability, and the potential contributions of AI to their recycling and utilization.

The methodology employed for this thesis involved conducting a comprehensive literature review with data primarily gathered from scientific articles and information obtained from companies' websites that are actively involved in the biomaterials sector. Initially, biomaterials and their applications were examined broadly, followed by specific inquiries into industrial uses and relevant companies. Recyclability was examined both broadly and, on a case-by-case basis for previously identified biomaterials. Subsequently, utilization of AI was first searched in recycling in general and the focused specifically on the recycling of biomaterials and predictive material development.

The data gathered on biomaterials in industrial applications and their recyclability primarily focuses on various wood-based biomaterials and bio-based plastics. The recyclability of these materials is found to be dependent on their individual features, as well as factors such as quantity and geographical location. The research highlights the significant presence of companies in Finland engaged in this sector. Furthermore, results show that specific machine learning algorithms have advanced general recycling practices, indicating potential opportunities for biomaterial recycling, although more research is needed in this area. Moreover, AI has already played a pivotal role in the development and utilization of biomaterials in industrial settings. It is worth nothing that the thesis provides a broad perspective on this topic suggesting that further research is necessary to delve into each biomaterial more comprehensively for more accurate results.

Keywords Biomaterials, recycling, artificial intelligence, industrial applications

Pages 38 pages and appendices 2 pages

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# 1 Introduction

Global surface temperature ranked 1.35°C above the 1901-2000 average of 12.3°C during January-March 2024 (National Centers for Environmental Information, 2024). Global warming has been caused by human activities, principally through emissions of greenhouse gases. The dominant cause for the greenhouse gases are the combustion of fossil fuels and industrial processes. All future changes due to climate change cannot be avoided or reversed, but they can be limited by deep, rapid, and sustained reduction of global greenhouse gas emissions. (IPCC, 2023, pp. 4,18)

Biomaterials have been considered as an alternative for fossil-based materials. They tend to have a lower carbon footprint and are more biodegradable than petrochemical products. (CLC, 2021) The EU's circular economy action plan includes strategies for decreasing our dependency on fossil fuels and aims to take measures on bio-based, biodegradable, and compostable plastics (The European Commission, n.d.). Furthermore, sustainability commitments regarding total material reductions, content sourcing and end-of-life fate are increasing within companies. Many of these commitments are relevant for chemical and material companies. (Brennan et al., 2021) As the demand for sustainable materials is increasing, the future of biomaterials seems promising.

Rapid advancements in computing, automation, and artificial intelligence (AI) are advancing biological science and the development of biomaterials. New innovations are emerging such as genetically engineered microbes that are replacing nylon, cement from bacteria and leather from mushroom roots. (Brennan et al., 2021) Additionally, AI is advancing the waste management sector and enables faster and more efficient recycling. AI can assist in waste logistics by reducing transport distances, saving time and costs. Furthermore, AI can assist in identifying and sorting the waste with an accuracy ranging from 72.8 to 99.95%. (Fang B et al., 2023)

The research for this thesis was commissioned by Design Center MUOVA which is the design unit of Vaasa University of Applied sciences. Muova is an expert in market-oriented design and their services are scalable to various types of companies regardless of their size and industry due to their customer-centric approach and close cooperation with companies (Muova, n.d.). The thesis is linked to the Massikka project, an initiative by Muova focused on designing a training program about the business opportunities in the bioeconomy. As the use of biomaterials is increasing in industrial and service design and as Muova takes on projects

regarding digitalization and artificial intelligence, the need for classifying the biomaterials in industrial use and the solutions artificial intelligence could provide was identified. Based on these needs and the topicality of the previously mentioned subjects, the research topic was decided, and the following research questions were formed:

1. What types of biomaterials are utilized in the industrial sector and what are their respective applications?
2. What recycling methods are used for these biomaterials?
3. In what ways can artificial intelligence assist in the recycling processes of biomaterials?
4. How can AI assist in the prediction and development of novel biomaterials?

Although replacing fossil resources with biomaterials might appear to be a simple solution, it should be examined critically. There is a limited number of forests and other natural resources that can be utilized for industrial materials. (Oulun yliopisto, n.d.) These forests play a crucial role in providing important carbon sinks and, due to the effects of deforestation, Finland very well may fall short of its goal of achieving carbon neutrality by 2035 (Ikävalko, 2024). The importance of envisioning the long term should be emphasized when developing new bioproducts and preventing previously made mistakes regarding the development and use of fossil materials. With the assistance of technology, some of the emerging needs for the future can possibly be acknowledged quicker and uses for biomaterials can be detected more efficiently. (Oulun yliopisto, n.d.)

## **2 Background**

The background provides an overview of biomaterials and AI. It is important to note that this thesis focuses on industrial use of biomaterial. Hence, the background does not delve deeply into the medical sector's utilization of biomaterials. Additionally, the AI section reviews machine learning in more detail as it relates to the research findings.

Recent research from scientific articles on sustainability, biomaterials and AI was readily accessible due to the current relevance of these topics. However, when it came to theses specifically related to biomaterials, most focused on specific materials or their applications in the medical field. Surprisingly, there were no theses found that provided a broad overview of biomaterials. On the other hand, however, there were numerous theses related to AI applications.

## 2.1 Biomaterials

In the medical field, biomaterials are commonly defined as natural or synthetic materials that work as replacement materials for parts or functions of the body. Biomaterials can be made of metals, ceramics, plastics, glass and living cells or tissues. Via reengineering, these materials can be turned into molded or machined parts, coatings, fibers, films, foams, and fabrics for biomedical applications. (National Institute of Biomedical Imaging and Bioengineering, 2017).

Biomaterials have become more common in industrial use and are often defined as biobased raw materials. These biobased raw materials have become some of the key materials for replacing current fossil fuels, chemicals, and other appliances. (Oulun yliopisto, n.d.)

### 2.1.1 Sustainability aspect of biomaterials

New biomaterials are seen as potential alternatives to petrochemical production due to their lower footprint and greater biodegradability. Biobased products can replace plastics, building materials and textiles. Other advantages of bio-based products include reduction of harmful microplastics, and issues related to cultivation of cotton. (CLC, 2021)

In January 2018, the EU set up a circular economy action plan which includes a strategy for plastics. The plastic strategy plays a significant role in Europe's transition towards a carbon neutral and circular economy. The plastic strategy aims to reduce dependence on fossil fuels and to take measures on bio-based, biodegradable, and compostable plastics. (The European Commission, n.d.) Biopolymers with properties similar to conventional plastics can be applied as alternatives in various sectors. A shift towards biobased plastics is seen as an opportunity for circular economy as it can decrease the dependence on fossil fuel consumption. Due to inconsistency in plastic waste management, biodegradable and biobased plastics can be very advantageous as a result of their biodegradable properties. (Rajvanshi et al., 2023) Additionally, a non-paper on bioeconomy by Estonia, Finland, Italy, Latvia, Spain, and Sweden released in February 2024 includes key action points for bioeconomy in the EU. One key area mentioned in the non-paper is "Climate and sustainability" which emphasizes the importance of supporting green transition inside societies by replacing fossil and non-renewable resources in product manufacturing. (Non-paper - Key Actions for Bioeconomy in the EU, 2024) The need to transition towards green initiatives is evident in various sectors, including the battery industry, driven by the rising adoption of electric transportation. The surge in demand for anode materials underscores the

need for sustainable alternatives. Biobased materials have potential to replace these unsustainable materials. (Stora Enso, n.d.-d)

Sustainability of biomaterials is not undisputed, as sourcing of the biomaterial can lead to different sustainability issues. Effects of biomaterial production regarding climate change cannot be omitted. With the increase of wood-based materials, it is critical to consider the effects the production has on the forests and the carbon sinks provided by forests. Wood-based bioproducts should be produced with a focus on longevity. (Oulun Yliopisto, n.d.) To determine the sustainability of the wood products, it is important to evaluate the sustainability at three different stages: raw material procurement, material manufacturing and end of lifetime (Goldhahn et al., 2021).

Generally, biomaterials are viewed as sustainable, but it is still necessary to conduct a report on the short-, medium-, and long-term potential of biomaterials in mitigating climate change. Climate Leadership Coalition (CLC) has proposed conducting this type of report to the EU, and additionally to create mechanisms based on the carbon footprint to incentivize the substitution of fossil materials with biobased, recyclable, and marine biodegradable materials. (CLC, 2021)

### **2.1.2 Future of biomaterials**

The use of biomaterials started to spread long before the age of petroleum. Wood, paper, leather, and textiles are bio-based materials that have been produced for thousands of years and exist still today. (McKinsey & Company, 2021) Various smart devices have been integrated into our society in the course of rapid technological developments. Due to enzymes, other proteins or cells, natural materials can react to external conditions, thus changing the properties of a given material. New bio-based smart materials aim to mimic these biological mechanisms. An example of this would be a microbial-based leather that could generate an ingredient with an ability to repair a broken spot when exposed to oxygen and water. (Nordlund, 2022)

Probable uses for biomaterials in the future include uses in packaging and textile materials. As digitalization and electronic applications are increasing, green electronics is a growing research area based on the use of bio-based materials in electronic components and products. One example of green electronics is nanocellulose, which can be used to make screens, sensors, and antenna materials. After use, metals can be separated from the devices and the biomaterial can be composted. The medical field is also an important area

for the future of biomaterials, as biomaterials can be used in growing tissues, delivering of medications and DNA into the body, cells, as well as different diagnostics. (Oulun yliopisto, n.d.) In recent years, advancements and innovations have emerged in the field of biomaterials. However, the absence of scalable new business models and commercial products has become a notable challenge in biomaterial development. (Haarla et al., 2017, p. 126).

Additive manufacturing, also known as 3D printing, is a fast-developing sector and convenient home printers are becoming more common. Open-source services enable downloading and printing objects without any specific education or knowledge. Due to this, advancements can be expected in filaments and in other materials suitable for 3D printing. Wood and ceramics are most likely to take the steps in this direction. Printed textiles mimicking woven fabrics, fleece, or mesh can be expected in the future as well, but it will take time until these fabrics can take the place of traditionally manufactured fabrics. Other possibilities for the future in the textile industry might include the growing of clothes via bacteria or fungi or producing clothes with shaped molds and liquid materials. Locally sourced materials can also be expected in the future, which would benefit the local economy and improve the entire production chain. (Haarla et al., 2017, pp. 138–139)

## **2.2 Artificial intelligence**

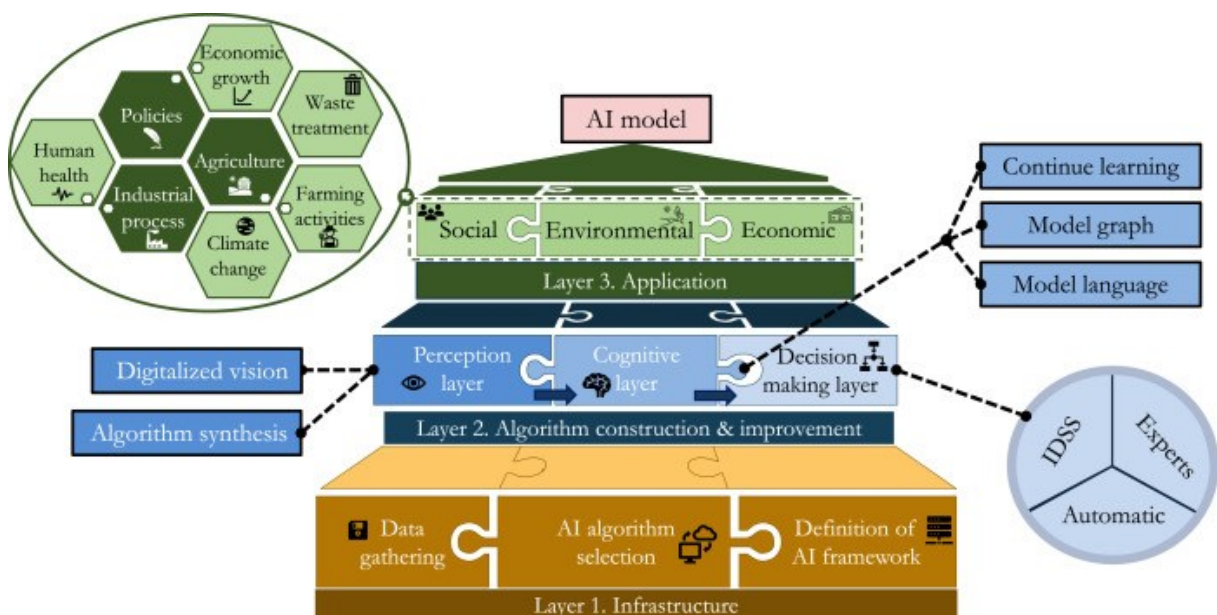
Artificial intelligence (AI) is intelligence of machines that is traditionally associated with human intelligence such as reasoning, learning, planning, or creating. With AI, technical systems can observe their environment, process their observations, and solve problems to achieve a specific goal. (European Parliament, 2020) The history of AI can be dated to the time when the first modern computers were built in the 1950s. Since then, there has been a shift of focus from AI based on formal logic to AI based on data and statistics. Over the past few years, there has been a rise in large language models (LLMs). Machine learning and deep learning are important and dominant disciplines of AI, which have the ability to learn from data and to improve their ability to make accurate classifications or predictions. (IBM, n.d.-a)

ChatGPT is one of the current breakthroughs in the field of AI; previous breakthroughs this large have been related to computer vision. Currently, the leap forward is in natural language processing (NLP). (IBM, n.d.-a) NLP combines statistical and machine learning models with computational linguistics, which allows for applications such as translations, summaries of

large volumes of text, and responding to typed or spoken commands (IBM, n.d.-b) Some other common applications for AI include virtual agents and chatbots in customer service, computer vision which can perform a specific action based on the derived information from images and videos, as well as weather forecasting that is enhanced with machine learning techniques. (IBM, n.d.-a)

Three process layers can map out the AI methodology as seen on the figure 1. The first layer is infrastructure, which includes the data collection and the framing of the initial definition of the intelligent algorithm. The second layer consists of three nodes: perception, cognition, and decision-making. The third layer comprises the application of the designed and optimized algorithm and it can provide a digitalization tool with the ability to evaluate variables of diverse nature such as industrial production, social organization, governance and waste management systems. AI is inherently linked with mathematics, as it utilizes the areas of statistics and probability which help in assessing the effectiveness of digital algorithms in solving or optimizing specific problems. (Arias et al., 2023)

Figure 1. AI framework mapped in three layers: infrastructure, algorithm construction and improvement and application (Arias et al., 2023)



### 2.2.1 Machine learning

Machine learning is a branch of AI that uses statistical learning and optimization techniques which enable computers to analyze datasets and recognize patterns. Through data mining,

machine learning can identify historic trends and predict future models. Machine learning algorithms update autonomously. Repetition is a significant benefit to machine learning, as, based on the analyzed data, the analytical accuracy improves on each run. (University of California, Berkley School of Information, 2020)

Machine learning can be divided roughly into four types of learning. One of these models is supervised learning, where the used dataset has been pre-labeled and classified by users. The opposite of this is unsupervised learning, where the used dataset is unlabeled, and patterns and relationships are identified by an algorithm without help from users. Semi-supervised learning includes a bit of both previously mentioned learning methods as it contains structured and unstructured data, which allows it to make independent conclusions. Furthermore, by combining the two datatypes, machine learning can acquire the ability to label unlabeled data. In reinforcement learning, the algorithm learns through experimenting by trial and error, as the dataset uses a system that either rewards or inflicts a penalty. (University of California, Berkley School of Information, 2020)

The University of California, Berkley School of Information (2020) has divided the supervised machine learning algorithm into three parts:

1. A decision process: Input data is handled, and estimation of the data's pattern is produced.
2. An error function: Involves measuring of predicted outcome with actual outcomes. With feasible known examples, error function can make comparisons that can determine the accuracy of the model.
3. An updating or optimization process: The algorithm updates decisions based on the miss to conclude the most accurate prediction.

An induction algorithm is part of machine learning and helpful in the real-time handling of advanced data sets but also in long-term endeavors. By using an induction algorithm, complex results can be obtained depending on the set up. An induction algorithm allows for the enhancement of knowledge acquisition in a given system. As an example, the enhancements can be related to the quantity of the data, filtering of noise or undesired results, or clarification of some data points. (Stoltzfus, 2022)

A more modern area of machine learning is deep learning, which automatically learns from data sets without human intervention. Vast amounts of raw data are required for the processing in deep learning and the predictivity of the data is dependent on the data quantities. (University of California, Berkley School of Information, 2020)

### **3 Methods**

The research for this thesis was conducted as a literature review. A literature review summarizes and explores the current state knowledge of a specific topic from different sources such as academic books and journal articles. The aim of a literature review is to present an overview of the research sources and to demonstrate how it aligns with the broader field of study. (McMaster University Library, n.d.)

The databases used for the literature search included Science Direct, Springer Link, and ResearchGate. Additionally, information from relevant websites, such as websites of companies that produce biomaterials, has been gathered. Furthermore, relevant books regarding biomaterials and AI have been used. The searches have been made between February-May 2024. In searching for relevant information, the following keywords and combinations thereof were used: “biomaterials”, “bio-based materials”, “artificial intelligence”, “machine learning”, “recycling”, “waste management”, “sustainability”, and “industrial applications”. The searches were conducted primarily in English, with some in Finnish, to gather information about biomaterial uses specifically in Finland.

The aim for this literature review was to map out the current state of biomaterials including common materials, their uses and recyclability. Additionally, the goal was to determine how AI is already assisting in recycling of biomaterials. Furthermore, the aim was to determine what the future possibilities and opportunities for the recycling of biomaterials are, how novel materials can be developed with the assistance of AI and how AI can help in developing the already existing biomaterials. Based on these, the previously mentioned research questions in introduction were chosen for this thesis.

Prior to commencing thesis writing, a data management plan, outlined in appendix 1, was implemented to ensure the availability and accessibility of research results. To address the first research question, different biomaterials and their uses were mapped. Given the broad spectrum covered by the term “biomaterials” and the dominant use of the term in medical applications, the scope of this research was narrowed down to industrial use. This decision

was guided by Muova's primary collaborations with companies operating in the industrial sector. The main geographic focus for the chosen biomaterials and for the companies working with these biomaterials was Finland, aligning with Muova's key engagements with Finnish enterprises. Moreover, data regarding biomaterials was gathered from other countries to enhance understanding on their qualities and functionalities.

Furthermore, a criterion for gathering relevant data was to include only studies from the past five years when researching AI's role in assisting recycling processes and material prediction. This criterion was chosen to ensure high-quality and up-to-date data, given the rapid advances in the field of AI. For other research questions, information was not gathered from sources that were more than seven years old. Approximately ten studies were disregarded during the research process due to the age criterion, lack of relevance such as focusing primarily on biomaterials in the medical field or being published in languages other than English or Finnish.

Once the industrial applications of biomaterials were identified, the subsequent task involved researching the recycling processes of the biomaterials. As these biomaterials are often stated to be more sustainable than their counterparts, it is significant to understand their recyclability and whether there are opportunities for innovative products or novel materials. Data on recycling methodologies were collected from scholarly literature, supplemented by information gathered from companies' websites, as they are typically required to provide guidance on product recycling procedures.

The subsequent phase of the research focused on investigating the recycling practices associated with the identified biomaterials and assessing the potential contributions of AI to these processes. This involved an exploration of AI's role of other materials such as general and organic waste, to discern how similar solutions could be adapted for the recycling of biomaterials. Furthermore, to answer the last research question, AI's solutions regarding the prediction of novel materials and uses were researched.

One of the limitations was related to selection bias. The chosen biomaterials for this research were narrowed down to the industrial sector, which conceivably limited the availability of literature to be used. A considerable amount of information was accessible regarding the role of AI in waste management and recycling. However, in addition to the previously mentioned criteria, the focus of AI applications in waste management was narrowed down to aspects relevant to the recycling of biomaterials. Consequently, a more in-depth exploration was conducted on the identification and sorting of waste materials, as well as the identification of

potential novel material uses. Furthermore, the material availability was limited. While there were pertinent studies and articles that could have been useful, many were either behind a pay wall or inaccessible due to other reasons.

## 4 Biomaterials in industrial use

Biomaterials are increasingly prevalent both in day-to-day life and across industrial applications. Due to the environmental problems related to fossil-based materials, demand for biomaterials has increased and especially forest biomaterials are seen as the primary future raw material, having the ability to even replace plastics and synthetic fibers. (Aalto university, 2021)

A comprehensive review of the biomaterials in industrial use was conducted. The biomaterials were divided into two main categories: wood-based biomaterials and other biomaterials, illustrated in table 1 and table 2, respectively. Additionally, tables were compiled based on each biomaterials' applications, examples of manufacturing processes, the fossil-based materials they potentially replace, notable companies in Finland engaged in their production. It is important to note that certain manufacturing processes may involve the use of other materials alongside the biomaterials listed. Furthermore, the presence of a blank table indicates insufficient availability of information for that specific category.

### 4.1 Wood-based biomaterials

Wood-based biomaterials such as nanocellulose, hemicellulose and lignin provide a plethora of future applications, from bionic materials to superconductors and growth substrates for synthetic biology (Haarla et al., 2017, p. 32). In addition to renewability, sustainability, and biodegradability, cellulose-based biomaterials have unique properties which enable exceptional and novel applications (Haarla et al., 2017, p. 31).

Table 1. Wood-based biomaterials

Biomaterial	Applications	Examples of manufacturing processes	Replaced fossil-based material	Companies in Finland

Cellulose	<ul style="list-style-type: none"> <li>• Paper/cardboard</li> <li>• Films</li> <li>• Textile</li> <li>• Chemicals and additives used in food and cosmetics</li> </ul>	<ul style="list-style-type: none"> <li>• Injection molding</li> </ul>	<ul style="list-style-type: none"> <li>• Plastic polypropylene</li> </ul>	<ul style="list-style-type: none"> <li>• UPM Formi</li> <li>• EcoAce</li> <li>• CH-Bioforce</li> </ul>
Hemicellulose	<ul style="list-style-type: none"> <li>• Packaging</li> <li>• Cosmetics</li> <li>• Food</li> </ul>	<ul style="list-style-type: none"> <li>• Blending flow casting</li> <li>• Casting</li> <li>• Drying film-forming solution on mold</li> </ul>	<ul style="list-style-type: none"> <li>• Plastics</li> </ul>	<ul style="list-style-type: none"> <li>• CH-Bioforce</li> </ul>
MCC	<ul style="list-style-type: none"> <li>• Pharmaceuticals and supplements</li> <li>• Textile fiber</li> <li>• Food ingredients</li> <li>• Cosmetics</li> </ul>			<ul style="list-style-type: none"> <li>• Nordic Bioproducts Group</li> </ul>
MFC	<ul style="list-style-type: none"> <li>• Textile fiber</li> </ul>		<ul style="list-style-type: none"> <li>• Cotton</li> <li>• Viscose</li> <li>• Polyester</li> </ul>	<ul style="list-style-type: none"> <li>• Spinnova</li> </ul>
Nanocellulose	<ul style="list-style-type: none"> <li>• Packaging</li> <li>• Fiber foams</li> </ul>	<ul style="list-style-type: none"> <li>• Solution casting</li> <li>• Melt extrusion</li> <li>• Injection and compression molding</li> <li>• 3D printing</li> </ul>		
Lignin	<ul style="list-style-type: none"> <li>• Plastics</li> <li>• Resins and adhesives</li> <li>• Carbon fibers</li> <li>• Hard carbon</li> <li>• Binder</li> </ul>	<ul style="list-style-type: none"> <li>• Extrusion</li> <li>• Injection molding</li> </ul>	<ul style="list-style-type: none"> <li>• Plastics</li> <li>• Phenol</li> <li>• Graphitic carbon</li> <li>• Bitumen</li> </ul>	<ul style="list-style-type: none"> <li>• UPM</li> <li>• Stora Enso</li> <li>• CH Bioforce</li> </ul>

#### 4.1.1 Cellulose

Cellulose is the most abundant polymer on earth. It consists of a 6-carbon glucose which is linked together by strong hydrogen bonds between hydroxyl groups, hence forming a linear cellulose polymer. Cellulose is familiar to many as it is used in various commercial products, such as paper and cardboard, films like cellophane, textiles like viscose and lyocell, and chemicals and additives used in cosmetics, foods etc. (Haarla et al., 2017, pp. 36–37).

UPM is a Finnish forestry company that has six different business sectors: UPM Fibres, UPM Energy, UPM Raflatac, UPM Specialty Papers, UPM Communication papers and UPM Plywood (UPM, n.d.-a) UPM Formi EcoAce is a bio-based product family which replaces plastic polypropylene with bio-based naphtha. It is produced by using by-products created during UPM's paper or pulp manufacturing processes. In addition to certified wood and cellulose fibers, the biocomposite contains bioplastics sourced from UPMS Biofuels plant called BioVerno naphtha. UPM Formi EcoAce SPB is a material of this product family that has a cellulose fiber loading from 30% to 50%. (UPM Formi, n.d.) It can be used in injection molded applications in place of polypropylene, filled polypropylene and several other plastics (UPM Formi, 2022).

CH-Bioforce is a company that develops biomass fractionation technology, and it is located in Espoo, Finland. With their BIOFORSENSE® technology, they have developed a CELLENSE™ material with a high  $\alpha$ -cellulose content of up to 98%. CH-Bioforce discloses that manufacturing of dissolving cellulose is suitable for applications requiring a high chemical purity and an oddly low hemicellulose content. The textile industry is stated to be the largest market for cellulose, where it applied as a substitute for cotton and oil-based raw materials. (CH-Bioforce, n.d.-a)

#### **4.1.2 Hemicellulose**

In contrast to cellulose containing only one type of sugar molecule, hemicellulose consists of various 6-carbon sugar molecules and 5-carbon sugar molecules (Haarla et al., 2017, p. 37). Approximately 25% of wood biomass consists of hemicellulose. It is an intriguing raw material due to its water solubility, biodegradability, and amorphous structure. Hemicellulose can be used in various applications such as packaging, cosmetics, and food production. (CH-Bioforce, n.d.-b). However, the molecular weight of hemicellulose is relatively low when compared to cellulose and, as result thereof, it has a low strength. As hemicellulose is often used in the form of a flat film, it is often processed by blending flow casting, casting and drying film forming solution in a mold. (Gómez-García et al., 2020) CH-Bioforce has developed a hemicellulose material called XYLENSE® in which the content of hemicellulose exceeds 95% (CH-Bioforce, n.d.-b).

### **4.1.3 Microcrystalline cellulose**

Microcrystalline cellulose (MCC) is an emerging material renowned for its special properties across scientific and industrial fields. Its properties can be finely adjusted through surface modification, enabling the material to be utilized for a wide range of application. MCC has unique chemical and physical properties, making it a favorable choice for applications ranging from nanomedicine to materials science. (Maturi et al., 2022)

Nordic Bioproducts Group is a startup founded in 2019 that focuses on the development of cellulose, biomaterials, and biotechnologies. In 2024, they started a commercial production for MCC. (Nordic Bioproducts, n.d.-a) They have a patented AaltoCell™ technology for MCC production. Their MCC is customizable to a specific particle size, shape, viscosity, and other attributes, which makes it a suitable material for diverse industries and applications. Some of their solutions are pharmaceuticals and supplements, food ingredients, textile fibers, as well as skincare and cosmetics. The company has also stated that their carbon footprint is 429 kg CO<sub>2</sub>e per produced ton of MCC. Additionally, sugars and other side streams are recovered from the production as by-products. (Nordic Bioproducts, n.d.-b)

### **4.1.4 Microfibrillated cellulose**

Microfibrillated cellulose (MFC) is a processed form of cellulose where the fibers have been stripped away by mechanical shearing, thus revealing the fibril bundles. These fibers are significantly smaller in diameter when compared to the original fibers and, additionally, they have the ability to interconnect and form a web-like structure. (Pinkney et al., n.d.)

Spinnova produces textile fiber from microfibrillated cellulose. They use pulp from paper production, which has been mechanically treated, to create microfibrillated cellulose. They have also stated that, although they have pioneered their process using wood, almost any kind of cellulose could be utilized as well. (Spinnova, n.d.)

### **4.1.5 Nanocellulose**

With mechanical or chemical applications, the individual cellulose fibrils or crystals can be separated within the cellulose fiber structure. The materials generated from this process, in which one or more of their external dimensions are at nano scale, are known as nanofibrils (CNF) and cellulose nanocrystals (CNC). To produce cellulose nanofibrils, mechanical treatment is required. This can be, for example, grinding, homogenization, or

microfluidization, often combined with enzymatic or chemical pre-treatment. (Haarla et al., 2017, pp. 39, 43)

Cellulose nanomaterials have various potential applications due to their nano-specific properties, such as small size, high aspect ratio, vast surface area, high strength and rigidity, gelation and shear thinning behavior, etc. These features enable increased strength in packaging and composites, while subsequently reducing weight. Furthermore, CN films have excellent oxygen and grease barrier properties which are beneficial for packaging materials. Additionally, CN are both biodegradable as well as biocompatible. (Haarla et al., 2017, pp. 43–44)

Novel structural materials with multi-scale fiber components (NOMA) was a research and education project that took place during 2015-2017 as a collaboration between the Technical Research Center of Finland Ltd (VTT), Lahti University of Applied Sciences (LAMK) and various companies, funded by project partners and Tekes. In the project, existing expertise regarding lignocellulosic fibers and their processing was utilized to create novel structural fiber foams and biocomposites. The aim of the project was to develop material combinations with features that enable producing elastic and rigid structures with good shape fidelity. Different bio-based ingredients such as alginate and cellulose nanofibrils (CNF) were used to form 3D printing pastes. The superior properties of CNF materials, such as mechanical strength and biocompatibility, make it suitable for 3D printing. Regardless of these advanced qualities, inorganic fillers and non-volatile components in material mixtures were needed due to CNF's low dry solids content. (Haarla et al., 2017, p. 116) To produce CNC-based nanocomposites, various processing methods have been developed. Some of these include solution casting, melt extrusion, ball milling, injection molding, compression molding and 3D printing. (Trache et al. 2020)

#### **4.1.6 Lignin**

Lignin is the second-most naturally abundant biopolymer on earth, and it can be found in the cell walls of plants. Lignin is a main by-product of pulp and paper production, where between 50 and 60 million tons of industrial lignin are generated every year. (Avella et al., 2023). Due to its polymeric nature, it can mimic resins, adhesives, and plastics.

UPM has a trademarked lignin product family called BioPiva™ which includes two products: UPM BioPiva™ 100 and UPM BioPiva™ 395GR. The UPM BioPiva™ 100 is purified softwood kraft lignin powder and the UPM BioPiva™ 395GR is softwood kraft lignin

granule with solids content of 95%. (UPM Biochemicals, n.d.-b) UPM has stated that their lignin can be utilized as a replacement for toxic petro-based phenol in phenolic resins. Other uses include plastics, animal feed and carbon fibers. (UPM Biochemicals, n.d.-a)

Stora Enso is a global supplier in the industry of packaging, biomaterials, and wood. In addition to this, Stora Enso is one of the world's largest private forest owners. (Stora Enso, n.d.-a) Stora Enso produces Lignode®, which is a hard carbon made from lignin. Lignode® is a bio-based alternative for graphitic carbon in lithium-ion batteries. Use of graphite is not sustainable as it is either mined or made from other fossil-based materials. Additionally, there are social and environmental problems related to the mining thereof. In addition to Lignode® being more sustainable, Stora Enso states that it allows for a faster charging and discharging, higher cycling stability and operates more effectively in lower temperatures. Furthermore, for some applications it is possible to mix Lignode® with graphite. (Stora Enso, n.d.-d) Another application Stora Enso has for lignin is Lineo™, which is used as a binder in asphalt mass as a substitute for bitumen (Stora Enso, 2020).

CH Bioforce has a material named LIGNENSE® which is produced by the company's BIOFORSENSE® technology. It is sulphur-free, reactive and has a low molar mass of 1500-3000 g/mol. (CH-Bioforce, n.d.-c)

In addition to some of the previously mentioned companies in Finland, Valmet has published an article that lists companies manufacturing lignin, including companies from Finland and abroad, such as Domtar and Lignin Industries (Ren Com). In the article, there is also mention of several companies that use lignin for conventional extrusion and injection molding. (Valmet, n.d.)

## **4.2 Other biomaterials**

This chapter covers other biomaterials found in industrial uses, mostly including bioplastics. In contrast to conventional plastics, bioplastics can be advantageous due to their biodegradability, low carbon footprint, energy efficiency, versatility, unique mechanical and thermal characteristics, and their societal acceptance (Nanda et al., 2021)

Table 2. Other biomaterials

Biomaterial	Applications	Examples of manufacturing processes	Replaced fossil-based material	Companies
PEF	<ul style="list-style-type: none"> <li>• Bottles</li> <li>• Trays</li> <li>• Packaging</li> </ul>		<ul style="list-style-type: none"> <li>• PET</li> </ul>	<ul style="list-style-type: none"> <li>• Stora Enso</li> </ul>
PHA	<ul style="list-style-type: none"> <li>• Medical applications</li> <li>• Agricultural applications, e.g. packaging and films</li> </ul>	<ul style="list-style-type: none"> <li>• Extrusion</li> <li>• Molding</li> <li>• 3D printing</li> <li>• Coating</li> </ul>	<ul style="list-style-type: none"> <li>• Plastics</li> </ul>	
PLA	<ul style="list-style-type: none"> <li>• Packaging</li> <li>• Textiles</li> <li>• Engineering plastics</li> </ul>	<ul style="list-style-type: none"> <li>• Injection molding</li> <li>• 3D printing</li> <li>• Extrusion</li> </ul>	<ul style="list-style-type: none"> <li>• Plastics</li> </ul>	<ul style="list-style-type: none"> <li>• Brightplus</li> </ul>
Bacterial cellulose	<ul style="list-style-type: none"> <li>• Food</li> <li>• Cosmetics</li> <li>• Medical applications</li> </ul>	<ul style="list-style-type: none"> <li>• Fermentation</li> <li>• 3D printing</li> </ul>		

#### 4.2.1 PEF

Furan dicarboxylic acid (FDCA) is an organic chemical compound found in nature. It is a primary raw material for bio-based plastics such as polyethylene furanoate (PEF). PEF can be used for the same applications as PET (Polyethylene Terephthalate), making it suitable for rigid applications such as the production of bottles and trays, but also for manufacturing flexible packaging. (Stora Enso, n.d.-c) Stora Enso has developed a FuraCore® process which consists of two compounds HMF (5-Hydroxymethylfurfural) and FDCA (2,5-Furandicarboxylic acid). HMF is extracted from renewable biomass and FDCA acts as a building block for bio-based plastics and materials. (Stora Enso, n.d.-b)

#### **4.2.2 Polyhydroxyalkanoate (PHA)**

Polyhydroxyalkanoates (PHAs) are biopolymers found in nature. Sugar-containing feedstock such as glucose derived from corn starch, and various microorganisms such as bacteria, yeast, or fungi, can be used in a fermentation process to also produce PHAs. PHAs are commonly used in the pharmaceutical and medical industries, but are starting to be utilized more in agriculture, for example in mulch films and packaging. However, PHAs are seldom used as pure materials in packaging and, instead, are mixed with other biodegradable plastics such as PLA or polycaprolactone (PCL). Additionally, PHA can be used as an additive to improve biodegradation properties. (Zhou et al., 2023) PHA containing bacterial biomass has been proven suitable for several applications, including extrusion, molding, coating, and 3D printing (Collet et al., 2022).

#### **4.2.3 Polylactic acid**

Polylactic acid (PLA) is a polyester made from renewable feedstock and is both biodegradable as well as recyclable. The raw material in PLA, lactic acid, is produced by fermentation of glucose or sucrose. PLA can be used in the production of packaging material, textiles, and engineering plastics. (Hagen R., 2021, pp. 231–236)

Brightplus is a Finnish company working with material development. Brightplus produces BrightBio materials for 3D-printing, injection molding and extrusion. BrightBio materials are made from polylactic acid and modified with BrightBio Technology. There are three different BrightBio materials: BrightBio Filament, BrightBio Tough Filament and BrightBio Heat Filament. They have some technical differences related to their technical qualities. BrightBio LOIMU is another alternative for plastics and is made from nature's own renewable monomers and polymers. It is designed especially for injection molding processes but can also be used in 3D-printing. There are seven different LOIMU products from semi-rigid to elastic features with various applications. (Brightplus, n.d.)

#### **4.2.4 Bacterial cellulose**

One of the purest forms of nanocellulose is bacterial cellulose. It is a promising material for various applications such as food, cosmetics, and medical applications due to its biocompatibility, biodegradability, and mechanical strength. Bacterial cellulose is formed at the interface between the culture solution and air when aerobic bacteria come into contact

with oxygen. Researchers from the Aalto University have developed a process where oxygen availability of bacteria has been modified in three dimensions with superhydrophobic molds and on different scales. This results in hollow and seamless nanocellulose-based materials. General applications for bacterial cellulose are industrial fermentation processes. However, there has been research regarding the production of filaments directly from bacterial cellulose with successful results. (STT, 2018)

### **4.3 Recycling of the biomaterials**

As biomaterials exhibit diverse characteristics, recycling approaches vary accordingly. Furthermore, recyclability of materials depends on their qualities, quantities, geographical location, and on the existing sorting technology. This section includes recycling methodologies for the biomaterials previously discussed, focusing on those for which information is readily available.

Arctic biomaterials, a Finnish company that develops biomaterials, states that, contrary to fossil oil-based materials, bio-based plastics bind carbon from the atmosphere. In 2020, only 1% of plastics originated from bio-based sources, although various companies are beginning to make a transition towards bio-based plastics. It is important to take this transition into account in the context of recycling and waste management systems as well. (ABM Composite, 2022)

#### **4.3.1 Mechanical recycling**

The functionality of waste management depends on the materials' features. For instance, bio-based plastics, such as bio-PE and bio-PP, do not require special treatment in waste management due to their identical chemical properties when compared to their fossil-derived counterparts. (ABM Composite, 2022) As an example, Stora Enso has conducted an internal study on the composites entering the polypropylene (PP) recycling stream and how it affects the mechanical properties of the recycled materials. There were four different materials chosen to represent the broad range of Stora Enso's product portfolio. Three of the materials were variations of Prime 20 materials and one recycled PP for benchmarking purposes. All materials consisted of a fiber content of 20%. The results indicated no direct impact from the materials on the mechanical properties of recycled PP. The recyclability of the material is also dependent on the sorting technology used, as, in the use of float sink tanks, a material with density over 1g/cm<sup>3</sup> will sink. In addition, the geographical location influences the

recyclability, because, depending on the location, the material may end up being used for energy recovery or may even end up at a landfill. Stora Enso stated that materials with up to 20% wood fibers have a density below 1g/cm<sup>3</sup> which will thereby float and are recyclable. Materials consisting of up to 20% wood fiber can also be recycled in the PP recycling stream when using Near Infra-Red (NIR) for sorting plastics. (Stora Enso, 2021)

Plastics can be recycled into secondary raw materials by mechanical recycling which preserves the composition of the polymer and its feedstock value, as well as its polymerization energy. Recycling of a bio-based material on its own requires large quantities of the respective material, at least 200 million kg annually. Recycling of a bio-based material in conjunction with conventional plastics carries the risk of deterioration of the quality of the recyclable plastic. Other risks in the mechanical recycling of bio-based products involve prospective cost and logistical problems with regard to their recovery and segregation. (Zaborowska and Bernat, 2023, pp. 69-70)

PLA recycling possesses these previously mentioned challenges related to the volumes of the material. Research conducted at the Technical University of Chemnitz indicated that up to 3 wt-% of PLA posed no harm to injection molded PP recyclates, allowing them to be included in the PP stream. With volumes larger than this, a dedicated, economically viable PLA stream would be possible. (ABM Composite, 2022) In addition to manual sorting, alternative methods such as separation by density variances or separation utilizing optical systems, which are based on NIR, have been suggested for identification and sorting of biobased products from the plastic stream. PLA can be sorted by NIR with an accuracy of 98%. Sorting of PLA from PET is not effortless with sight separation or separation based on density and even a mere 0.1% of PLA content can negatively affect PET recycling. (Zaborowska and Bernat, 2023, p.70) Moreover, many PLA-based products can be organically recycled in composting facilities, though it is still dependent on local guidelines and composting infrastructure. (ABM Composite, 2022)

Mechanical recycling has its downsides as it decreases bio-based products' molecular weight, inherent viscosity, thermal resilience, and microhardness. To enhance the characteristics of bio-based material recyclates, one suggestion involves mixing of chain extenders into the recycled materials, thereby increasing the molecular weight of the bio-based polymers. Mixing mechanically recycled PLA with a chain extender has been proposed for PLA, as well as organic peroxide which improves its viscosity. The degradation state of the PLA material and the number of additives have an impact on the effectiveness of this method. Blending PLA with virgin polymer can also increase the molecular weight and

inherent viscosity. Additionally, to improve the recyclability of polyhydroxybutyrate (PHB) and to delay the degradation process, blending PHB with virgin polymers or integrating stabilizers and/or chain extenders has been proposed. (Zaborowska and Bernat, 2023, p.70)

### **4.3.2 Chemical recycling**

Chemical recycling of bio-based materials includes the breaking down of polymers into smaller molecules and removing them from monomers and/or oligomers contaminants. Chemical recycling enables the reproduction of identical polymers which may lead to a decrease in the use of virgin materials in plastic manufacturing. Some of the techniques for chemical recycling include partial or complete hydrolysis, pyrolysis, which is otherwise known as thermal degradation, alcoholysis and dry heat. These methods and material affect the finished product of chemical recycling. (Zaborowska and Bernat, 2023, p.70)

The loncell-F process uses a mix of cellulose and lignin to manufacture textile fibers. This method has been seen as an enhancement for the chemical recycling of textiles, offering design opportunities within a circular economy context. Due to lignin's natural brown color, a range of natural brown hues can be added to textiles without the need of any additional dyes. The combination of these hues with knitting or weaving allows creations of garments entirely made from wood. This would benefit fiber recyclers in identifying the material content without the need of guessing from among the estimated 27,000 commercial dyes currently on the market. Additionally, the use of lignin would replace harmful petrochemical dyes. (Haarla et al., 2017, p. 96)

### **4.3.3 Organic recycling**

As the waste from bio-based products often ends up in biowaste streams, the suggested waste management method is anaerobic digestion (AD) or composting. However, all bio-based products are not biodegradable or compostable. The term biodegradable means that 90% of the organic matter transforms into CO<sub>2</sub> within 6 months in composting environment or at least 50% of the organic matter converts into biogas within two months, based on theoretical biogas production. (Zaborowska and Bernat, 2023, p. 71)

PLA poses similar environmental contamination risks with regard to conventional plastics when composted in ambient temperatures. However, it provides opportunities to commercial composting facilities, as PLA goes through a rapid hydrolysis when exposed to temperatures

at or above 55-62 °C and at a high moisture content of the air of more than 60%. Additionally, composting processes seem capable of tolerating high levels of PLA without notable effects on pH levels and subsequent microbial community activity, thereby sustaining compost quality. Nonetheless, further research is recommended to investigate the long-term effects of continuous large-scale PLA input into commercial composting streams. (Karamanlioglu et al., 2017) Commercial starch and starch/PCL-based materials have shown promising degradation results, breaking down by 70% after 12 weeks under real composting conditions. The composting efficacy is dependent on environmental factors such as temperature or pH. (Zaborowska and Bernat, 2023, p. 72)

Anaerobic digestion (AD) is an option for the treatment of bio-based products and production of biogas. AD of bio-based materials such as cellulose, starch, and starch/PCL, PLA; PBAT and PHA have a lower energy impact when compared to composting at home or at an industrial setting, and incineration. Additionally, for some materials, AD can be a more effective method than composting. (Zaborowska and Bernat, 2023, p. 74) However, materials like cellulose film and PLA capsules did not fully degrade and/or break down in a thermophilic AD with a temperature of 55 °C in 21 days (Shresta et al., 2020).

Based on the characteristics of the bio-based product, it can be determined if AD or composting is possible. Frequently, the bio-based products are not fully biodegraded under anaerobic conditions, and they require a lot of time which results in difficulties if implementing waste management in technical scale. Overall, the organic recycling, including AD or composting, is often more sustainable or economically viable, although it should be looked at case-specifically depending on the material. (Zaborowska and Bernat, 2023, p.76)

#### **4.3.4 Company case example**

Sulapac is a Finnish company that produces a variety of products, including cosmetic packaging and cutlery that are intended to replace plastics. Sulapac's main components are biodegradable biopolymers, side stream wood and natural clay minerals which function as fillers. In the event of a product ending up in nature, Sulapac has stated that their products biodegrade into CO<sub>2</sub>, water, and biomass within the same timeframe as a natural material such as a tree leaf or a piece of wood. Additionally, the product does not release any hazardous chemicals that could harm the environment. A third-party industrial company has tested and proven the recyclability of Sulapac, excluding Barrier and Heat recipes, to be technically feasible. Chemical recycling allows the carbon within the material to circulate almost infinitely. However, Sulapac has stated that the infrastructure is still under

development for the chemical recycling, though the technology does already exist. Tests have proven the feasibility of mechanical recycling for Sulapac's materials, as the materials can be collected and sorted out of a mixed waste stream without interfering with the current mechanical recycling of conventional fossil-based or bio-based non-biodegradable plastics. Moreover, the Sulapac materials are industrially compostable and most of them possess a BPI or a Seedling certificate. (Sulapac, n.d.)

## **5 AI solutions regarding recycling and biomaterials**

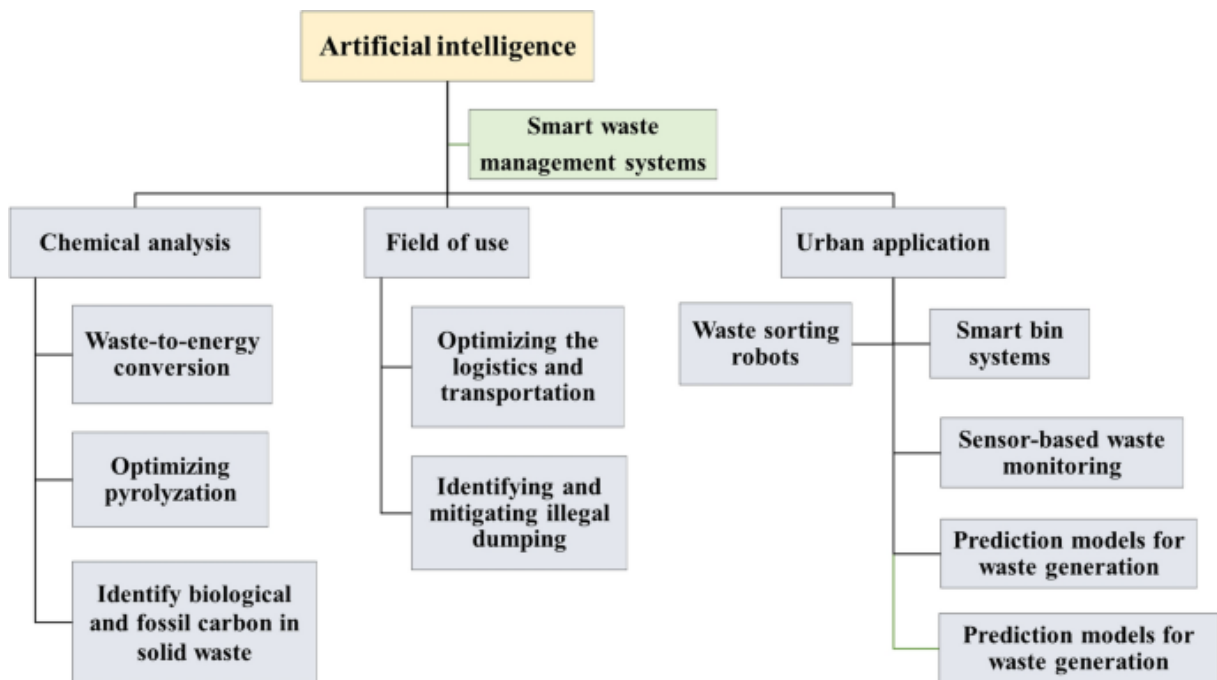
This section provides a comprehensive overview of the potential applications of AI in recycling, encompassing both general recycling practices and specific recycling and utilization of biomaterials. The first part examines the various ways in which AI can contribute to the recycling process, with a particular emphasis on sorting and model prediction. Subsequently, the focus shifts to AI's ability to assist in the recycling of biomaterials, as well as its involvement in the development of biomaterials. This includes enhancement of the existing materials as well as the exploration of AI-driven methods for creating novel materials and products.

### **5.1 Advantage of AI in general recycling**

As the amount of generated waste is rising, challenges related to pollution, waste management and recycling are becoming ever more apparent. AI has been seen as one solution to tackle these challenges, as it can be applied in waste-to-energy, smart bins, waste-sorting robots, identifying materials and much more. With AI, some of the challenges related to logistics can be effectively dealt with, as it can reduce transport distance by up to 36.8% and provide for both time and cost savings by up to 28.22% and 13.35%, respectively. The accuracy for waste identification and sorting can range from 72.8 to 99.95% via utilization of AI. (Fang et al., 2023)

Below, in figure 2 Fang et al., (2023) have illustrated the five key aspects in the application of artificial intelligence in waste management: waste type and generation, utilization of AI in waste management, AI-based optimization of waste transportation, detection and reduction of illegal dumping and waste treatment practices with AI, as well as the use of AI in analyzing the composition of waste. This section 5.1 will focus on utilization of AI in waste management and especially on material segregation and prediction.

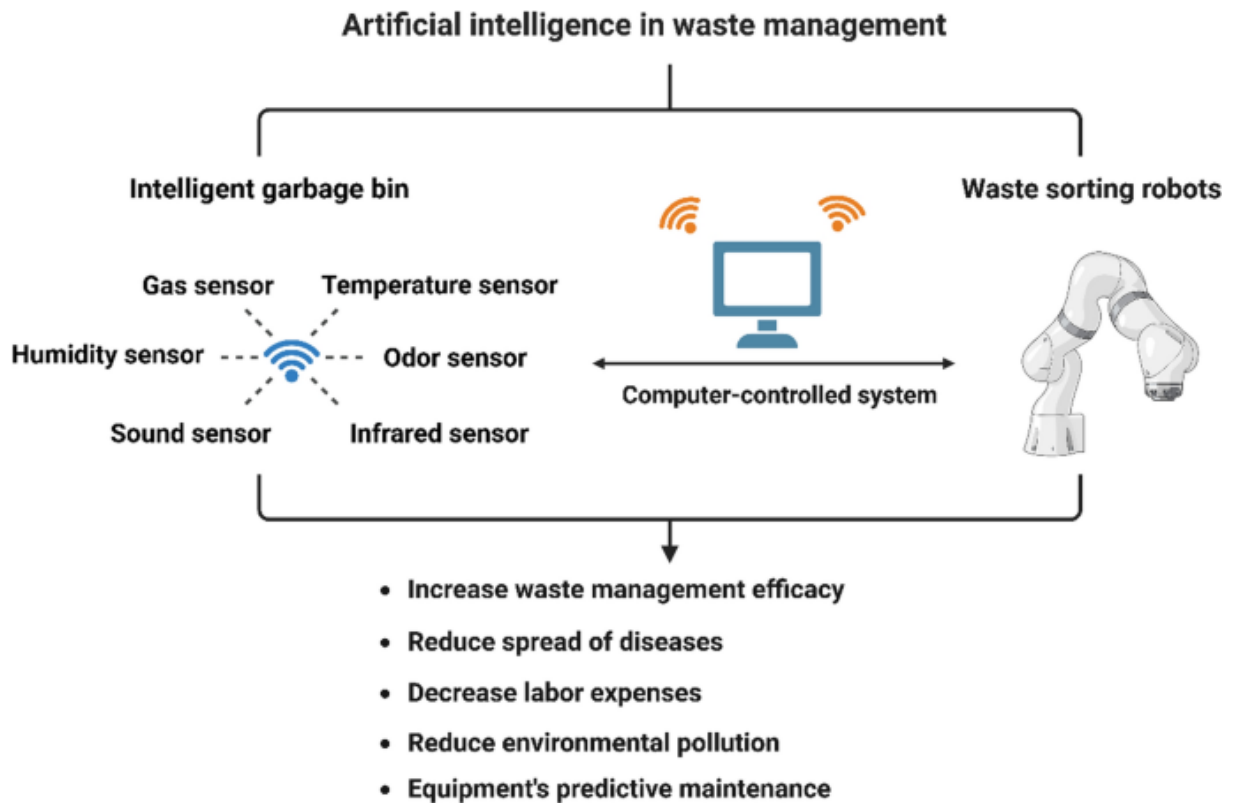
Figure 2. Key concepts of artificial intelligence in waste management (Fang et al., 2023)



Sensor-based waste monitoring seen in figure 3, involves sensors tracking the quantity of waste generated and identifying its sources. Additionally, it enables the assessment of waste management strategies in a particular area. A standard architecture for wireless sensor networks for solid waste treatment may incorporate various sensors such as temperature, humidity, odor, infrared, gas, and sound sensors. (Fang et al., 2023)

AI can be utilized in real-time monitoring of waste to optimize the collection routes and prevent overflow. Moreover, intelligent sorting enables more efficient recycling and reduction of contamination. An increase of speed and accuracy is made possible with the use of robotic arms for sorting in recycling facilities, which subsequently reduces the reliance for manual labor. Additionally, AI allows for predictions regarding maintenance of waste-sorting equipment, reduction of downtime and prolongs the lifetime of equipment. To improve the efficiency of waste collection and processing, optimization of waste management through AI can take various factors into account, such as traffic, weather conditions, and population density. (Fang et al., 2023)

Figure 3. Sensor-based waste management (Fang et al., 2023)



### 5.1.1 Material segregation and sorting

Garbage classification can be highly valuable for municipal solid waste management and the utilization of robots can significantly enhance the efficiency of this process. According to Koskinopoulou et al. (2021), Fang et al. (2023) states that advanced visual and operational capabilities are necessary to function in industrial environments in garbage classification, as they are highly heterogenous, intricate, and unsteady environments. Improved AI algorithms for distinguishing waste and the development of waste identifying sensors and cameras are indispensable when it comes to the accuracy and efficiency of garbage classification robots. (Fang et al., 2023)

To effectively decrease the dependency and extraction of raw materials, machine learning has been implemented for material segregation by using an induction algorithm. In this procedure, plastic, glass, and metal objects can be detected from large volumes of trash by using light transmission techniques. The machine learning induction algorithm is adaptable to evolving circumstances and can incorporate new conditions and findings with preloaded data. Furthermore, there is potential to integrate disparate sensor data into the decision-making process. (Gupta et al., 2019, pp.181, 183)

NC State researcher Lokendra Pal from the university's Department of Forest Biomaterial, has been developing a smart waste management system for the collection and classification of organic materials in non-recyclable waste. The items in the non-recyclable waste are too deteriorated for recycling because of contaminants of organic substances such as oil, grease, and dirt. Ideally, these materials could still be transformed into new products, energy, and fuel. The smart waste management system will consist of smart sensors, visual cameras, and hyperspectral cameras with an automated waste sorting machine to examine non-recyclable waste items. Compared to a digital camera which has the ability to distinguish three color bands of light, hyperspectral cameras can visualize a wide range of bands on the electromagnetic spectrum. By using this technology, detection of chemical characteristics that would otherwise remain undetectable is possible. To improve the system in differentiating waste items during scanning, Pal and his fellow collaborators are also analyzing waste items that cannot be recycled. They are evaluating their physical, chemical, thermal, and biological properties, including moisture, density, particle properties, surface area, crystallinity, calorific value and more. This metadata will be stored in a cloud database for machine learning training and testing which will later help in improving the identification and classification of non-recyclable waste. This can enable a more fine-tuned development of commercially friendly, efficient renewable carbon resources for the production of biofuels and value-added products. (Moore, 2023)

Deep learning has the potential to improve material sorting and segregation processes. One example thereof is the implementation of various techniques and optical sensors in a waste-sorting robot that can accurately distinguish various types of waste. Instance segmentation is a type of deep learning technology that can detect the outlines of all objects in an image, including construction and demolition waste. This can be beneficial for many reasons, as the manual handling of construction waste poses various safety risks and is often inefficient. (Fang et al., 2023)

### **5.1.2 Model prediction**

Different model predictions such as statistical, machine learning, deep learning and fuzzy models have been proposed to improve waste generation prediction. AI algorithms possess special capabilities such as data input, learning and prediction and are therefore considered to be the most advanced models. (Fang et al., 2023)

Artificial neural networks are nonlinear models with various qualities such as robustness, fault tolerance and the capability to depict complex relationships between variables in multi-

variable systems. Due to these features, they are commonly used to model various urban waste management processes. Artificial neural networks multilayer perceptron, support vector regression algorithms, linear regression algorithms, decision tree algorithms, and genetic algorithms are machine learning algorithms that can be applied to create models with enhanced predictive performance on small datasets predominantly comprised of categorical variables. (Fang et al., 2023)

## **5.2 AI solutions and biomaterials**

In the previous chapters, an assessment of various biomaterials and their recyclability was conducted. Due to the inherently varying features regarding the recyclability of each material, the examination of AI solutions, specifically their recyclability and development in a broader sense, is a challenging endeavor. Consequently, only select biomaterials were chosen for the analysis based on the availability of the respective research data.

### **5.2.1 Automated recycling**

To automate detection and separation of biodegradable and compostable packaging, a study in the UK has been conducted which included applications of hyperspectral imaging (HSI) with the analysis specifically on the spectral region 950-1,730 nm. In the experiment, to construct a classification model for the compostable materials plastics, different chemometric techniques were applied, such as principal component analysis (PCA) and partial least square discriminant analysis (PLS-DA). Materials used in the experiment were compostable materials like sugarcane and palm leaf derivatives, compostable plastics (PLA, PBAT), alongside conventional plastics (PP, PET, and LDPE). The approach in the study involved a classification model with an input of machine learning algorithms with the capability to identify and categorize several fragments over the size range of 50 x 50 mm to 5 x 5 mm. The outcome of the study revealed that both PCA and PLSA-DA achieved classification scores of 100% for materials larger than 10 x 10 mm. However, the sizes of materials could not be disregarded; when dealing with material sizes of 10 x 10 mm or below, the misclassification rate increased to 20% for sugarcane-derived and 40% for palm leaf-based materials. Additionally, sizes of 5 x 5 mm affected the misclassification rate of LDPE and PBAT as it was increased to 20%. In these conditions, the misclassification rate for sugarcane and palm leaf-based materials increased to 60% and 80%. However, the misclassification rate for PLA, PP and PET remained at 0%. (Taneepanichskul et al., 2023)

## 5.2.2 Novel products and materials

Predictive modeling driven by AI has proven to be beneficial for the design and analysis of biomaterials. AI-powered predictive modelling can improve biomaterial production, depict their characteristics, and predict efficacy. Conventional methods of analyzing characteristics such as rigidity, biocompatibility and degradation rates of biomaterials is often expensive and time-consuming. However, AI predictive algorithms can estimate these features for novel biomaterials using existing data. For example, machine learning algorithms can utilize a dataset containing known biomaterial properties to forecast the physical attributes of novel materials based on their structural features and chemical composition. The design process of biomaterials frequently requires iterative modifications to both the chemical composition and architecture. These modifications are necessary to achieve specific qualities and functionalities desired for the material. AI can develop virtual prototypes and simulate their performance in silico, which can accelerate the design process. For instance, AI-powered simulations can predict how adjustments to a polymer's molecular structure affect its mechanical properties or how alterations to the surface chemistry of a biomaterial impact its interactions with cells. This is especially beneficial in the medical field, as AI can additionally assist in personalization of biomaterials for patients and analyze patient-specific data and modify it to meet each patient's specific needs. As the field of biomaterials is quickly developing, the ability of AI-driven predictive modeling in biomaterials to continuously learn and adapt is advantageous. However, it should be noted that there can be obstacles when it comes to achieving the full potential of AI in biomaterials. One factor is the accessibility of diverse, high-quality, and thoroughly annotated datasets. The quality of data used directly affects the accuracy and capacity of models for generalization. Researchers' and institutions' extensive cooperation to produce and exchange comprehensive biomaterial datasets can help in overcoming these barriers. Deep learning models' rationale behind their predictions are harder to understand. It is essential to develop interpretable AI approaches in biomaterials research to improve the reliability and applicability of AI-driven predictions. Moreover, data privacy, bias in AI algorithms, and ethical use of AI should be considered in AI driven biomaterial research and especially in the field of healthcare. (Rajitha et al., 2024)

Researchers from Aalto University's Computational Electronic Structure Theory (CEST) and the Department of Bioproducts and Biosystems conducted a study which demonstrated AI's ability to advance the production of biomaterials. Their study focused on the extraction of lignin. Determining the optimal extraction conditions for the valorisation of lignin is challenging. These conditions may include the temperature in the hot-water reactor during wood processing, duration of the reaction, and the ratio of wood to water. In addition to the

amount of extracted lignin, the aforementioned conditions affect the physical and chemical properties of the extracted lignin itself. A machine learning method called Bayesian Optimization was used in the course of the research to determine the most optimal extraction conditions for several lignin-based products. In the study, their AI approach involves constructing a computer model with the capability to predict both the quantity of extracted lignin and its properties for a specific combination of experimental conditions. As is the case with conventional AI methods, the Bayesian Optimization requires a stream of data from which it can learn and improve. However, in contrast to other methods, the data collection is directed by the algorithm itself. (Löfgren, 2022)

There are various companies around the world that work with biomaterials and are utilizing AI in the development of these materials. One of these companies is Atacama Biomaterials, which is a company located in the United States that uses generative algorithms to discover new chemical structures of synthetic or artificial origin and, in addition, work with recycled wood pulp. One example is the utilization of AI to predict the mechanical resistance of a packaging material by using the original data stored from the material and then making a prediction with new formulations. (Gonzales-Rojas, 2022)

In a study conducted by Signori-lamin et al. (2022), prediction of cellulose micro/nanofiber aspect ratio and yield of nanofibrillation was researched using machine learning algorithms. Aspect ratio and yield of nanofibrillation are two key properties of nanocellulose and predictive monitoring of these could assist in the controlling and optimization production processes of the manufacturers. In the study, three different machine learning algorithms were applied: Multiple linear regression (LR), random forests (RF), and artificial neural networks (ANN). Key factors to achieve sufficient results were linked primarily to the chemical composition of pre-treated pulps, HPH intensity, and easy to measure nanocellulose parameters. The results of the study showed not only the potential of using machine learning models in acquiring data on yield and aspect ratio, but also that it depends on the accessibility of measurements and sensors. Aspect ratio proved easier to model than the yield of nanofibrillation. Each machine learning model showed promising results, although ANN surpassed RF and LR models with regard to correlation coefficient which, presumably, is related to the complexity of the ANN model. Future recommendations regarding the study included the availability of larger data sets to advance the prediction and model generalization as well as the inclusion of other pulp types from both wood and non-wood feedstocks and other types of pre-treatments. (Signori-lamin et al., 2022)

## 6 Conclusion and discussion

In general, the future of biomaterials appears promising with Finland emerging as one of the leading countries in terms of their utilization. Finland's extensive history of a wood-based economy has contributed to advancements in both the technology and the knowledge related to wood processing (Haarla et al., 2017, p.121). Despite numerous innovations and studies in biomaterial development in recent years, challenges continue to persist, in particular with regard to the establishment of scalable business models and commercial productions (Haarla et al., 2017, p.126). However, the findings of this thesis revealed a presence of companies in Finland engaged in the development of biomaterials and related technologies. Many of these materials utilized in the industrial setting were wood-based materials and bio-based plastics, all showing promising potential for future production. The uses varied between materials, many proved to be suitable for manufacturing processes like injection molding, although many materials would require blend of another material. For nearly all the materials, it was feasible to identify the fossil-based counterpart they were potentially replacing. Identifying these materials along with their applications and the companies involved could potentially provide valuable insights and solutions for Muova and other organizations seeking solutions in this area.

The recycling of biomaterials is highly dependent on the materials' features, but also on other factors such as quantities, geographical location, and on the existing sorting technology. Three main recycling methods for biomaterials were found: mechanical recycling, chemical recycling, and organic recycling. Mechanical recycling had showed promising results for different bioplastics, although often a large volume of materials was required for it to be viable. Organic recycling was seen as often the most sustainable and economically viable option.

Although there are many studies related to AI and recycling, the research around biomaterials remains relatively limited. As AI technology is rapidly advancing and biomaterials are becoming more prevalent, one can expect more studies in the coming years related to this topic. Moreover, when considering the existing technology and research regarding AI solutions in general recycling, one can infer that this knowledge can, to a certain extent, be implemented in the recycling of biomaterials. Challenges regarding the recycling of PLA were mostly related to the volumes of the materials and the effects on conventional plastics. NIR was proposed as a potential solution for the recycling of PLA. A departure from fossil-based plastics and subsequent transition towards the use of more bio-based plastics can potentially lead to more efficient waste management in the future, in particular when

utilizing AI technologies to assist with material sorting and any economic challenges that may arise.

As AI is already providing support in the prediction of features for novel biomaterials, there is perhaps potential to predict possible new uses for recycled biomaterials or to identify innovative ways to make use of waste streams in biomaterial utilization. It appears that many companies and universities are currently working on implementing AI to assist in the development of biomaterials and it goes without saying that a quantum leap has been made in this field in recent years. The results proved examples of how predictive algorithms have the ability to estimate features for novel materials and how AI can develop virtual prototypes. One example included the use of Bayesian Optimization technique which could determine the most optimal extraction conditions for lignin-based products.

In the course of this research, data on biomaterials and their recyclability was sourced from several companies' websites. It should be noted that the data obtained from these sources is to be examined critically, as companies are naturally more inclined to present a biased perspective to protect their own interests.

## **6.1 Challenges and recommendations**

As this research took on a broader approach in examining multiple biomaterials, conducting a more detailed study of each biomaterial could yield valuable insights into their recycling potential, novel material options, and the role of AI in their processing and/or development. One of the challenges encountered was related to scoping out relevant information, as delving into each biomaterial individually would have been an extremely labor-intensive task. Recycling methods are often dependent on the features of the materials and, therefore, research for each material itself would be needed.

It is worth noting that *biomaterial* is a broad term which can lead to confusion, as it is often used interchangeably with any bio-based materials, bioplastics, and biocomposites. Moving forward, further research could focus on biocomposites as their usage as an industrial material seems to be increasing. Applications like injection molding and 3D printing often include at least two different bio-based materials. In addition, research on bioplastics could be beneficial given the abundance of literature on the topic. Organic recycling was mentioned as the suggested recycling method for biomaterials. Therefore, it would be beneficial to carry out further research on the potential opportunities AI offers in improving composting or anaerobic digestion. In addition, more in-depth research on the companies that are providing

AI solutions for recycling would be beneficial. Further research could also include interviews with different companies that work with biomaterials and companies that produce AI solutions to recycling.

Haarla et al. (2017) listed some of the challenges related to having viable business ecosystems. The challenges are mostly related to the unpredictability of the future and how to filter relevant information. After conducting this thesis, I see opportunities in AI solving some of these challenges related to biomaterials, as AI has proven able to predict some features of biomaterials and help in the development of uses.

As the need for sustainable materials and reduction of fossil-based materials is increasing, further research should encompass the calculation of biomaterials' sustainability. While this thesis briefly addressed the sustainability aspect of biomaterials, there remains an opportunity for in-depth analysis of each material's sustainability metrics.

In carrying out this research, it would have been valuable to know potential waste streams generated from the utilization of biomaterials, as well as the feasibility of AI-assisted recycling or predicting novel applications for these waste streams. However, due to limited available information on these topics, they were not incorporated into the study. Nevertheless, they present promising courses of action for further research.

## **6.2 Learning approach**

Before starting this thesis, I possessed a basic understanding of biomaterials and their applications. I was already familiar with many companies in Finland that were involved in biomaterial production, recognizing Finland's prominent role in wood-based biomaterials. However, my knowledge of the specific chemical properties of biomaterials was limited and outside of my area of expertise. Similarly, while I had a general understanding of AI, I lacked detailed knowledge of specific machine learning algorithms. However, my background in bio and circular economy proved beneficial, as my studies provided me with a fundamental understanding of many topics relevant to this thesis.

A significant challenge I encountered was the scope of the project. Upon conducting research, I came to realize that biomaterials comprise a wide range of materials and applications. Focusing on just one single material within the context of my research questions could have yielded enough content for an entire thesis. While conducting general research into this topic is valuable, further research is necessary to delve into the specifics of

individual materials. Additionally, having a more extensive background in chemistry and computer science could have been advantageous for this type of research.

Despite my lack of knowledge in certain areas, I was able to gather a significant amount of information on the thesis topic. Throughout this process, I gained valuable insights into various biomaterials and developed a broader understanding of their industrial applications, and I believe this newfound knowledge will prove beneficial in future endeavors in the bioeconomy sector.

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## **Appendix 1. Data management plan**

### **1. General description of data**

The data of the thesis will be based on:

1. Professional information: Publications of professional organizations or expert organizations.
2. Scientific studies: Scientific research, dissertations, and research articles.

Following databases can be used to retrieve data:

- ACM Digital Library
- Science Direct
- Springer Link
- Research Gate

HAMK Finna will be used as a search engine for finding reliable literary sources. Formats can include books, articles and electronic sources.

### **2. Consistency and quality of the data**

Consistency and quality of data will be controlled via the following factors:

- Reliability: Checking carefully who is the author and what are their credentials. Checking what is their knowledgeable experience in the field they are writing about.
- Objectivity: Checking if the author represents an idea or an interest group and if it is a fact or an opinion.
- Topicality: Including up-to-date data and checking the release dates.
- Coverage: Checking that the topic has been covered in a sufficiently broad and diverse manner.
- Target group and purpose: Inspection of who the information is intended for and why the source is published.

### **3. Ethical and legal compliance**

Following ethical principles will apply to the thesis (from HAMK thesis guidelines):

- The author of the thesis respects the dignity and autonomy of human research participants.
- The author of the thesis respects material and immaterial cultural heritage and biodiversity.
- The author of the thesis conducts their research so that the research does not cause significant risks, damage or harm to research participants, communities, or other subjects of research.

No personal data will be collected for this thesis (e.g. interviews) that would require research permits and more careful storing of the data.

Data will be owned by the author Minnamari Kuusisto and by the client Muova.

#### **4. Storage and backup during the research project**

Data will be stored in two cloud services: Google Drive (personal account) and One Drive (school account). No sensitive data will be stored in these cloud services.

#### **5. Opening, publishing, and archiving the data after the research project**

The thesis can be disclosed for further use.

- Thesis plan will be stored for 1 year in previously mentioned cloud services.
- Writer will store the thesis for at least 3 years after the completion.
- Data management plan will be stored as part of thesis.

#### **6. Data management responsibilities and resources**

Author of the thesis (Minnamari Kuusisto) will be responsible for the data management.