BIOMATERIALS & REGENERATIVE AGRICULTURE: LINKAGES & OPPORTUNITIES

The Case of the Great Lakes Region, Michigan

materiom

A study by Materiom with support from the Wege Foundation

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01 EXECUTIVE SUMMARY

This project is the first of its kind to explore how biomaterials – materials that are 100% biobased and biodegradable – could be sourced from, and cycled back to support, regenerative agricultural systems. This informs a key principle of the circular economy: the regeneration of natural systems. Today, biomaterials are being developed from primary food crops that compete for arable land, or are derived from byproducts of industrial agriculture that degrades natural ecosystems. To chart a future of truly 'regenerative materials,' – those that can benefit both human and natural systems – this project explores how biomaterials that substitute petroleum-based plastics can also help regenerative agriculture, supporting its role in drawing down carbon, providing food security, and strengthening the resilience of natural ecosystems. The study focuses on regenerative agricultural practices in the Great Lakes Region in Michigan.

The report first considers to what extent regenerative agriculture can be a source of feedstock for biomaterials production. The literature states that a minimum of 2.4 tons/acre of cover crop residues are necessary to maintain soil organic carbon in no-till systems. This means that an average of 20-30% of residues from cover crop biomass (e.g. lignocellulosic biomass) can be used as feedstock for various purposes, including biomaterials production. Lignocellulosic biomass for biomaterials production can also be obtained from selective, non-destructive harvesting or pruning of main crops (e.g. perennial crops such as apple trees) and additional crops that have been co-located with main crops in polycultural systems (e.g. plants that support pest control).

The report goes on to consider to what extent biomaterials production can be a resource for regenerative agriculture systems. We identified specific biomaterial ingredients that, at the end of life, have significant potential to provide nutrient return by way of compost. These include chitin/chitosan, sodium alginate, carrageenan, keratin, gelatin, and whey protein. Our research shows that these ingredients are capable of meeting the nutrients needed in crop cultivation, specifically nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, and carbon. Biomaterials were also found to be rich in carbon, offering a way to enrich soils and draw down atmospheric carbon.

This study provides the foundation for creating circular economy practices at the regional level in Michigan, where regenerative farmers and biomaterial developers can work together. By translating these insights into practice, our ultimate goal is to incentivize the development of biomaterials that can avoid plastics pollution, while simultaneously helping to draw down carbon through the promotion of healthy soils.

02 INTRODUCTION

This report presents the background, scope, objectives, and main findings of the Great Lakes - Regenerative Byproducts Project conducted by Materiom with support from the Wege Foundation (Sept. 2021-Sept. 2022). The project aimed to explore the linkages between regenerative agriculture and biomaterials so as to enhance the resilience and sustainability of local communities and markets, through the development of circular economy models, mainly focusing on the Great Lakes Region, Michigan (USA).

The project had two interlinked research objectives to explore:

1. **Regenerative agriculture systems as a resource for biomaterials production,** analyzing the potential to develop biomaterials from abundant sources of biomass linked with regenerative industries, e.g. cover crop residues and buffer zone pruning. To do so, commonly adopted regenerative agriculture practices, as well as those specific to the Great Lakes region, were identified through literature reviews and interviews with local stakeholders. The availability of potential biomass sources for biomaterials production has been quantified and compared with the amounts needed to sustain crops and regenerative agriculture practices.

2. **Biomaterials production as a resource for regenerative agriculture systems,** analyzing the potential contributions of biomaterials at their end of life to the development of regenerative agriculture systems, e.g. capacity to act as fertilizer/nutrient sources, provide pest control, and/or soil support. To achieve this goal, the nutrient content of the most commonly produced biomaterials – as well as the most commonly used ingredients for their production – was analyzed, highlighting those with significant potential to provide nutrient return flows at their end of life as compost. In addition, other beneficial services that could be provided by biomaterials were analyzed, including ground coverage to suppress weeds or provide soil support.

To illustrate the findings of this research, representative examples have been developed of (a) potential biomaterials that could be sourced from regenerative farms in the Great Lakes Region, and (b) potential benefits from biomaterials' biodegradation or decomposition in regenerative agricultural fields in the Great Lakes Region.

The report is organized into five sections: *Section One* provides an overview of the background, scope, and objectives of the project, describing the motivation behind the project, and providing definitions of regenerative agriculture and biomaterials; *Section Two* focuses on the first research objective, exploring regenerative agriculture systems as a resource for biomaterials production; *Section Three* concerns the second research objective, analyzing biomaterials production as a resource for regenerative agriculture systems; *Section Four* presents some of the main regenerative agriculture systems in the Great Lakes Region, with representative examples of potential biomaterials that could be derived from such systems and potential benefits that biomaterials could offer back to these systems; *Section Five* summarizes the main research findings and indicates potential future research directions. References and Acknowledgements sections accompany the report, together with one appendix with supplementary information.

1.1 PROJECT MOTIVATION AND SCOPE

The Need for Regenerative Agriculture

Intensive and mainstream agriculture around the world is responsible for serious environmental degradation of soil, water and air and related ecosystems. Modern farming practices are resulting in deforestation, nutrient and topsoil depletion, and contamination of soil and water bodies, through overgrazing and massive use of synthetic fertilizers and pesticides. More land areas are becoming drought prone, plants and animals are increasingly susceptible to nutrient deficiencies, and substantial volumes of greenhouse gas (GHG) emissions are generated annually, contributing greatly to global warming and climate change[1,2] (Figure 1A).

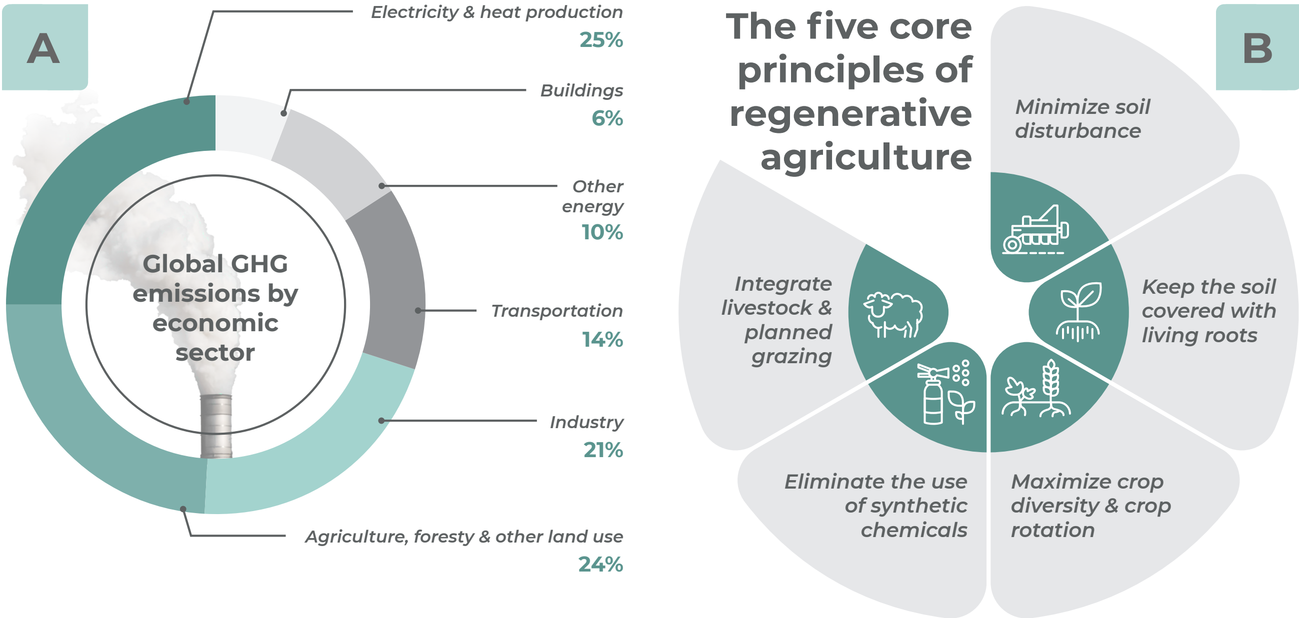

Figure 1: *A) Global GHG emissions by economic sector[3,4]; B) The five core principles of regenerative agriculture[1,7-9].*

Regenerative agriculture is an alternative means of farming that can address the above-mentioned adverse impacts, by enriching soil quality, improving its carbon capture and storage capacity, and enhancing biodiversity.

Despite rapidly growing interest in regenerative agriculture, there is no commonly accepted legal or regulatory definition of the term[1,5]. The term was coined by Robert Rodale to describe a holistic kind of farming that goes beyond sustainable, not only maintaining resources, but improving them[6]. Given the above, regenerative agriculture can be defined as a system of agricultural practices and principles that seek to improve land productivity and strengthen ecosystems and community resilience by providing both environmental and socio-economic benefits, including:[1,5,6,7]

Environmental benefits:

- Enriched soils and resilient land areas;
- Enhanced biodiversity/ecosystem services;
- Improved water quality;
- Increase the capacity of soil to capture carbon & reverse global warming.

Socio-economic benefits:

- Improved farmer profitability and increased income;
- Reduced exposure of farmers to harmful agricultural chemicals;
- Reduced exposure to extreme weather events and climate change impacts;
- Climate-resilient and food-secure communities.

Regenerative agriculture is a system of agricultural practices and principles - e.g. minimal soil disturbance, soil coverage with a diversity of plants, maximum crop diversity, elimination of chemical intervention, and livestock integration - that seek to improve land productivity, strengthen ecosystems, and enable community resilience by providing both environmental and socio-economic benefits.

The five core principles of regenerative agriculture are presented in Figure 1B, and concern minimal soil disturbance, soil coverage with a diversity of plants so that roots can continue to build soil and sequester carbon, maximum crop diversity, elimination of chemical intervention, and livestock integration. The main regenerative agricultural practices, as described in different sources, are summarized and presented in Table 1.

TABLE 1: THE MAIN REGENERATIVE AGRICULTURE PRACTICES[7-10]

Regenerative Agriculture Practice	Description
No/low till	Tilling weakens soil structure. Tilled soil collapses on itself, hardens, and over time loses its ability to absorb water or allow roots to grow. It should be avoided in regenerative systems.
Crop diversification/ polyculture	Crop diversity and rotation decreases pest and disease pressure, while supporting biodiversity and improving soil health.
Soil coverage with living plants and crop residue	Soil coverage protects it from wind, sun, hard rain, and erosion, while increasing microbial activity. Coverage increases carbon sequestration, as at least half of the cropland carbon is fixed aboveground in plant biomass.
Cover cropping - maintenance of living roots year-round	Living roots enhance nutrient retention from crops while providing food supply to soil microbes. They also enhance carbon sequestration, filter water, and improve soil function.
Composting	Compost provides an enriched variety of nutrients for crops and increases food supply to soil microbes.
Integration of grazing livestock	Grazing provides natural pruning which leads to new plant growth and avoids over-compaction of soil. In addition, livestock can be a natural fertilizer source inviting helpful insects to aerate the soil and spread organic matter. Livestock movement increases nutrient cycling by trampling crop residue.

The Need for Biomaterials and Regenerative Feedstocks

Climate change, environmental pollution, and depletion of petroleum resources necessitate an urgent transition from petroleum- and fossil-based polymers and polymer composites to biomaterials, i.e. biopolymers and biocomposites derived from renewably sourced biomass, such as plant extracted sugars, starch, residues, and waste.

The production of petroleum-based plastics, synthetic resins, and fibers has grown unsustainably. Currently, 400 million tons of plastics are produced annually, with this amount projected to reach 1 billion tons per year by 2050[11,12]. Of these 400 million tons, 300 million tons per year end up as plastic waste, most (80%) accumulating in landfills, dumps, and the natural environment, taking about 500 years to biodegrade[13]. Only 9% of plastic waste is currently recycled, while according to the United Nations, 150 million tons of plastic are already polluting the world's oceans, jeopardizing aquatic ecosystems and human health[13]. At the same time, the annual GHG emissions associated with the extraction, transportation, processing, and manufacturing of petroleum-based resins and fibers are reaching almost 1 billion tons of CO_2-eq. and are expected to triple by 2050[14]. Transitioning away from petroleum-based plastics and composites and towards more sustainable materials is a critical leverage point for the decade ahead.

The development and adoption of sustainably-derived biomaterials is a promising pathway for transitioning away from petroleum-based plastics. Bioplastics is an umbrella term assigned to polymers that meet one or more of the following conditions[11,15-18]:

- Their monomers were derived from renewable resources (biomass) and then polymerized through chemical mechanisms;
- They were extracted directly from biomass;
- They are biodegradable;
- They were produced through biological processes.

The use of the term bioplastics for fossil-derived degradable plastics is discouraged, as it is misleading.

The most widely used biobased and/or biodegradable bioplastics are presented in Figure 2A. Polylactic acid (PLA) is the most commonly used biopolymer derived from fermented plant starch from corn, cassava, maize, sugarcane, or sugar beet pulp. Polyhydroxyalkanoates (PHAs) are natural polyesters produced through the fermentation of glucose, sugar, or lipids by microorganisms. Biobased polymers can also be derived from natural polysaccharides such as starch (e.g. corn, potato, cassava, wheat, and rice) and cellulose (e.g. peel, husk, and bagasse), or proteins, such as soybean plants and wheat gluten.

Biobased and/or biodegradable polymer resins can be mixed with natural fibers such as wood, hemp, and cellulose, or fibers derived from agricultural or industrial residues or waste to make biocomposite materials that meet or exceed the mechanical properties and functionalities of their petroleum-based counterparts[19]. A wide range of sustainably sourced fiber options with promising properties is available in Figure 2B.

Apart from biopolymers and sustainably sourced fibers, biomaterials can also be made using other naturally derived resources, such as chitin, agar, and gelatin, as well as unavoidable food waste.

Interest in biomaterials is growing rapidly. However, biomaterials are not, by definition, more sustainable than fossil-derived materials. In many instances, a considerable reduction of GHG emissions results from the use of renewable feedstocks. Nevertheless, these benefits can be counterbalanced by side effects of feedstock farming, such as acidification potential and eutrophication due to increased use of fertilizers and pesticides. Moreover, when biomass for biomaterial production is derived from food crops - currently, 0.02% of global agricultural land use is devoted to producing precursors for bioplastics - ethical concerns arise about the potential competition with food security, especially in local settings[11]. **Hence, regenerative feedstocks derived from regenerative industries and processes, such as regenerative agriculture, can be among the ideal feedstock sources for sustainably developing biomaterials.**

400 mtons of petro-chemical plastics are produced annually, 75% of which ends up as plastic waste - the majority accumulating in landfills, dumps, and the natural environment. Climate change, environmental pollution, and depletion of petroleum resources necessitates an urgent transition away from petroleum- and fossil-based polymers

Figure 2: *A) Most widely used bioplastics[11]; B) Fibers and fillers from sustainable sources[19].*

03 RESEARCH OBJECTIVE 1: REGENERATIVE AGRICULTURE SYSTEMS AS A RESOURCE FOR BIOMATERIALS PRODUCTION

The first research objective analyzed the potential of regenerative agriculture systems to provide biomass feedstocks for making biomaterials. As cover crop residues play an essential part in regenerative farming, this potential feedstock is analyzed separately, followed by other potential regenerative feedstocks.

3.1. BIOMATERIALS SOURCING FROM COVER CROP RESIDUES

Cover crops are used as placeholders in empty, post-harvest fields to completely cover the soil surface. They're comprised of select species with known beneficial properties, planted in rotation or concurrently with main/cash crops to solve certain problems or provide specific services (Table 2). After growing for a predetermined length of time, the plants die back due to winter temperatures or are mowed down, forming a protective mulch[20-22].

Growing seasons and growth rates are critical factors affecting cover crop selection. Some cover crops are better suited to cooler growing seasons while others thrive in the summer heat. Fall and winter cover crops, such as winter rye, wheat, and barley, are widely used to protect and condition soils during the fallow cold season. Not all winter cover crops produce during winter; many are winter-dormant or winter-hardy, like hairy vetch, winter rye, and crimson clover, meaning that they survive winter and resume growth in early spring when they put on the bulk of their biomass. Warm-season cover crops, such as buckwheat, cowpea, and red clover, are commonly used in the spring or summer, to balance soil nutrients between other crops. While most cover crops are fast-growing annuals (e.g. berseem clover, Austrian winter pea, and rye), there are a few perennials (e.g. red clover, crown vetch, and alfalfa) commonly used for living mulch and erosion control[23].

Usually, it takes ~4-8 weeks for cover crops to establish healthy roots and ample foliage[24]. After providing the desired services, cover crops are terminated to prepare planting beds for the main crops. Depending on their size they can be mowed, trimmed, cut, or pruned, while winter-killed cover crops, such as rye, oats, and wheat, produce sufficient quantities of autumn-grown biomass to protect the soil. Cut material can be made into compost, used to mulch beds, or tilled into the soil[23].

The amount of cover crop residues that could be removed without harming the soil or compromising its nutrient content is a key aspect in determining whether and which biomaterials could be sourced from regenerative agriculture systems. Complete removal of cover crop residues should be avoided as it would be detrimental to soil health. On the other hand, no removal has adverse effects on soil productivity and water quality; and thicker mulch mats tend to inhibit early plant growth, possibly reducing yields[25-34]. Moreover, in some cases, a surplus

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of biomass that might be present on the land can lead to nitrogen robbing from the main crops, as high carbon to nitrogen ratios (C:N) can increase biological activity and cause a greater demand for nitrogen. Hence, removing a certain amount of biomass can be beneficial for the soil and the crops.

The removal rate of biomass should be based on soil type (clay, sand, silt), slope, and prevailing weather conditions. Individual farmers can make

The removal rate of cover crop residues for use in biomaterial production should be based on soil type, slope, and prevailing weather conditions. Recent studies suggest residue removal should be lower than 20-30% in order to maintain soil health and productivity.

scientific assessments of suitable removal rates using commercially available software tools. In one study conducted in Nebraska, corn yield declined by 2 bushels per acre for each ton of crop residue removed[25-34]. Recent studies suggest that about 20-30% of the total crop residue could be removed, based on ground cover requirements to control soil erosion. However, other studies suggest that residue removal should be lower than 20% in order to maintain soil quality and nutrient cycling for long-term soil productivity[25-34].

TABLE 2: TYPES OF COVER CROPS AND PROVIDED SERVICES FOR SOLVING SPECIFIC PROBLEMS[23]

Problem to be Addressed	Cover Crops	Provided Services
Provide Nitrogen	Clover, vetch, peas, radish, rye, sudangrass, and sorghum-sudan hybrids, grains	N-fixing and N-scavenging
Improve Soil Structure	Tillage radish, daikon radish, clover, vetch, rye, sudangrass, sorghum-sudan hybrids, and mustards	Soil aeration; producing byproducts that help adhere soil particles
Add Organic Matter or Biomass	• Legumes: Clover, partridge pea, and vetch • Fibrous plants: Grasses and grains • Perennial clovers: White and red clover	• Legumes break down quickly, providing nutrients, but leaving behind little lasting biomass • Fibrous plants break down more slowly. They tie up nutrients, but build stable humus, or organic matter in soils • Perennial clovers provide both benefits, with the leaves breaking down quickly while the roots and stems contribute to biomass accumulation
Reduce Soil Erosion	Clovers, annual ryegrass, Austrian winter peas, crown vetch, sudangrass, sorghum-sudan hybrids, rapeseed, mustards, and cowpeas	Providing good cover and a dense root system helps stabilize soils and combat erosion
Manage Pests	• Crimson clover: Blooms to support beneficial insects • Buckwheat: Supports large populations of beneficial insects and pollinators • Cereal rye: Reduces soil-borne diseases and root-knot nematodes. Not suitable for crops impacted by cutworms and wireworms • Wheat: Suppresses diseases and nematodes • Mustards: Suppresses nematodes • Rapeseed: Suppresses Rhizoctonia root rot fungus	Producing compounds that help fight soil-borne pests, while some are excellent at attracting beneficial insects

TABLE 2: TYPES OF COVER CROPS AND PROVIDED SERVICES FOR SOLVING SPECIFIC PROBLEMS[23] (CONTINUED)

Problem to be Addressed	Cover Crops	Provided Services
Suppress and Control Weeds	• Suppressing seed germination: Hairy vetch, buckwheat, and daikon or forage radish, which suppresses weed seed germination • Competition: Peas, clovers, buckwheat, rye, and oats • Allelopathy: Buckwheat, brassicas including rapeseed, mustards, and radishes, sorghum and sorghum–sudangrass hybrids, and subterranean clover. Winter rye is effective against pigweed, lambsquarter, purslane, and crabgrass. Some crops such as lettuce are sensitive to allelopathy, while others benefit from it.	• Reducing light penetration into soils suppressing weed seed germination • Preventing seed germination through competition: Dense-growing cover crops and cover crops with aggressive root systems • Producing a chemical deterrent in the roots, called allelopathy
Manage Nutrients	• Cereal rye, buckwheat, brassicas • Legumes, such as clover, vetch, and partridge pea	Nutrient cycling; improving availability of nitrogen (N) and phosphorus (P) in soils
Provide Lasting Residue or Mulch	Yellow blossom clover, ryegrass (Lolium), rye (Secale cerelae), sudangrass, sorghum-sudan hybrids, and barley	Providing a long-lasting mulch to suppress weeds and conserve soil moisture

Cellulose - a dominant component of common cover crop residues - is among the most promising candidates for replacing synthetic polymers because of its abundance and eco-friendly properties such as renewability, biocompatibility, and biodegradability.

Moreover, research has shown cover-crop derived cellulose is suitable for use in the biopolymers industry given it displays similar characteristics to commercially available cellulose.

According to most studies, a minimum of 2.4 tons/acre of cover crop residues are necessary to maintain soil organic carbon in no-till systems[34]. The residual cover crop biomass (lignocellulosic biomass) can be used as feedstock for various purposes, including biomaterials production.

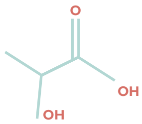
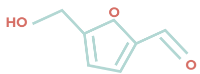
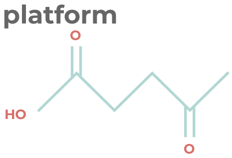
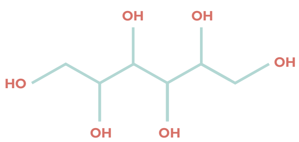
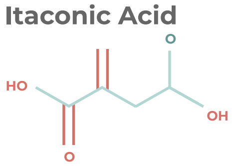
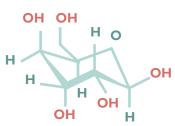
Cellulose is one of the main, and most dominant components of lignocellulosic biomass, along with lignin and hemicellulose[35,36]. It is among the most promising candidates for replacing synthetic polymers because of its abundance and eco-friendly properties such as renewability, biocompatibility, and biodegradability. In a recent study conducted by researchers at Tuskegee University in Alabama[35], cellulose isolated from rye, oat, clover, vetch, and barley residues, grown under regenerative practices (Table 3), was characterized and compared with commercial cellulose using spectroscopic (Fourier transform infrared - FTIR and Raman spectroscopy) and thermogravimetric analyses (TGA). The performed analyses indicated that the cover-crop derived cellulose had similar peaks and patterns to commercially available cellulose, indicating the suitability of cover crop residues as feedstocks for the biopolymers industry. In addition, the maximum degradation temperature from cellulose isolated from black oat (370 °C) was higher than commercial cellulose (350 °C), suggesting that this particular feedstock could be a good candidate for biopolymers in applications requiring relatively high-temperature uses, such as for microwavable containers.

Cover crop residues can provide cellulose-derived monomers (e.g. glucose) for the synthesis of biopolymers, as well as cellulose fibers, cellulose derivatives (e.g. cellulose acetate, cellulose esters), and nanocellulose (e.g. cellulose nanocrystals/CNCs, and cellulose nanofibers/CNFs). These can be used as matrices and fillers for the production of high-performance biocomposites, biopolymeric films, and functional bio-nanomaterials for a wide range of applications from energy storage to biomedical devices[36]. Examples of the main cellulose-derived biopolymers that could be produced from lignocellulosic biomass from cover crop residues are presented in Table 4.

TABLE 3: MEAN DRY WEIGHT OF EXTRACTIVES AND LIGNOCELLULOSIC COMPONENTS OF COVER CROPS[35]

	Dry weight (%)			
Cover Crops	**Extractive**	**Hemicellulose**	**Cellulose**	**Lignin**
Abruzzi rye	46.30	25.17	25.26	2.56
Black oat	52.17	20.82	25.17	1.77
Crimson clover	62.22	9.53	25.58	3.35
Hairy vetch	53.71	14.29	27.24	4.86
Winter barley	53.40	20.88	19.36	1.42

TABLE 4: EXAMPLES OF BIOPOLYMERS MADE FROM CELLULOSE-DERIVED PLATFORM CHEMICALS[36]

Cellulose-based monomer	Polymerizable monomer derived	Corresponding polymers
Ethanol platform	Ethylene	Polyethylene, polythylene oxide chloride, polystyrene, polypropylene (Copolyers), polybutadinem acrylonitrile-butadiene-styrene, acrylonitrile-butadiene-styrene-butadiene
	1,3-butadiene	
Lactic acid platform 	Propylene glycol	Polyester, polycarbonates, polyurethanes, polypropylene oxide
	Lactide	Poly(lactic acid) and its multifunctional polymeric (nano) composites and blends such PLA-PHB systems, composites and nanocomposites
5-HMF platform 	Bifunctional furan monomers, such as (BHF, FDC)	Polyurethanes, polymides, new polyesters, (PEF), (PPF)[a] or other polycondensaters furan-based polymers
	MBL, γMMBL, βMMBL	Sustanable methylene butyrolactone polymers
Levulinic acid platform 	3HV, 4HV	Biopolyesters (polyhydroxyalkanoates)(PHA) and their copolymers such as poly(3-hydroxybutyrate-*co*-3-hydroxybutyrate)(PHBV) and composites
	Diphenolic acid	Polycarbonates
	LA ketals	Polyurethanes and thermoplastics
Sorbitol platform 	Isosprbide, sorbitan	Polyesters, polyamidesm polycarbonates, copolyesters, polyurethanes, polyethene, isosorbide terephthalate
	Propylene, ethylene	Polyathene and polypropylene
Itaconic Acid 	(βMMBL), 2-methyl-1,4-(butanediamine/butanediol)	Sustainable methylene butyrolactone polymers, new polyesters, polyamides
	Acrylic/methacrylic acid	Polyacrylic acid, polymethylmethacrylate
Glucose 	Glycopolymers	Glycopolymers, glycopolymers incorporatin systems

Biomaterial feedstocks including wool, cotton, nettle yarns, sisal fibers, hemp, natural latex, and cork dust can be sourced from polycultural regenerative agroecosystems. Imagine aligning a product's material palette to plants that can grow in the same polycultural field.

3.2. BIOMATERIALS SOURCING FROM OTHER RESOURCES

Apart from cover crop residues, lignocellulosic biomass for biomaterials production can be derived from other components or practices of regenerative agriculture systems. For example, the selective, non-destructive harvesting or pruning of either the main crops (mostly concerns perennial crops and trees) or of buffer zones, or other crops that have been placed together with main ones to offer specific services, as in the case of polycultures.

Polyculture, also called intercropping, is the practice of growing more than one crop species in the same space, at the same time, aiming to mimic the diversity of natural ecosystems. Species in polycultures sustain each other and minimize the need for human intervention, providing specific services to one another, such as pest and weed control (Table 5). Legumes, such as clover, are among the most commonly intercropped crops. Polycultures of legume-cereal mixtures, legume-grass mixtures, and wildflower mixtures are very common. One of the most well-known, historic polyculture examples is "*the three sisters*", which involves intercropping of maize, beans, and squash plants. The maize (corn stalks) provides a structure (natural trellis) for the beans to grow on, the beans provide nitrogen for all of the plants, while the squash acts as a living mulch that maintains soil moisture and prevents weeds from growing. Cover crops and strip cropping (growing different plants in alternating rows) are forms of polyculture[37,38].

Natural fibers, such as wool and cotton, derived from plants or livestock integrated into regenerative agriculture systems can also be used for making biocomposites.

The EU projects Syntropia[39] and Syntropic Materials[40] look into plant/animal-based biomaterials derived from polycultural regenerative agroecosystems. Through these projects, a library for identifying potential regenerative biomaterials is being developed, while biobased shoes have been designed from plants that can grow in the same polycultural field (biomaterials used: hemp and nettle yarns and fibers, PLA, natural latex, cork dust, wool fibers, sisal fibers) (Figure 3).

Figure 3: *Samples from the Syntropic Materials library on pant/animal based biomaterials.*

TABLE 5: POLYCULTURE SERVICES[38]

Provided Services	Examples of Crops in Polycultures
Nutrient provision (increase soil fertility)	Legumes, such as clover, provide nitrogen compounds to neighboring plants by fixing nitrogen from the air with symbiotic bacteria in their root nodules. This enables the grasses or other neighbors to produce more protein and hence to grow more.
Trap cropping (alternative plants to attract pests away from a main crop)	Nasturtium is a food plant for some caterpillars which feed primarily on members of the cabbage family (brassicas); planting it around brassicas protects the food crops from damage.
Host-finding disruption	Specialized pests will often have more difficulty locating a favorable host plant inside of a polyculture, e.g.: companion planting of clover and cabbage can be disruptive to cabbage root flies.
Pest suppression	• The smell of marigold foliage is claimed to deter aphids from feeding on neighboring plants, such as pea aphid, green peach aphid, and glasshouse and potato aphid. • The onion smell puts off carrot root fly, while the smell of carrots puts off onion fly.
Predator recruitment	Compost provides an enriched variety of nutrients for crops and increases food supply to soil microbes.
Provision of protective shelter	Several crops can provide protective shelter to different kinds of plants, whether as windbreaks or as shade. For example, shade-grown coffee, especially Coffee arabica, has traditionally been grown in the light shade created by scattered trees with a thin canopy, allowing light through to the coffee bushes, but protecting them from overheating.
Soil structure	• Coffee plants grown under several tree species providing valuable resources for the coffee plants such as shade, nutrients, and soil structure. • Maize in Three Sisters provides a structure for the beans to grow on, the beans provide nitrogen for all of the plants, while the squash suppresses weeds on the ground.

04 RESEARCH OBJECTIVE 2: BIOMATERIALS PRODUCTION AS A RESOURCE FOR REGENERATIVE AGRICULTURE SYSTEMS

The second research objective assessed the potential contributions of biomaterials at their end of life to the development of regenerative agriculture systems. Supporting the nutrient needs of crops through composting was identified as one of the main potential benefits that biomaterials could provide and is analyzed in this section, followed by other beneficial services that could be provided by biomaterials, including ground coverage to suppress weeds and soil support.

4.1. BIOMATERIALS TO SUPPORT NUTRIENT NEEDS

Nutrient provision and management is critical for crop growth as well as for increasing or maintaining crop yields. To meet crop needs throughout a growing season, soil fertility must be consistently high. In general, there are fourteen essential nutrients that should be supplied to crops, including both macronutrients and micronutrients (Table 6), with nitrogen being the most essential one. Macronutrients are needed in more significant amounts by the plants, however, micronutrient deficiencies can be equally damaging to yield and profitability[41].

TABLE 6: ESSENTIAL CROP NUTRIENTS[41]

Element	Chemical Symbol	Chemical Forms Absorbed by Crops
Primary Nutrients		
Nitrogen	N	NO_3^-, NH_4^+
Potassium	K	K^+
Phosphorus	P	$H_2PO_4^-$, HPO_4^{2-}, PO_4^{3-}
Secondary Nutrients		
Calcium	Ca	Ca^{2+}

Supporting the nutrient needs of crops through composting has been identified as a key potential benefit that biomaterials can provide regenerative agriculture.

TABLE 6: ESSENTIAL CROP NUTRIENTS[41] (CONTINUED)

Element	Chemical Symbol	Chemical Forms Absorbed by Crops
Magnesium	Mg	Mg^{2+}
Sulfur	S	SO_4^{2-}
Micronutrients		
Boron	B	BO_3^{3-}
Chlorine	Cl	Cl^-
Copper	Cu	Cu^+, Cu^{2+}
Iron	Fe	Fe^{3+}
Manganese	Mn	Mn^{2+}
Molybdenum	Mo	MoO_4^{2-}
Nickel	Ni	Ni^{2+}
Zinc	Zn	Zn^{2+}

Cover cropping, livestock integration, and the use of composted biological materials, such as crop residues, or food and animal waste, are the most common regenerative agriculture practices for providing nutrients to crops and soil. Compost provides nutrients in forms that are available over more extended periods than conventional fertilizers[42]. Manure, and feedlot manure, in particular, will return nutrients to the soil[43].

The concentration of nutrients in crop residues varies with the season, management practice, time of harvest, and location. In addition, crop residue components differ in nutrient concentration, with leaves and husks having higher nutrient concentrations than stalks. Typical nutrient contents for dry corn and sorghum residues are about 8 kg N, 2 kg P_2O_5, 15 kg K_2O, and 1.5 kg S per ton[43]. Cover crops also affect the nutrient cycling in soils, for example, legume cover crops fix atmospheric nitrogen, while cereal cover crops absorb the remaining nitrogen leftover from previous crops, reducing nitrogen leaching potential[44].

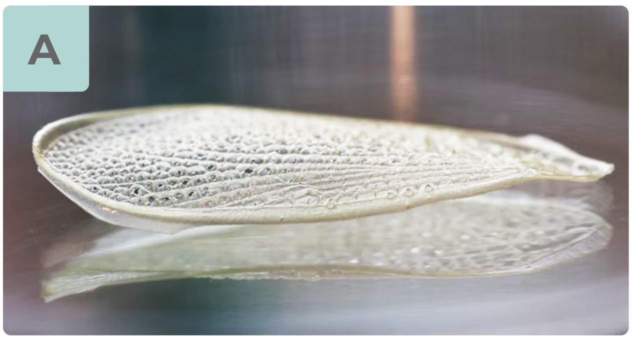
During the project, commonly produced biopolymers, as well as commonly used ingredients for biomaterial production, were indexed based on their nutrient content. Table 7 presents selected biopolymers and biomaterial ingredients with significant potential to provide nutrient return flows at their end of life and support the nutrient needs of crops as compost in regenerative agriculture systems.

Research has identified 15 biopolymers and biomaterial ingredients with significant potential to provide nutrient return flows at their end of life and support the nutrient needs of crops as compost in regenerative agriculture systems.

TABLE 7: BIOPOLYMERS AND BIOMATERIAL INGREDIENTS WITH NUTRIENT CONTENT

Biopolymer / Biomaterial Ingredient	Nutrient Content (wt%)	Source
Chitin	N: 6%	45
Chitosan	N: 6-7%	46
Sodium alginate	Na: 4%	47
iota-Carrageenan	S/SO_4^{2-}: 28-30%	48, 49
kappa-Carrageenan	S/SO_4^{2-}: 25-30%	48, 49
Gelatin	N: 17-18%	50, 51
Keratin	N: 15-18%; S/SO_4^{2-}: 2-5%	52
Casein	N: 13%; P: 1%	53, 54
Collagen	N: 18%	55
Whey protein	N: 3%	56
Calcium carbonate	Ca: 40%	57
Egg shells	Ca: 38%	58
Mussel shells	Ca: 38%	59
Oyster shells	Ca: 38%	59
Silk fibroin protein	N: 18%	60, 61

Based on the nutrient content shown in Table 7, different biopolymers or biomaterials could potentially provide primary and secondary nutrients back to regenerative agriculture systems. As an example, researchers from the Wyss Institute at Harvard University have developed a 100% biobased and biodegradable bioplastic, named Shrilk[63], using chitosan (a sugar found in shrimp shells) and a protein from silk called fibroin that mimics the microarchitecture of insect exoskeletons. Shrilk rapidly biodegrades when placed in compost, releasing nitrogen-rich nutrient fertilizer (Figure 4).



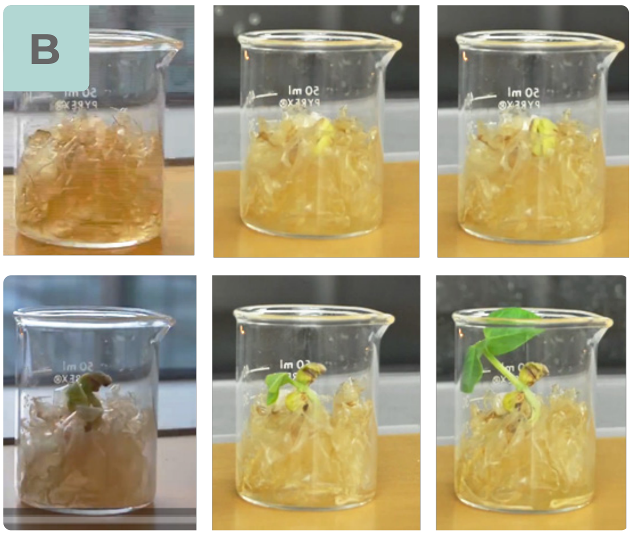


Figure 4: *A) The Shrilk bioplastic[62]; B) Snapshots of a three-week time-lapse of a California Blackeye Pea plant growing in a bioplastic-based soil[62].*

At the end of life, biomaterials can contribute the carbon and organic matter needed by plants and soil microbes back into the soil. Improving soil organic carbon supports soil aeration, water retention, biological productivity, and nutrient holding capacity.

4.2 BIOMATERIALS TO SUPPORT OTHER SERVICES

Apart from supporting the nutrient needs of crops, biomaterials could provide additional beneficial services to regenerative agriculture systems.

Carbon (C) is a critical element for soil function and contributes significantly to healthy soil conditions. Increased soil organic carbon levels are linked with increased yields and productivity. Higher soil organic carbon promotes soil structure, providing greater physical stability. Hence, soil aeration and water retention improve, while erosion and nutrient leaching risks are minimized. Soil organic carbon is also important for the chemical composition and biological productivity of agricultural fields, affecting their fertility and nutrient holding capacity[63].

Carbohydrate polymers of microbial and plant origins, such as bacterial cellulose and polyhydroxyalkanoates (PHAs) as well as polymers from starch and lignin, could provide a great carbon resource. In particular, lignin has a carbon content of ~ 65 wt% while cellulose has a carbon content of ~ 44 wt%[64]. Therefore, biopolymer sheets, films, and other objects could be used (after their end of life) to add beneficial carbon and organic matter needed by plants and soil microbes back into soils. An example of such a biopolymer material has been developed by researchers at the University of Maryland, who used woodchips to create a strong lignocellulosic bioplastic that could be used in various applications and be naturally degraded by microorganisms in the soil in a couple of months (Figure 5)[65].

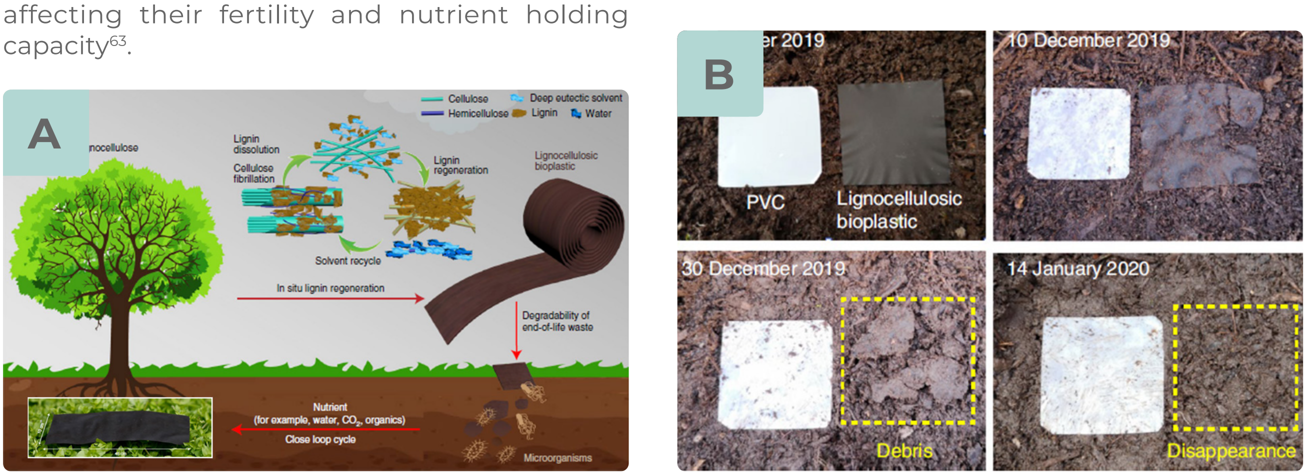


Figure 5: *A) Schematic demonstrating the preparation and degradability of the lignocellulosic bioplastic[65]; B) The biodegradability tests of the lignocellulosic bioplastic and PVC under moist soil[65].*

Biopolymers could also be used for covering roots and soil in the same way that synthetic landscape fabrics are used to retain moisture and act as weed barriers. They can also be used for supporting soil so as to reduce the risk of soil erosion or agricultural run-off. Biopolymer sheets could stabilize soils and reduce light penetration when needed. Biochar, or charred biomass, can be used as an excellent soil amender that can sequester carbon. It is highly absorbent and therefore increases the soil's ability to retain water, nutrients, and agricultural chemicals, preventing water contamination and soil erosion. Soil application of biochar may enhance both soil quality and be an effective means of sequestering large amounts of carbon, thereby helping to mitigate global climate change. The use of biochar as a soil amendment can offset many of the problems associated with removing crop residues from the land[66].

05 THE CASE OF THE GREAT LAKES REGION, MICHIGAN, US

The Great Lakes are among the most important natural resources in the world. With 21% of the world's surface freshwater, 10,000 miles of shoreline, and 30,000 islands, they provide habitat for a variety of fish and wildlife, including more than 200 globally rare species, and drinking water for more than 40 million people. The Great Lakes Region's immense network of coastal marshes, inland wetlands, and forests provides critical ecological services, such as water filtration and storage, flood control, nutrient cycling, and carbon storage. The Great Lakes - Superior, Michigan, Huron, Erie, and Ontario (Figure 6) - also offer unmatched opportunities for shipping, industry, tourism, and outdoor recreation that have fostered one of the largest economies in the world[67-69].

After California, Michigan is the second most diverse US state when it comes to cultivated crops – both in terms of agricultural production volumes and per area of cultivated land. The Great Lakes Region in particular has diverse agricultural production, as the soil fertility, abundant water resources, and climate of the area provide ideal conditions for corn, soybeans, and hay crops, as well as 15% of the country's dairy products. Between the production of crops and livestock, the Great Lakes Region produces $14.5 billion in annual agricultural sales. However, due to the growing development and intensification of the region's farmland, many places struggle with water quality issues, loss of essential fish and wildlife habitats, and an increase in toxic algae blooms[67].

Figure 6: *The Great Lakes Region and its land uses[67].*

Pollution, caused by urban runoff and sprawl, sewage disposal, agricultural intensification, and other sources, damages aquatic ecosystems and poses risks to human health[68]. By adopting regenerative agriculture practices, such as cover crops, conservation tillage, composting, and buffer strips, soil stability in the area can be significantly increased, avoiding sediment and nutrient release into water bodies while improving water quality and local ecosystems. The adoption of such practices has been accelerated during the last decade and several projects and strategies have been initiated in this direction, as presented below.

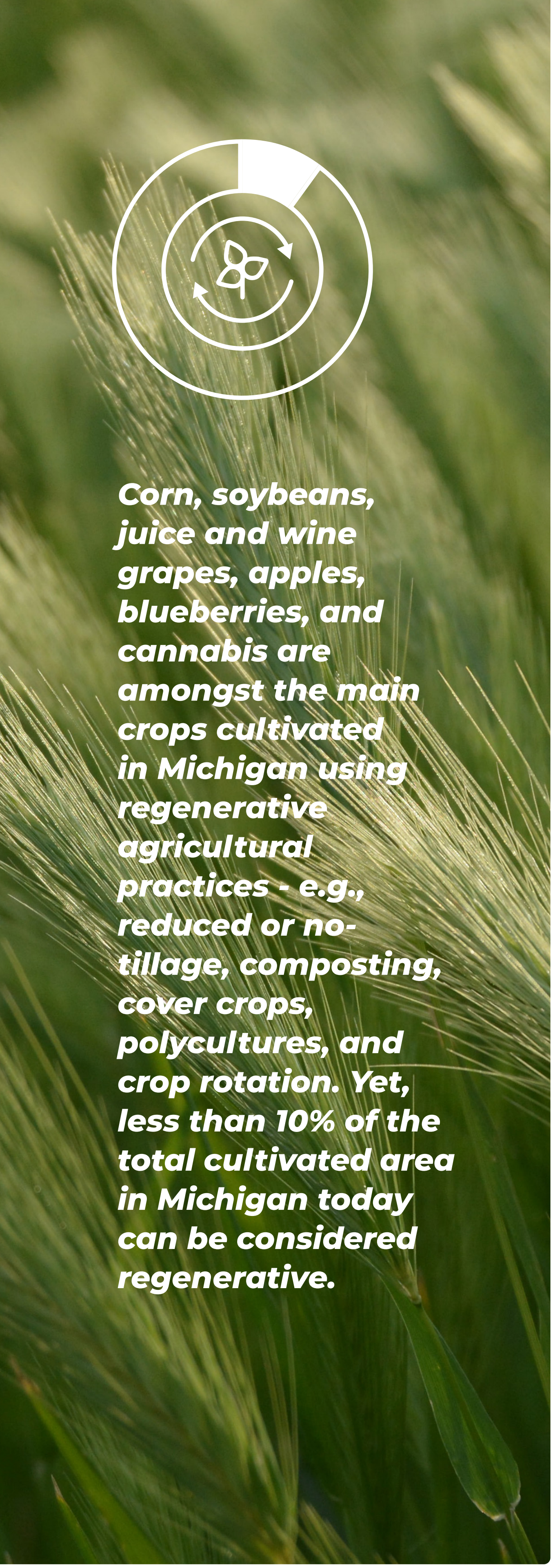
Soil stability can be significantly increased within the Great Lakes Region by adopting regenerative agriculture practices - avoiding sediment and nutrient release into water bodies while improving water quality and local ecosystems.

5.1 REGENERATIVE AGRICULTURE IN THE GREAT LAKES REGION, MI

According to Dane Terrill, from Crop Services International (a company providing consulting and technology services and products to growers transitioning to more sustainable growing paradigms in Michigan and throughout North America for over 40 years) less than 10% of the total cultivated area in Michigan today can be considered regenerative, while ten years ago regenerative farms represented less than 5% of the total arable land. That said, in contrast to organic farming, there is no official certification for regenerative agriculture yet.

The main crops cultivated in Michigan - including the Great Lakes Region - under regenerative agricultural practices, both in acres of land and in kg of production, are row crops, e.g. corn and soybeans, juice and wine grapes, apples, blueberries, and to a smaller extent cannabis.

In the case of row crops, the main regenerative agricultural practices applied concern reduced or no-tillage, use of locally sourced compost and manure for improving soil fertility and plant health, as well as application of carbon sources such as fish, molasses, and organic acids to enhance soil organic carbon levels. Cover crops are also very common, primarily using cereal rye, as it can co-exist with almost any crop, it is easy to cultivate, cold hardy, and has high N and lignin content. Diverse



species of cover crops including ~5-10 species at the same time, such as radishes, clovers, legumes, and vetch are used in the area. Polycultures and crop rotation are important for soil health when row crops are cultivated. Some farmers may grow corn and then in the next season grow cover crops, then soybeans, then cover crops, and then corn again to increase biomass from different crop root structures, increase biodiversity, and replace essential nutrients.

For perennial crops, such as blueberries and apples, more compost and less manure is applied, while fish, sugar, and organic acids are commonly used as carbon sources. In addition, soil microbes are applied in various forms, e.g. compost tea, to increase biological activity and enhance soil health. Roots and planting rows are often covered with mulch, wood chips, or synthetic landscape fabrics to suppress and control weeds and retain soil moisture. Very few farmers cultivating perennial crops actually use cover crops as they are not needed for these crops; those implementing cover crops mainly focus on reducing the need for herbicides. The most common cover crop blends for this purpose include clovers, radishes, sun hemp, and sunflowers (the last two shall be replanted after three years). Polycultures and crop rotation are not common in perennial crop systems.

The most commonly applied compost is sourced from dairy manure and other locally collected organic residues and is supplied by a large, local commercial compost company (Morgan Composting Inc). Its typical composition (% wt.) is 1 N, 1 K, 1 or 0.5 P and it is usually applied once per year, either in spring or in fall (the growing season in Michigan is short). It can also be mixed with chicken manure compost to increase N content from 1 to 4. Municipal compost is used by some farmers in the area as well.

Some representative regenerative agriculture case studies existing in the Michigan part of the Great Lakes Region as well as relevant initiatives are presented in Table 8.

TABLE 8: REPRESENTATIVE REGENERATIVE AGRICULTURE CASE STUDIES AND RELEVANT INITIATIVES

Name	Description
Great Lakes Restoration Initiative (GLRI)[68]	The GLRI was launched in 2010 with USDA's Natural Resources Conservation Service (NRCS) as one of a number of federal agency partners. GLRI helps NRCS accelerate conservation efforts on private lands located in targeted watersheds throughout the region. Through GLRI, NRCS works with farmers and landowners to combat invasive species, protect watersheds and shorelines from non-point source pollution, and restore wetlands and other habitat areas.
Sustain Our Great Lakes Program[69]	A public-private partnership designed to sustain, restore, and protect fish, wildlife, and habitat in the basin by leveraging funding, building conservation capacity, and focusing partners and resources towards key ecological issues. The program achieves this mission, in part, by awarding grants for on-the-ground habitat restoration and enhancement.
Great Lakes Protection Fund[70]	The governors of the Great Lakes states created the Fund in 1989 to help them protect and restore their shared natural resources. The Fund is the first private, permanent endowment created to benefit a specific ecosystem, and its mission is to identify, demonstrate, and promote regional action to enhance the health of the Great Lakes ecosystem.
The Great Lakes Incubator Farm (GLIF)[71]	Located on Grand Traverse County's historic Meyer Farm property, GLIF is an active land-based agricultural program that fosters the growth and development of new and beginning farmers in Northwest Lower Michigan. By cultivating new producers in this region, the GLIF program aims to: aid in the succession of local farmland, create a local farming model based on principles of regenerative agriculture, build resilience in our local food economies, and create a lasting culture of health and wellness.
General Mills Three-Year Regenerative Dairy Pilot in Michigan[72]	In 2020, General Mills started a three-year regenerative dairy pilot program in western Michigan, a key sourcing region for its fluid milk supply. General Mills has partnered with consultants Understanding Ag and dairy cooperative Foremost Farms to pilot regenerative practices and provide support to participating dairy farmers.
Sierra Club Michigan Chapter: Regenerative Agriculture Project[73]	Volunteer-led organization supporting sustainable and regenerative farms.

TABLE 8: REPRESENTATIVE REGENERATIVE AGRICULTURE CASE STUDIES AND RELEVANT INITIATIVES (CONTINUED)

Name	Description
Michigan State University (MSU) - Student Organic Farm[74]	The MSU Student Organic Farm is a 15-acre, certified organic year-round teaching and production farm. It offers an immersive, hands-on farming experience for undergraduate crew members, participants of the Organic Farmer Training Program, and volunteers. The farm also collaborates with MSU faculty to offer courses in organic farming, internships, interdisciplinary experiential educational activities, and research opportunities.
Verdant Hollow Farms[75]	Verdant Hollow is a 225-acre sustainable farm located in the heart of Southwest Michigan's agricultural belt. It produces vegetables, pasture-raised meat, and eggs. They apply rotational grazing, no tilling, permaculture, and cover cropping, while having a rainwater catchment system to minimize resource use.
Beaverland Farms[76]	A regenerative farm, growing nutrient-dense fruits and vegetables on 2 acres of arable land in Brightmoor, Detroit. Their practices involve minimum till, rotational planting, and crop diversity.
Better Way Farms[77]	A family-owned and operated farm in South Haven, Michigan producing USDA Organic and Certified Transitional blueberries, practicing cover cropping (clover, buckwheat, legumes, radishes), composting, and avoiding any use of toxic chemicals.
Shady Side Farm[78]	A farm that raises grass-fed lamb and beef and grows organic dry beans and grains using practices that regenerate the land and protect the soil and water for future generations in Holland, MI since 1992.
Earth First Farms[79]	A certified organic apple orchard, fruit, and vegetable farm situated on more than 100 acres of rolling land in Southwest Michigan, including apple trees, peaches, strawberries, blueberries, ground fruit, and an array of vegetables that vary annually.

5.2 BIOMATERIALS EXAMPLES SOURCED FROM REGENERATIVE AGRICULTURAL PRACTICES IN THE GREAT LAKES

To illustrate the research findings of the project, representative examples of potential biomaterials that could be sourced from a regenerative farm in the Great Lakes, MI region have been developed. The assessment methodology used and the examples developed are presented in the following sections.

Assessment Methodology

The steps followed to assess the quantity and quality of the potential biomass sources to be used as biomaterials feedstock can be applied to any farm and are presented in the decision tree shown in Figure 7.

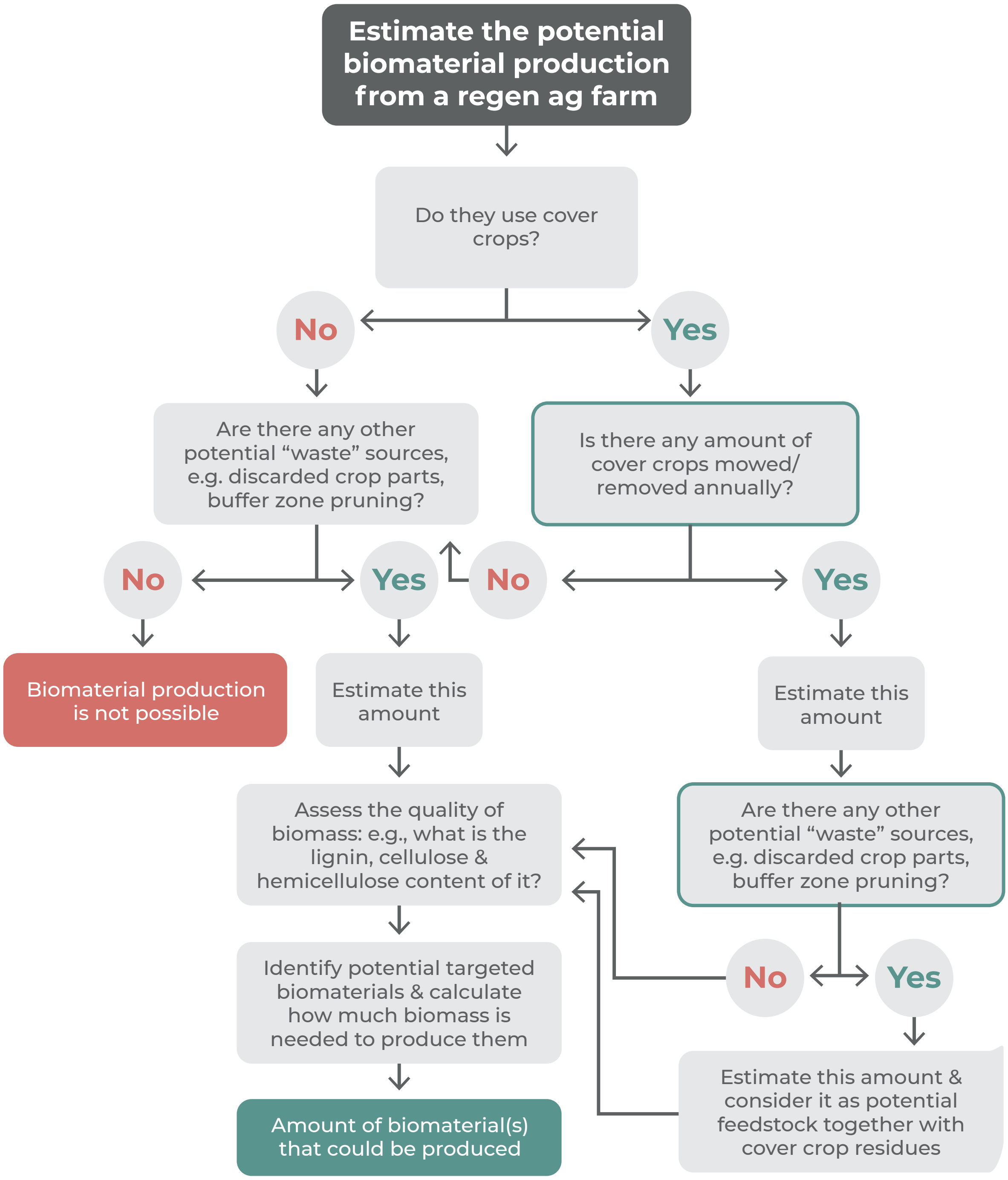


Figure 7: *Decision tree to estimate the potential biomaterial production from a regenerative farm.*

As shown in Figure 7, the amount of available biomass (if any) is first quantified, taking into account as potential sources cover crop residues or any other type of discarded biomass that could be generated and removed from the field, e.g. discarded parts of the main crops or buffer zone pruning. Then the quality of this biomass is assessed considering its composition, and based on this, potential biomaterials that could be produced from this biomass are identified via literature reviews or expert consultation. Lastly the amount of biomass needed to produce these biomaterials is estimated and translated into required amounts of arable land, harvested crops, and residues. These steps have been followed in the case study described below.

Case Study: Earth First Farms, Berrien Center, MI

Earth First Farms is a certified organic apple orchard, fruit, and vegetable farm situated on more than 100 acres of rolling land in Southwest Michigan. According to our conversations with Tom Rosenfeld from Earth First Farms, they own five different properties of 85 acres of apples in total, all certified organic since 2007. They produce other additional fruits and vegetables, such as blueberries, but we decided to focus on apples, as this is their main crop. Apples are also a typical crop for MI, which is the third largest state for apple production in the US, after Washington and New York.

Apples are perennial crops that don't need cover crops. Locally sourced composting manure from turkey or cow is added to the soil as a primary macronutrient source, mostly provided either by a large, local turkey operation, or by Morgan composting (cow manure, this is the most preferable option). Typically the composting manure contains ~5% of N and 1-2 tons of it is added once per year, always in the fall, as the farm has assessed that a constant amount of 45 kg of N/acre needs to be present in the soil. It takes three years for the composting manure to fully release its nutrients into the soil (⅓ of nutrient content is released each year). Foliar application of micronutrients, such as B, K, and Mg, is implemented via liquified sprays (Morgan's custom blend) as the farm's soil type is B-deprived. Molasses, fish hydrolysate, and compost tea are also applied for extra nutrients and biological activation to enable nutrient cycling and enhance disease and pest control. Foliar applications take place continuously throughout the growing season.

In each acre, Earth First Farms grows ~100-120 apple trees, which yield 3,600 kg of apples/acre, amounting to a total yield of 270-320 tons of apples per year. Cider is also produced. Although they don't use cover crops, residues and "waste" are generated on the farm: imperfect or irregular-looking apples are discarded from production together with residue pulp from cider-making. It is estimated that 14-23 tons of the total production is discarded annually either as bad-looking apples or as pulp residue from cider making.

In addition, there are residues from trimming, pruning, and mowing the apple trees once a year in the winter. The total annually trimmed biomass is estimated to be 230-270 kg/acre. The bigger pieces of residues are collected and burnt, while the remaining are collected in the aisles between the trees to enhance biological activity and maintain biodiversity. The bigger pieces represent less than 5% of the total trimmed biomass, i.e., around 11-14 kg/acre.

The amount of annually generated biomass sources that could be used as biomaterials feedstock is presented in Table 9.

TABLE 9: POTENTIAL BIOMASS FEEDSTOCKS FROM EARTH FIRST FARMS

Residue Source	Amount Produced Annually (tons)
Discarded apples and pulp from cider-making	14-23 tons
Trimmed biomass	0.93-1.2 tons
Total biomass residues	**15-25 tons**

Apple residues can be collected and pressed to make apple pomace. The acidic nature of apple pomace, with its high sugar and low protein content, makes it unsuitable for landfilling and animal feedstock[80-83]. It has a high moisture and biodegradable organic content which can be used for bioplastic production. Apple pomace consists mainly of cellulose (7%–44%), starch (14%–17%), pectin (4%–14%), and insoluble lignin (15%–20%)[80,84].

Following the methods described in Gustafsson et al., 2019[80] (Figure 8), bio-based films and 3D fiberboards can be made by blending the apple pomace with glycerol, a colorless, odorless, viscous bio-based liquid widely used as a sweetener in the food industry, and citric acid monohydrate, a tricarboxylic acid found in citrus fruits. These films and fiberboards may be suitable for various applications of high market demand, such as edible/disposable tableware or food packaging. Considering an average of 18.5 tons of apple pomace generated annually, about 925 tons of bio-based polymer films and about 25 tons of fiberboards could be produced per year, having significant tensile strength and low elongation (~16.5 MPa and ~11%, respectively), while contributing to the solution of issues related to petroleum-based plastic film production and apple pomace disposal.

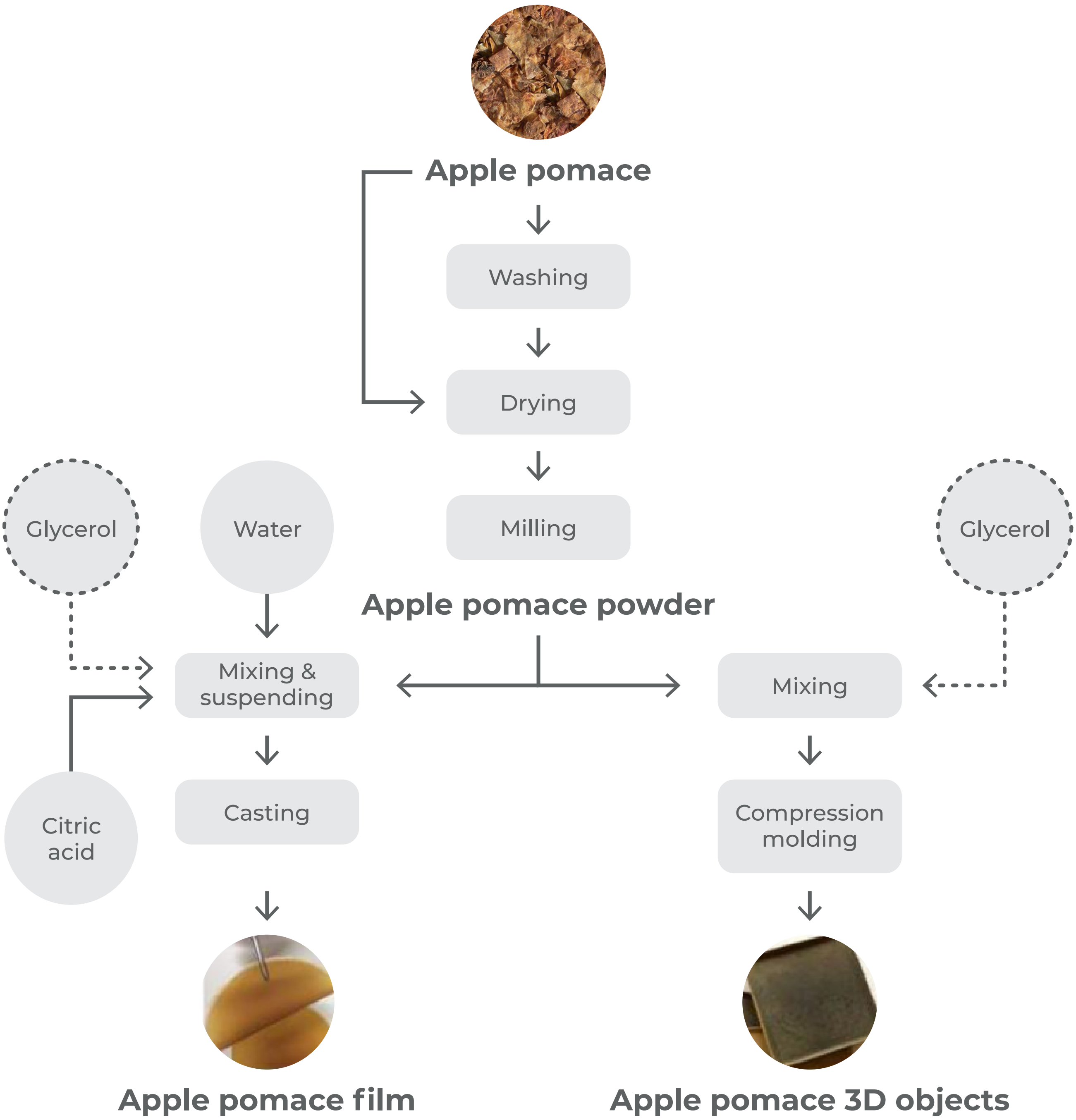
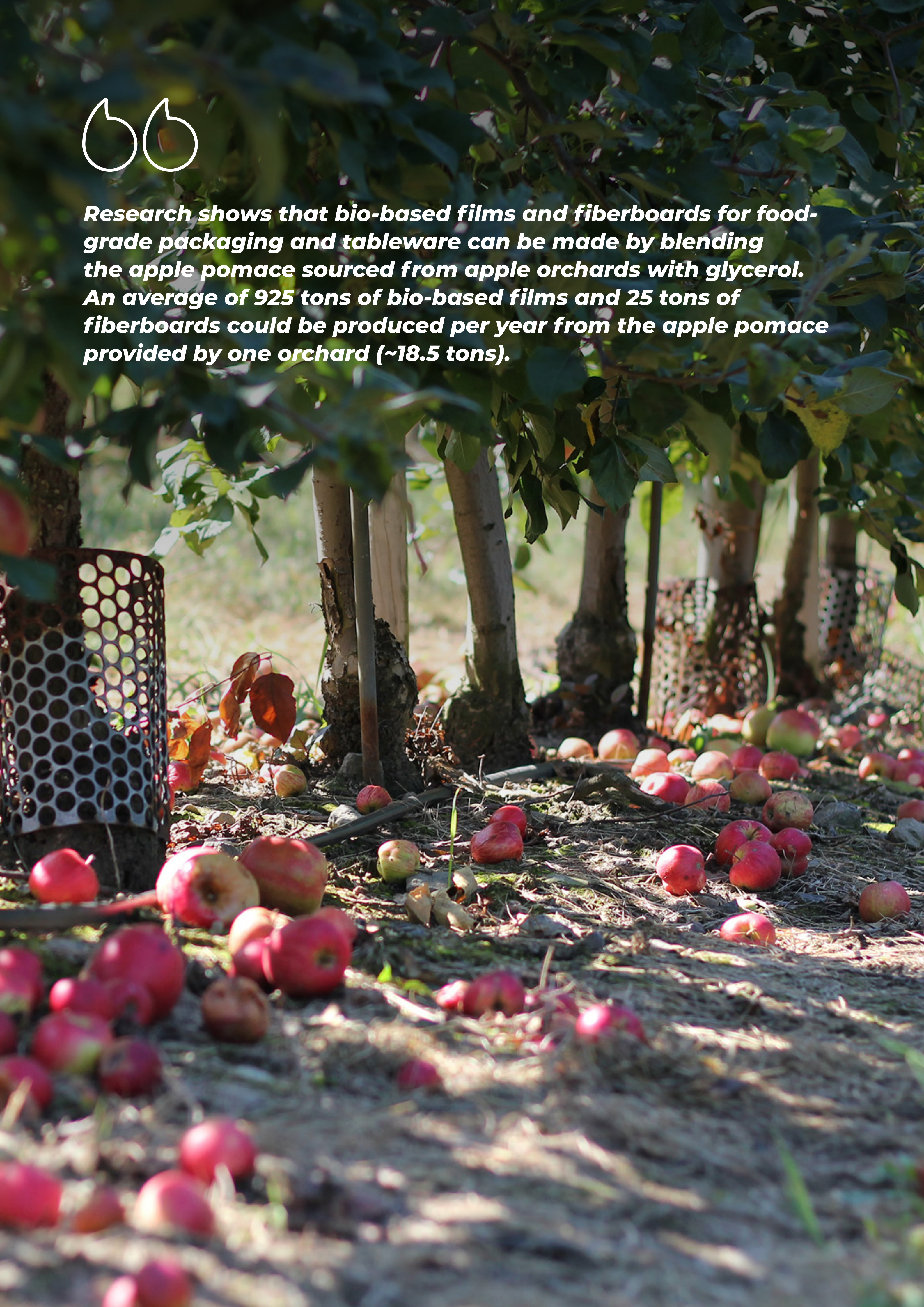


Figure 8: *Methods used for production of bio-based films and 3D objects from apple pomace[80].*



Research shows that bio-based films and fiberboards for food-grade packaging and tableware can be made by blending the apple pomace sourced from apple orchards with glycerol. An average of 925 tons of bio-based films and 25 tons of fiberboards could be produced per year from the apple pomace provided by one orchard (~18.5 tons).

The trimmed biomass residues could be also used to produce biopolymers, as the major components of raw wood powder are ~46% cellulose, ~30% hemicellulose, and ~19% lignin[65]. Following the methods described in Xia et al., 2021 (Figure 9)[65], the collected trimmed biomass could produce strong, biodegradable, lignocellulosic bioplastic films if blended with chlorine chloride, oxalic acid, and water. Considering an average of 1 ton of trimmed biomass generated annually, about 35 kg of strong, lignocellulosic bioplastic of very high tensile strength (~128 MPa) could be produced from the Earth First Farms.

Figure 9: *Fabrication of the lignocellulosic bioplastic by the in situ lignin regeneration method[66]: A) Wood powder, a waste byproduct from wood processing; B) Large-volume cellulose–lignin slurries produced; C) Formulation of the deep eutectic solvent (DES) used, composed of ChCl and oxalic acid; D) Formation of hydrogen bonding between ChCl and oxalic acid; E) Experimental demonstration of the preparation process of the lignocellulosic bioplastic by casting with a glass rod; F) A large-scale sheet of lignocellulosic bioplastic (100×15×0.1 cm)[65].*

5.3 BIOMATERIALS EXAMPLES THAT COULD BENEFIT REGENERATIVE AGRICULTURE IN THE GREAT LAKES

To illustrate the findings of this project, representative examples of potential benefits from biomaterials biodegradation in regenerative agricultural fields in the Great Lakes, MI region have been developed. The assessment methodology used and examples developed are presented in the following sections.

Assessment Methodology

The steps followed to assess the potential contributions of specific biomaterials to support the nutrient needs of crops grown in regenerative farms are presented in the decision tree shown in Figure 10.

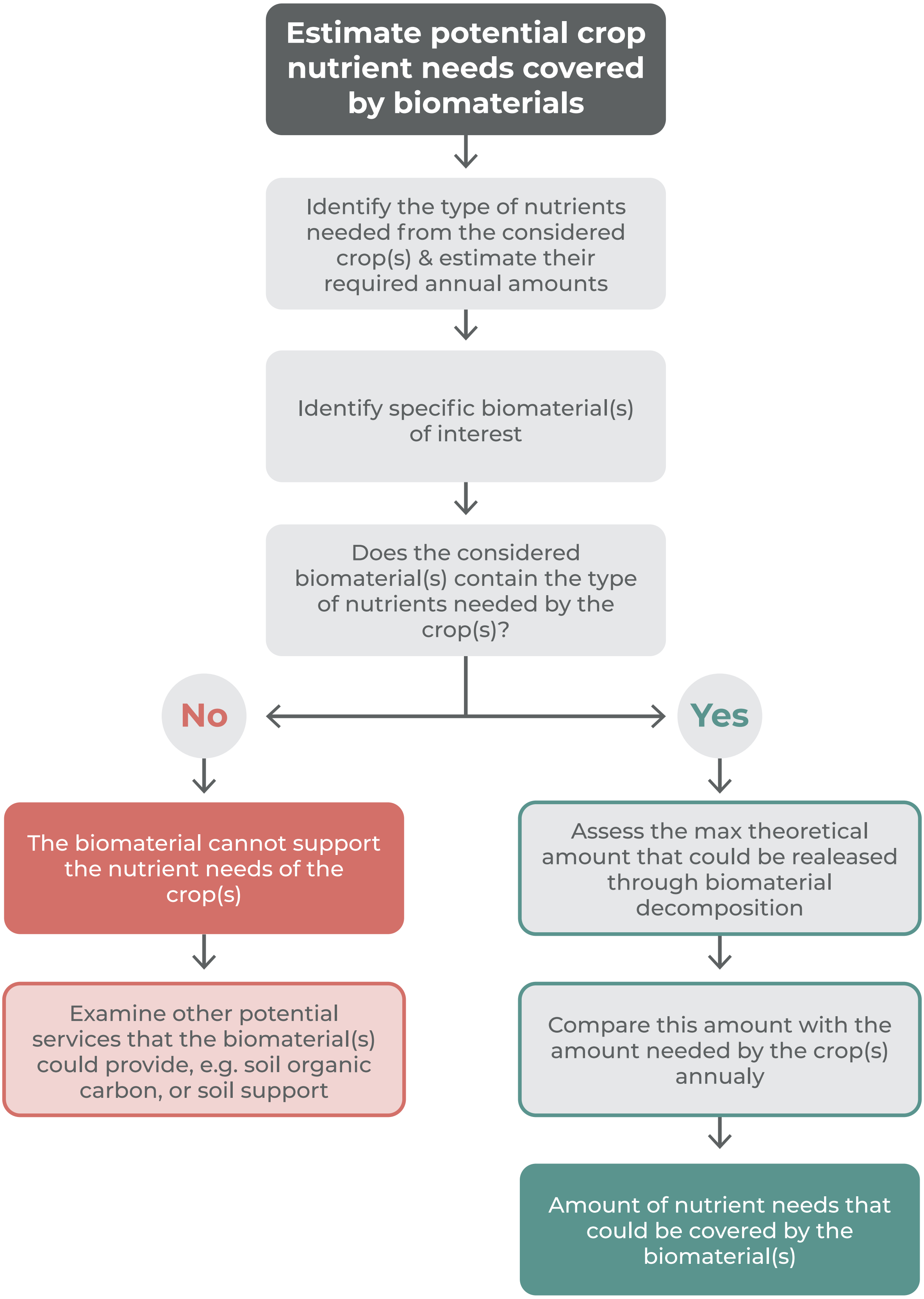


Figure 10: *Decision tree to estimate the potential nutrient needs of crops grown in regenerative farms that could be covered by the biodegradation of biomaterials.*

CASE STUDY: BETTER WAY FARMS

Better Way Farms is a family-owned and operated farm in South Haven, MI producing USDA Organic and Certified Transitional blueberries, practicing cover cropping (clover, buckwheat, legumes, radishes), composting, and avoiding any use of toxic chemicals. According to our conversations with Joseph Jessup from Better Way Farms, they grow seven different varieties of highbush blueberries on a total of 104 acres of land (Elliott: ~20 acres; Aurora: ~20 acres; all other five varieties are ~15 acres each). Their yields vary and the average typical yield is ~2,000 kg/acre, which is lower than the state's average yield for conventional berries (~2,300 kg/acre), while yields of conventional farms at the specific regions within MI state can be greater than 3,600 kg/acre.

Cover crop blends are applied to all 104 acres, and are mainly composed of three different types of clovers, some legumes, buckwheat, and oats. Cover crops are reseeded every three years. They are just mowed - not terminated - to allow easy access to the main crops, and all the generated plant biomass stays on the field. No residues or any other potential "waste" biomass sources are generated.

The main fertilizer source applied is the locally sourced Morgan's K2 compost blend. The compost is applied twice per year (once at the beginning of April and once after six weeks). It was estimated that ~545 kg/acre are applied each time (~1,000 kg/acre/yr). At the same time alternative compost products are being tested with different nutrient ratios and different sources of nutrients, as it is believed that the release curve of K2 might be slow (and also result in yield variations).

Nitrogen (N) is the most significant nutrient needed by blueberries, according to Joseph Jessup. Given the fact that the currently applied compost contains ~0.02 kg N/kg and that ~1,000 kg compost are applied annually per acre, the crops need ~20 kg N/acre/yr. Chitin, which is the most abundant aminopolysaccharide biopolymer occurring in nature, degrades in soil producing carbon dioxide and ammonium-N. A relevant soil incubation study demonstrated that chitin contains ~6% N per weight, which is released as ammonium-N in the soil after biodegradation[85]. Hence, ~330 kg of chitin biopolymer would be needed yearly per acre (or 80 g chitin/m^2) to cover the N needs of blueberries.

Nitrogen and sulfur are essential nutrients needed by blueberries, an estimated 20 kg of Nitrogen and 40 kg of Sulfur are needed per acre each year. Research has shown that biomaterials rich in chitin, gelatin, and carrageenan can meet these need by way of compost at the end of life.

Gelatin – a protein commonly derived from collagen taken from animal body parts – is commonly used to make biomaterials, and could also be used to cover the N needs of blueberries. Gelatin contains 17% N per weight[50,51] (Table 7), hence, 120 kg of gelatin would be needed annually to provide 20 kg N per acre (or 30 g of gelatin/m^2).

Apart from N, Sulfur (S) is another essential nutrient needed by blueberries. S deficiency of crops, reported with increasing frequency over the past two decades on a worldwide scale, reduces yield and affects the quality of harvested products[86]. Currently applied compost contains 0.04 kg S/kg and taking into account that ~1,000 kg of compost are applied annually per acre, we can conclude that blueberries need ~40 kg S/acre/yr. Iota-type carrageenan is a natural polysaccharide biopolymer obtained from edible red seaweeds which has an ester sulfate content of about 28-30% per weight[48,49]. Therefore, 145 kg iota-type carrageenan would be needed per acre (or 35 g of iota-type carrageenan per m^2) to cover the annual S needs of blueberries.

Research shows that regenerative agriculture systems can provide a significant feedstock source for biomaterials production in cases where cover crop residues or other sources of waste biomass are allowed to be removed from the field.

06 DISCUSSION & CONCLUSIONS

From the performed research it can be concluded that regenerative agriculture systems can provide a significant feedstock source for biomaterials production in cases where cover crop residues or other sources of waste biomass – such as discarded crop parts or buffer zone pruning – are allowed to be removed from the field (as in the case of Earth First Farms in Berrien Center, MI). By quantifying the availability of potential biomass sources and analyzing their quality, they can be matched with different types of relevant biopolymers or biomaterials.

In addition, the biomaterials market can be an essential resource for regenerative agriculture systems, enabling a potential paradigm shift from conventional to regenerative farming if biomaterials are applied to such systems after their end of life. Various beneficial contributions of biomaterials to regenerative farms have been identified, including acting as fertilizer and supporting the nutrient needs of crops (as in the case of Better Way Farms in South Haven, MI), or as a means of pest and weed control or as soil support.

These interesting and mutually beneficial linkages between the regenerative agriculture and biomaterials production industries could enable the production of locally sourced, sustainable materials for packaging, clothing, or structural applications, substituting their petroleum-based counterparts, while enhancing food security and resilience of natural and socio-economic systems. Such beneficial impacts become even more timely and relevant in the Great Lakes Region, given the vulnerability of its ecosystem and the existing pollution issues.

Given the significance of the topic and the extremely limited and scattered relevant information reported in the literature, the following areas of future research have been identified:

- A systematic study would be needed across different agricultural systems and crops to assess the precise amounts of biomass that could be removed from the fields to serve as biomaterials feedstocks without harming the cultivated crops. A structured and comprehensive database could be developed, covering and assessing all local native species and including all potential farms (such as those presented in Table 8).

- The experimental validation and systematic analysis of the nutrient content and nutrient release mechanisms of different biomaterials would be needed to quantify the nutrient support that could be provided to specific crops and regenerative systems. Biodegradation studies of selected biomaterials over time in the soil and climatic conditions of the Great Lakes Region, supported by elemental, spectroscopic, and thermogravimetric analyses would significantly enrich the limited knowledge on the topic. Additional potential services that could be provided by selected biomaterials such as soil support, moisture retention, and water filtration could be tested and validated under local conditions.

Establishing alliances and partnerships with local stakeholders, such as the Michigan State University as well as local producers and farmer consulting companies, would be a key factor enabling the above studies.

Research shows the biomaterials market can be an essential resource for regenerative agriculture systems, enabling a potential paradigm shift from conventional to regenerative farming if biomaterials are applied to such systems after their end of life.

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APPENDIX - USEFUL DEFINITIONS

Carrageenans

Carrageenan is a family of water-soluble polysaccharides extracted from red seaweed. Depending on the species, carrageenans constitute between 30% and 80% of the algae cell wall, which play a protective and structuring role. There are three different types of chemical structures of carrageenan: kappa, iota and lambda, which generate diverse kinds of gels. Kappa produces a rigid and brittle gel, while iota-carrageenan forms a soft and elastic gel. Lambda-carrageenan does not create a gel but is used as a thickener in the food industry.

Cellulose

Cellulose is the most abundant naturally occurring polymer in the biosphere. Besides being a key structural component of the plant's cell walls and vegetable fibers, it is synthesized by many bacteria. Cellulose is not soluble in water and is formed by microfibrils with a stiff, ordered structure responsible for strength and resistance in plants. Although it is one of the most abundant biopolymers in nature, it is mainly extracted from wood today. Moreover, it is a low-cost by-product of several sectors, which has led to experimentation with its extraction from secondary biomass sources such as food waste.

Chitin

Chitin is the second most abundant natural polysaccharide in nature. It can be found in a wide range of living organisms in the form of structural crystalline microfibrils, like in sea animals, insects and fungi. However, it is mainly extracted from crab and shrimp shells. Chitin is an excellent polymer for material making due to its mechanical properties and low general solubility, which are critical attributes for films and materials. Besides, it has great capacities for fat-binding capacities, antibacterial activities, biodegradability and immunological activities.

Chitosan

Chitosan is one of the main subproducts of chitin, which can be obtained by partial deacetylation of chitin. If chitin reaches 50% deacetylation, it becomes soluble in acidic solutions and is called chitosan. Like chitin, chitosan has excellent attributes for making films and materials.

Collagen

Collagen is one of the key proteins that gives structure to skin and connective tissues. There are several types of these fibrous proteins, but it is found most abundantly in tendons, ligaments, skin and bone.

Gelatin

Gelatine is a sub-product of collagen that is extracted via hydrolysis from bones, skin (hides), and connective tissues of mainly pigs and cattle, fish and poultry. Gelatine is a hydrocolloid, a substance that produces gel in contact with water. Its properties vary depending on the quality of the gelatine, measured as low (150), medium (150-200) and high (220 - 330) bloom value.

Hemicellulose

Hemicellulose is a natural polysaccharide usually present along cellulose and lignin in the cell walls of plants and natural fibers. It has a crystalline structure that is very strong and insoluble in water, which makes it an excellent material reinforcer.

Keratin

Keratin is a family of fibrous proteins that play a vital role in the body of vertebrate animals, composing and structuring elements like hair, feather, claws, or horns. It is not soluble in water and is very tough, similar to chitin. Keratins can be categorized in alpha and beta keratin.

Lignin

Lignin is a natural polymer that composes the plant tissues along with cellulose, hemicellulose and pectin. Lignin fills the gaps between these other components, being fundamental for the rigidity and lifespan of plants and vegetal fibers.

Pectin

Pectin is a nonstarch polysaccharide that composes part of the plant cell walls. It provides structure to plants' cell walls and contributes to their intracellular adhesion and mechanical resistance along with other cell wall components like cellulose, hemicellulose, and proteins. Because it is easy to dissolve, it is used as a gelling, thickening, and stabilizer agent in the food industry. Also, it is used in cosmetic, pharmaceutics and biomedical applications.

Silk fibroin protein

Fibroin is a beta-keratin protein that is present in silk and produced by various insects. Raw silk combines fibroin and sericin proteins, where sericin plays the role of bonding together the fibroin filaments. Fibroin is insoluble in water, having applications as a material component for tissue engineering or pharmaceutical applications.

Sodium alginate

Sodium Alginate is one of the most common derivatives of Alginic Acid (Alginate). Alginates are polysaccharides that compose the intercellular structure of brown algae cell walls, constituting between 18 and 40% of the algae's dry biomass. These carbohydrates can form gels quickly when mixed with metal cations like calcium, magnesium, manganese, aluminum, and iron, which facilitates making films and coatings. Moreover, these films can be strong and present suitable oxygen barriers; however, they have a low resistance to water because of their high hydrophilic and biodegradability properties.


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