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MDPI

Review

Increase of Miscanthus Cultivation with New Roles in Materials Production—A Review

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Received: 27 January 2020; Accepted: 11 February 2020; Published: 21 February 2020

Abstract: Recent changes in the EU green aims can help to overcome economic obstacles in the slow upscaling of *Miscanthus* cultivation. Using *Miscanthus* can permanently fix CO_2 within building materials thereby aiding the EU climate goals with the increased use of regrowing materials, as well as carbon fixation. Economic obstacles in the slow upscaling of *Miscanthus* cultivation are targeted by recent changes in the greening aims in the EU. *Miscanthus* can fulfill a valuable dual function in aiding the EU climate goals by achieving permanent CO_2 fixation within building materials. In contrast to energetic use, persistent applications create stable markets allowing for a reduced risk in the establishment of long term cultured perennial crops. However, the development of different building materials requires an understanding of the combination of the biological and technical aspects. This work presents an overview of the development of the general aspects for the agricultural product *Miscanthus* and the scientifically reported developments of *Miscanthus* used as feedstock in polymers, particle boards, and cementitious materials. While the product performance can be evaluated, the understanding of the influence by the input biomass as a main contributor to the product performance needs to be reinforced to be successful with a goal-oriented development of *Miscanthus* based products. The key feedstock parameters governing the technical performance of the materials are identified and the knowledge gaps are described.

Keywords: *Miscanthus*; CO_2 fixation; greening; lignocellulosic biomass; silica rich perennial plants; building material; construction material; composites

1. Introduction

The European Union (EU) has set key targets to reduce the amount of greenhouse gas emissions, to a level of 20% of the 1990 emissions, by the year 2020 and to reduce further to 40% by 2030 [1]. The Cultivation of perennial biomass crops will increase CO_2 sequestration [2]. Since 2018 *Miscanthus* has been included in the so called 'Greening' of the EU (Regulation (EU) 2017/2393), which might be advantageous for farmers to cultivate *Miscanthus*.

The genus *Miscanthus* is part of the grass family (*Poaceae)* of the Poaceace with possible cultivation in a wide geographical context, spanning different climate zones from south to north Europe [3–5]. The perennial species of this genus were originally introduced as ornamental plants [6].

In recent decades, scientific interest and cultivation has increased due to the expected yield potential of the lignocellulosic biomass [3,6,7] with respect to the low input requirements in soil and fertilizer use, shifting the focus to the production of lignocellulosic biomass with *Miscanthus* [3,4,8–11]. Recent projections predict that *Miscanthus* will be able to contribute 5% to the global energy needs in the 2090s [12].

Eleven 11 million ha of marginal land in the EU have been deemed suitable [13], due to a high tolerance for abiotic stresses [14] as well as water use efficiency C_4 cycle of the plant [15].

The EU has set goals to increase the contribution of bioenergy, to the total energy production, to 20% in 2020 and 32% in 2030, proportionally [1]. The bioenergetic application of *Miscanthus* is often suggested to contribute to the reduction of fossil fuel consumption [3,5,16–21]. Next to the replacement of fossil fuels by *Miscanthus* and the carbon fixation in terms of the below ground biomass, a non-energetic long-lasting application of the above ground biomass could actively contribute to the reduction of anthropogenic CO_2. However, the available biomass is currently limited to 19,000 ha in the EU [5], due to high investment costs of the establishment [5] and the uncertainties in the market stability [5]. In order to develop a larger sustainable market, higher valued applications should be co-developed together with the bioenergetic usage.

This work aims to review the conversion of *Miscanthus* for materials production in order to facilitate the guided research of higher valued applications, with a focus on building and construction materials. A short description of the plant with a brief coverage of the agronomic processes and valorisation context will be given, followed by the research in higher valued applications such as a fiber material in polymer composites, raw materials in the research around particle boards, as well as insulation panels and the research of cementitious materials.

2. Agroeconomic Factors of *Miscanthus*

2.1. *Miscanthus Botanical Summary*

In south and mid European climates, *Miscanthus sinensis* and *Miscanthus* × *giganteus* genotypes are primarily suggested for biomass production, while *M. sinensis* is also recommended for northern Europe [4]. However, only *M.* × *giganteus* is currently grown commercially [5]. The *Miscanthus* plant consists of distinguishable morphological and anatomical main components. The rhizomes and roots serve as permanent below ground biomass and the culms and leaves serve as aboveground biomass.

The leaves of *Miscanthus* are typically long, slender, and fibrous, and they contribute to a significant part of the fresh biomass (30%) [22,23]. Culms display a smooth epidermis under the leave-sheaths and show a lignified sclerenchyma and cortex in the outer ring of the cross-section and less lignified, porous parenchyma in the inner ring [22].

The vegetation period of *Miscanthus* starts in April/May and ends in the autumn (October) [23]. Depending on the genotype and growing conditions, the plant reaches a height of up to 4 m [14,24]. In autumn, the senescence of the perennial begins. Nutrients and sugars are relocated to the rhizomes; however, the time point of completed senescence and ⩾80% loss of greenness may vary between late October to late November [25]. During autumn and over the winter period, genotype dependent leaf losses and drying of the culms occur. Depending on wind and snow conditions, some lodging of the culms could also occur [4].

The chemical composition of *Miscanthus* is reported as 40–60% cellulose, 20–40% hemicellulose, and 10–30% lignin [26] in the organic compounds, and 2–5% ash, as mineral components [27]. However, the chemical composition is subjected to numerous influences, such as inherent genotypic variations [5,26,28,29], the weather conditions of the growth period, the local soil quality, the agronomic practices in fertilization [5,29], and the harvesting time [4,5,29].

2.2. *Establishment*

The establishment of *Miscanthus* is considered as a main cost factor during the lifespan of cultivation, with estimated costs as high as 70% [20]. The main contributor to these estimated costs, next to the land use of the field, are the efforts in rhizome propagation and planting [5,6,20,30,31]. Furthermore, the initial establishment contributions are in the land preparation before planting, initial fertilizer use, herbicide use and weeding, as well as irrigation during the initial growth period [6,31].

The high prize requirement for the rhizomes is caused by the effort of vegetative multiplication in nursery fields [16,20,31]. Next to the land use for vegetative multiplication, there are fuel and labor costs involved. Rhizome planting is logistically challenging, as live plant parts have to be harvested, transported, and planted without loss of vitality [31]. The technology of in vitro propagation is estimated to be even more expensive [5,20,30]. Current efforts have been made in the development of alternative propagation techniques, such as seedling plug planting of greenhouse cultivated plugs [5].

Alternatively, direct sowing under mulch film has shown potential even though the survival rate was only 20% and the agronomic protocols need to be refined for economic applicability [32]. Depending on the soil and climate conditions, the establishment methods have to be adapted. The solutions include the planting of rhizomes under a film cover to emulate a warmer, more humid micro-climate [5]. After the establishment of the stand, the cultivar yield is expected to be stabilized after 2–3 years and remain roughly constant during the use phase, up to 25 years [5].

2.3. Biomass Harvest

Miscanthus can be harvested in different forms, depending on which aggregate size will be required for the intended application. Some applications, such as thatching [33] require long or full-length stem materials. Other applications, like particle board [34], fiber in polymer [35] composites, or as an addition to concrete [36,37], may not require large stem pieces and accept particles as input. In that case, harvesting can be carried out by a maize harvester where the biomass is directly blown onto a transport vehicle. Alternative harvesting and transport modes encompass on-field baling where the integrity of the stems is not a prerequisite [38]. If longer transportation distances are unavoidable or direct energetic applications are intended, the harvested material can be further compacted to pellets or briquettes [39].

The harvesting process has major influences on the quality and economics of the biomass and no general applicable standard has been set to date [38,40–42]. The energy requirements during harvest can be reduced by modificationsto the machinery, including oblique angle cutting [43,44]. An increase in harvesting speed was obtained by using serrated blades to increase the theoretical field capacity from 1.35 to 2.23 ha h^{-1} [45]. Not only the particle size and storage stability are affected but also the biomass composition, in terms of the moisture and actual chemical component availability, are directly influenced by the harvesting time and on-field processing [4,6,26,46,47].

2.4. Yields in Geographical Context

Local production of *Miscanthus* appears to be feasible in a European context [3,6]. Lewandowski et al. [6] reported successful cultivation of *Miscanthus* in non-irrigated fields of *Miscanthus* × *giganteus* in a wide range of locations, from Portugal to Sweden, and a broad, viable range of climates for cultivation was indicated in the literature [3–6]. The general yields, over a range of climatic conditions, were put on 10 t ha^{-1} to 25 t ha^{-1} in a European context, by Lewandowski et al. [6]. The yields increase in warmer climates, but decreases in the case of drought stress have to be expected [3,6,20].

2.5. Transport

A challenge to the production of materials from *Miscanthus* is the availability of biomass at the specific processing site. The biomass demand of a production facility has to be met without exceeding a proportionality of the transportation cost. The transportation proportionality is a pay-off between the biomass value and volume against the transportation distance. The low density and low value material of *Miscanthus* necessitates a local value adding chain to be economical. Assumptions for the viable transport distances of raw *Miscanthus* biomass are generally valued below 100 km [16,19,39]. The transportability remains limited by densification options in labour and energy demand, as well as the alteration of material properties instituted by the chosen densification process [5].

2.6. Feedstock Parameters

The feedstock parameters can be divided into three main fields: the macroscopic scale, the microscopic scale, and the molecular scale. The macroscopic scale consists of demands to the transport qualities, including the bulk density [39,48], or the culm and chip size [22], moisture content [4,35,48,49], and the aspect ratio [50–52] of the biomass. Onthe microscopic scale, the surface properties, in terms of roughness [50,53,54], pore sizes [54,55], surface chemistry [22,52,56], and fibrillation of particles [57], could be relevant. For the molecular scale, one may consider the chemical aspects of the feedstock. This would dividethe chemical composition into relative amounts of valuable extractable or separable molecules [5,28,58], as well as possible process-inhibiting constituents [4,15,59–61]. The parameters on the molecular level of the feedstock are dominated by the chemical composition and the molecular structure of the extractables, due to the stage of development and genotype.

The growth and senescence results in morphological differences, such as the leaf–stem ratio in varieties or hybrids, thereby alter the composition of the feedstock and the viability for different applications, like fermentation [62] or direct combustion [46,63,64]. Abiotic stresses influence the growth and senescence cycles, such that varieties may be screened for optimum climate–plant combinations [4,5,46]. Furthermore, variations in the extracted molecules from different plant parts may be expected. Lignin extracted from different plant components (stem and leaf) displayed different polymer characteristics [28].

Additionally, the chemical structure of the biomass can be relevant in terms of the embedding and possible release paths of molecules in the biologic matrix (i.e., recalcitrance and crystallinity) [5,15,58,65,66]. Kaack et al. [65], for example, related the chemical and morphological traits. Statistical analysis yielded a statistical relation between the modulus of elasticity, the area of the outer ring, and lignin, as well as the area of parenchyma and cellulose, and the area of vascular bundles and cellulose, thereby suggesting *Miscanthus* × *giganteus* as part of a likely group of genotypes for the production of building materials. Research and knowledge are thus highly specific and dependent on the chosen application.

The agronomic biomass end-product *Miscanthus* will have to be converted to a viable feedstock depending on the chosen valorisation chain. The applications are diverse, such that feedstock requirements depend on the follow up refinement. An application such as light weight concrete, as examined by Pude et al. [67], requires stem fragments with relevant parameters on the macroscopic scale; whereas the fabrication of nano-cellulose as a polymer reinforcement, as investigated by El Achaby et al. [68], requires a feedstock rich in crystalline cellulose.

Energetic applications are well understood such that the feedstock characteristics can be defined by the parameters of processing, pre-treatment, transport, storage and harvest, and the chemical composition of the plant variety itself [5,26,58]. The research is focused on the latter plant specific traits, such as increased biomass yield [5], reduced recalcitrance (lignin content) [18], and increasing sugar or starch content [20,58], but the genetic viability required for successful mass-scale deployment was determined to be a key issue [11]. On the other hand, in the context of biorefinery the pre-treatment parameters and methods structurally researched are aiming at less energy intensive [26] or less chemically demanding processes [19,26]. A recent research model is even targeted at the online analysis of a feedstock in order to be able to adapt the running process by the input feed [69].

The combination of optimal feedstock parameters is complex as components, such as lignin, may be used as a value generating sidestream, depending on the used processes [28,70].

3. Polymer Composites

3.1. Miscanthus Biomass in Polymers

Modern polymeric materials with natural fibers in composites have gained much attention as reinforcements [71]. The function of the added material can vary from the reduction of weight or price of a composite [49,51,72] up to the improvement of the structural parameters of the product [51,73]. However, the employment of *Miscanthus* biomass in polymer systems is complex and an overview on the general aspects and tendencies is given.

Difficulties in the reinforcement mechanisms are caused by the fiber to matrix compatibility [52], the dispersion of the fibers within the matrix [52], and possible degradation of the fiber during the processing [35,49,74]. The fiber to matrix bond may be strongly influenced by hydrophilic particles and hydrophobic polymers, leading to insufficient adhesion [50,52,56,73]. Matrix compatibilizers can be used to improve the interface adhesion by blending the polymer with a co-polymer, such as maleic anhydride [50,52,75], grafted polypropylene, or by reactive activation with a peroxide [76]. However, the necessity for compatibilization is dependent on the specific polymer system as a good interfacial bond was reported in poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) [56,77].

The biomass particle parameters of size, alignment, and dispersion in the matrix determine the degree of mechanical reinforcement that is possible [50,52,74,76]. A strong influence of fine particles via the reduction of mechanical properties and the necessity of the removal of irregular dust was reported by Girones et al. [50]. A homogeneous dispersion of fibers is required as reinforcement effects are anisotropic and the misalignment of fibers can lead to a weaker specimen [51]. Smaller fibers with a high length to width aspect ratio are related to tensile strength increases, due to the higher specific surface area [50].

The processing of polymers and fibers can degrade the integrity of the fibers by process heat and prolonged heat (residence time) [49–51], as well as by physical shear forces causing fiber size reduction [51,74]. Gamon et al. [74] have investigated the influence of different extrusion screw speeds. They reported that extrusion at 150 rpm was the best trade-off between low energy requirements for slow speeds and sufficient homogenisation and fiber bundle preservation at high speeds, in a twin screw extruder. Other pathways of *Miscanthus* biomass incorporation into a composite were tried with alternative pre-treatment methods, such as pyrolysis [78,79], corona discharge [80], and the extraction of cellulose crystals [68,81].

3.2. Technical Aspects of Composite Manufacturing

Johnson et al. [35,49] investigated the influence of *Miscanthus* fiber loading, particle size, and the processing temperature on the impact performance of biodegradable Novamont Mater-Bi© Polymer. The processing variables were the extrusion speed (15%, 30%), fiber loadings (10%, 20%), particle sizes (⩾3 mm, ⩽1 mm), and temperatures (175 °C, 190 °C). The impact load of the fiber reinforced compound was increased up to 30% for increased heat and a 20% fiber loading of partilces below 1 mm. The increase in impact load was assumed to be caused by weak adhesion between the *Miscanthus* fibers and the polymer-matrix, and this resulted in fiber pull-out. The temperature was assumed to be a main factor and was later validated as the only significant factor for these process conditions [35,49,82].

Kirwan et al. [51] researched the influence of different processing parameters on the flexural rigidity and modulus of *Miscanthus* in a commercial poly(vinyl alcohol) (PVA) blend. Analysis of the parameters was carried out by a fractional–factorial design of an experimental statistical method, in order to find the influence of the fiber length (2 mm, 4 mm), volume (10%, 20%), washing temperature (72 h at 25 °C, 3 h at 100 °C), processing temperature (190 °C, 200 °C), and the blending of poly(vinyl acetate) PVAc (5%, 10%) into the PVA. The flexural rigidity was improved from 61.8 to 123.4 N mm^{-2} with a combination of a hot washing with short fibers at 20% fiber load in a 5% PVAc /PVAXX W63 blend processed at 200 °C. The same combination reached an improvement of the flexural modulus from 2700 to ≈9500 N mm^{-2}.

Combinations analysis of different factors showed that temperature was the main parameter and this is in accordance with other reports [35,49,82]. A loss of interfacial adhesion between particles and the matrix was observed by scanning electron microscopy (SEM). Furthermore, the hot washing fiber pre-treatment was concluded to be beneficial to the modulus and strength. The removal of soluble starches were assumed to have caused increased adhesion leading and strength. The analysis of the fiber length was impeded by size reduction during the processing and the analysis of reclaimed fibers in size and aspect ratios of the longer feedstock were found to be similar to the short fibers.

Bourmaud et al. [52] analysed the mechanical properties at different fiber loading ratios (20%, 30%, 40%) with maleic anhydride (MA) compatibilizer (0%, 2%, 5%) in two different matrices of polypropylene (PP) and polylactic acid (PLLA). In the PP matrix, the addition of 2% compatibilizer improved the tensile modulus from 1051 to 2309 N mm^{-2}, 2742 N mm^{-2}, and 3453 Nmm^{-2} for increasing fiber loadings. In the PLLA matrix, the addition of 2% compatibilizer improved the tensile modulus from 3401 to 5337 N mm^{-2}, 5492 N mm^{-2}, and 6652 N mm^{-2} for increasing fiber loadings. The improvements of the tensile modulus is assumed to be caused by improved fiber dispersion and interfacial bonds. Further addition of compatibilizer did not show significant improvements. Therefore it was concluded that an optimal amount is below the 5% compatibilizer addition. The strength at yield in PLLA decreases from 60.4 to 40.8 N mm^{-2}, 37.9 N mm^{-2}, and 39.3 N mm^{-2} with the addition of the fibers, which was attributed to poor lengths and aspect ratios.

Nagarajan et al. [56] incorporated *Miscanthus* at a loading of 30% in a biodegradable matrix blend. The matrix blend used was based on poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) and poly(butylene adipate-co-terephthalate) (PBAT). The impact strength of the *Miscanthus* composites was decreased from 369.93 to 35.76 N mm^{-2} while the tensile strength was increased from 21.60 to 23.30 N mm^{-2}. It was assumed that the high lignin content in *Miscanthus* led to increased interfacial bonding with the polymer. The energy dissipation on impact by fiber pull-out was reduced and a critical failure of the fibers caused a reduction of the impact strength.

Zhang et al. [77] investigated the feasibility of a co-injected PHBV/*Miscanthus* core in a poly (butylene succinate) PBS/PBAT blend skin. Co-injection molding of a PHBV/*Miscanthus* core into a neat PBS skin decreased the notched impact strength from 29.8 J m^{-1} for a single injected PHBV/*Miscanthus* matrix to 29.2 J m^{-1}. Co-injection moulding of a PHBV/*Miscanthus* core into a PBS/PBAT skin increased the notched impact strength to 139.8 J m^{-1}. The unnotched impact strengths were increased from 112.6 to 322.1 J m^{-1} for neat PBS and 398.7 J m^{-1} for a PBS/PBAT blend. The tensile strength values were $\approx$ 18 N mm^{-2} for a single injected matrix, 28 N mm^{-2} for a PBS skinned composite, and 19 N mm^{-2} for the PBS/PBAT composite. The flexural strength values were $\approx$ 32 N mm^{-2} for a single injected matrix, 37 N mm^{-2} for a PBS skinned composite, and 20 N mm^{-2} for the PBS/PBAT composite. The different combinations of the mechanical values led to the conclusion that co-injection molding may be used to design *Miscanthus* composite materials according to specific performance requirements.

Chupin et al. [72] contrasted the common use of culms and tested the reinforcement capabilities of rhizome biomass of *Miscanthus* × *giganteus* in poly ethylene (PE) composites. Using a fiber loading of 30% with particles retained between 100 µm and 200 µm, sievescreen specimens, for rhizome mass and stems, were produced. The tensile strength decreased for the rhizome composite from 7.62 N mm^{-2} for neat PE to 7.45 N mm^{-2}, while the stem composite increased the value to 13.5 N mm^{-2}. The low tensile strength of the rhizome composite was assumed to be caused by a low aspect ratio of rhizome fragments as well as a lower intrinsic strength due to a higher proportion of hemicelluloses in the rhizomes (35%) compared to the stem (21%).

El Achaby et al. [68] investigated the potential of *Miscanthus* fibers for the production of reinforcing cellulose nanocrystals (CNC) for potential usability in polymer systems. By employing sulphuric acid hydrolysis on *Miscanthus* × *giganteus* CNC with an aspect ratio of 37, a crystallinity of 76% could be obtained. The addition of 8% CNC improved the tensile properties of starch based nano-composite films to 118% in tensile strength and 150% in Youngś modulus.

Miscanthus has been tested in different polymer systems with a strong focus on processing and feasibility within a given combination, as shown in Table 1.

Table 1. The different biocomposites produced based on *Miscanthus* fibers and particles.

Process	Polymer Blend	Compatibilizer	Variable/Question	Author/Group
Injection molding	Mater Bi©	-	process variables	Johnson et al. [35]
Injection molding	Mater Bi©	-	process variables	Johnson et al. [49]
Injection molding	PVA	-	process variables	Kirwan et al. [51]
Injection molding	PP	MA	fiber loading/compatibilizer	Bourmaud et al. [52]
Injection molding	PLLA	MA	fiber loading/compatibilizer	Bourmaud et al. [52]
Injection molding	PHBV/PBAT	-	biomasses	Nagarajan et al. [56]
Injection molding	PP	MA	process variables	Girones et al. [50]
Injection molding	PP	MA	genotypes	Girones et al. [50]
Injection molding	PHBV	di-cumyl peroxide(DCP)	feasibility	Muthuraj et al. [76]
Injection molding	PBS/PBAT	MA	feasibility	Muthuraj et al. [75]
Injection molding	PE	MA	feasibility	Chupin et al. [72]
Injection molding	Nylon	pyrolysis	process variables	Ogunsona et al. [78]
Injection molding	PBS/PBAT	-	process variables	Muthuraj et al. [83]
Co-Injection molding	PBS/PHBV	-	feasibility	Zhang et al. [77]
Thermo-compression	PP + PLA	corona discharge	pre-treatment	Ragoubi et al. [80]

3.3. Summary and Conclusions: Miscanthus Polymer Composites

The polymer to fiber bond of *Miscanthus* in polymer systems can be improved by compatibilizing agents blended into the polymer matrix [50,52,75,76]. A high hemicellulose content of the feedstock is suspected to have detrimental effects [52,72]. The main reported parameters governing the performance of the polymer compounds are the high length-to-width aspect ratio of the particles [50,72], the degree of fiber loading [52], and the dispersion of fibers within the matrix [52,74]. Extrusion of the polymers and fibers causes degradation of the biomass under certain conditions [49–51,74].

In general, a potential for the application of *Miscanthus* as a feedstock material in polymer systems is expected [49,51,73]. Further research should include the influences of the chemical composition of the feedstock on the mechanical performance. However, a focus should be on the comminution, the fiber degradation during extrusion, and the dispersion of the particles inside the produced matrix.

4. Particleboards

4.1. Miscanthus in Conventional Particle Boards

Currently, several researchers have investigated the possibility of wood substitution with alternative resources and processes [34,54,55,84–88]. In this case, the main driving force is the relatively high competition of the wood resource and the subsequent economic benefit of replacement or partial replacements of wood with existing agricultural by-products. *Miscanthus* is part of the tested alternatives even though it is not strictly a by-product, as the other tested materials are.

Miscanthus may be employed as a wood substitute if a sufficient amount of appropriate adhesive binder is used [34,84,85,89]. However, the binder systems were found to be limited by the chemical environment, in terms of an increased pH and pH buffering capacity excluding urea formaldehyde and phenol formaldehyde binder systems [84], as well as a limited surface adhesion on the stalks [54]. Therefore, it was suggested that the chemical environment and surface properties may be modified by high pressure refinement [84]. A full substitution by non-wood biomass was only applicable with *Miscanthus* and at the drawback of increased resin requirements of methylene diphenyl diisocyanate (MDI) for acceptable panel properties [84]. Further drawbacks were expected in the amount of extractives and mineral content in terms of silica [84]. Tool wear by abrasion and chemical corrosion is caused by extractives and silica in the long run [90].

Balducci et al. [55] investigated board production based on parenchyma rich raw materials in order to decrease the compound weight. It was supposed that inherently lighter materials could achieve higher mechanical properties compared to wood particle boards, which do not conform to EN 312 at low densities. The particle boards derived by low density materials reached modulus of elasticity (MOE) values ranging 560–1270 N mm^{-2} and did not conform to EN 312 by MOE (1600 N mm^{-2}) or by flexural strength (13.0 N mm^{-2}), and are thus not directly applicable for general indoor use.

The special structure of the *Miscanthus* parenchyma limits the internal bond strength (IB) as the weak link in the superstructure, even though other mechanical parameters indicate the general application of wood substituted boards under dry conditions [89].

In a substitution experiment of wood at two MDI resination levels (4% and 6%), the MOE, modulus of rupture (MOR), IB and thickness swelling (TS) were determined according to EN 312 P1. However, stagnation of MOR (14 N mm^{-2}), MOE (1700 N mm^{-2}) and IB (0.35 N mm^{-2}) was reported for *Miscanthus* with increasing binder content, whereas the wood reference did increase in IB from 0.85 N mm^{-2} to 1.1 N mm^{-2}, implying that the particle to binder interaction reached a particle inherent limit in *Miscanthus*. A performed micro-structural analysis showed collapsed parenchyma cells in the *Miscanthus* specimen after the IB test. It was concluded that the structure of the parenchyma is responsible for the weak bonds and subsequently suggested that a removal of the parenchyma fraction prior to pressing could improve the board properties.

Tröger et al. [34,85] investigated the improvement options of wood substituted *Miscanthus* boards by means of flax fiber mat reinforcements [85] and multilayered board constitutions [34]. Flax fiber mat reinforcement of the *Miscanthus* MDI particle boards led to MOE values of 5990 N mm^{-2} and flexural strength values of 39.6 N mm^{-2}, which is comparable to glass fiber reinforced panels [85]. The TS of the *Miscanthus* based -flax fiber reinforced- boards over 24 h was reported as improved by 9.5%, which is half of the used spruce references (15.8–18.0%). However, the internal bond strength (IB) of the *Miscanthus* based board was lowered (1.21 N mm^{-2}) compared to the spruce reference (1.52 N mm^{-2}), indicating that the *Miscanthus* interaction with the binder is not optimal or that the parenchyma introduced a breaking point.

Multi-layered systems with 50% *Miscanthus*/wood core and varying surface layers displayed increased bending strength (23.0 to 39.6 N mm^{-2}) and MOE (3500 to 6000 N mm^{-2} by flax fiber reinforcement). However, even the non-reinforced multilayer variant of pure *Miscanthus* strands in the surface layers and displayed performance, which was equal to the reference wood standard produced, suggesting that a partial wood substitution is technically feasible. However, due to the MDI requirement, the economic feasibility was considered to be insufficient.

At a partial wood substitution level of 50% in Douglas-fir (Pseudotsuga menziesii) boards, PF binders were found to keep the IB at suitable levels [54]. While the parenchyma content likely decreased the IB of the boards, [55,89], Park et al. [54] considered the slender particle geometry of *Miscanthus* as responsible for the increased MOE at higher wood substitution levels and lower binder amounts (9% vs. 11% PF). An offsetting effect is observed at increased resin content (11%) where the MOE is raised from pure *Miscanthus*: ≈1600 to ≈2100 N mm^{-2} for full wood composition [54]. An improved particle-binder bond was suggested for the wood, due to the low porosity and stalk surface properties of the *Miscanthus* epidermis.

4.2. Miscanthus Biomass in Binderless Fiberboards

A different development in the particleboard research is the investigation of binding processes without the addition of synthetic binders. The two main reasons behind this are the strict legislation on formaldehyde emissions, which poses new requirements on the existing binders, and the high contribution of the binder price to the total cost of materials [87].

Lignocellulosic biomass can be converted into self-adhesive boards. The plastification of thermoplastic lignin is intended to be the main contributor to the binding effect. The binding effects are influenced by mechanical contact, molecular contact, and interaction, chemical bonding as well as the structural integrity of the composite as is elaborated by Hubbe et al. [88] in more detail. Due to the complexity and mutual influence of the effects governing the overall properties of the produced board, a main focus in the research is the influence of the biomass pre-treatment and processing conditions on the mechanical properties of the board. An overwiev of Miscanhtus based particle boards with and without added binders is given in Table 2.

Velásquez et al. [86] produced binderless fiberboards from material of *Miscanthus sinensis* by steam explosion pre-treatment in a masonite process and analysed the pre-treatment and pressing conditions. The highest total MOE and MOR values reached were 6050 N mm^{-2} and 48.2 N mm^{-2}, respectively, with an IB of 1.2 N mm^{-2}. The feedstock was obtained by severe (4.0) steam explosion treatment at 216 °C for 3.5 min and moderate pressing conditions at 180 °C. By variations of combinations, different estimated response surface diagrams were produced to predict the behavior of a mechanical product parameter by variations in either pre-treatment or processing conditions. The pre-treatment stage was concluded to have a higher influence on the physiochemical properties than the hot pressing stage.

Next to the physical particle disintegration, chemical degradations also occur during the masonite process. Improved water absorption and thickness swelling behavior was assumed to be correlated with decreased hemicellulose content by hydrolysis for increasing the pre-treatment severity. The increased physical degradation also led to an improvement of IB, by increasing the particle contact. In contrast to the *Miscanthus* particle boards produced with binders, the binderless boards have a higher density by compression and physical disintegration, such that the porous structure of the parenchyma would be collapsed, and water absorption takes place through swelling of the hydrophilic fibers.

Velásquez et al. [91] researched the physio-mechanical response of binderless *Miscanthus* fiberboard through size reduction of a steam exploded raw material through grinding. The IB was improved by 50% via grinding. It was concluded that grinding size reduction of particles treated with low severity parameters led to defibrillation of fiber bundles and increased the contact area and the strength of the bonds in pressing. Due to uninhibited MOE and MOR values, a significant length reduction of the fibers was considered improbable.

Velásquez et al. continued with [92], the experimental influence of feedstock and process conditions by investigating an increased span of parameter ranges in pre-treatment severity and pressing, and the subsequent changes in mechanical particle board parameters. The specific conditions are evaluated to maximize the MOE and MOR values, which reached theoretical values of 7500 N mm^{-2} and 61.2 N mm^{-2}, respectively. In the steam explosion pre-treatment, a temperature of 203 °C with a pre-treatment time of 7.35 min is found to be optimal and pressing in a three stage process at 220 °C and a pressure of 12.1 MPa is considered optimal.

Next to the pure binderless boards, Velásquez et al. [86] investigated the addition of exogen kraft lignin powder for partial substitution of *Miscanthus sinensis* by steam explosion pulp in hot pressed particleboards. By pressing with reduced temperatures at 170 °C with 20% exogen lignin substitution, MOE values of 5900 N mm^{-2} were predicted. Further increasing of the temperatures and lignin content was reported to cause internal bubbles, limiting the bonding of the composite. It was concluded that substitution of the pulp is possible without quality loss if pressing temperatures are reduced. Further improvement was reported for the mixing of fibers with lignin prior to the steam explosion.

Two causes were suspected for the improvement, first, the removal of volatile substances that otherwise may lead to destabilizing the formation of gas bubbles, and second, an increased homogenisation of the exogen lignin and cellulosic fiber. Reduced material requirements from improved properties were concluded to translate into economic benefits with reduced energy requirements of the process. The volatile substances suspected as cause for bubble formation at elevated temperatures should be removed during the steam explosion and better homogenisation of exogen lignin and cellulosic fibers is likely. Being able to reduce the amount of steam exploded material and the required pressing temperature translates into economic benefits in terms of energy.

Binderless boards without steam explosion pre-treatment were produced by Moll et al. (2018) [93] by hot pressing hammer-milled *Miscanthus* × *giganteus* particles. The particle boards were produced from different sieve-fractions of a single hammer-milling step, in order to determine the influence of the particle size on the mechanical board properties. The particle fraction passing a 0.25 mm sieve-screen resulted in the highest MOE (1200 N mm^{-2}), whereas particles between a 0.5 mm and 0.75

sieve-screen resulted in much reduced MOE values (190 N mm^{-2}). It was concluded that a good control of the fine fraction would be required to produce particle boards in hot pressing with specific target properties.

4.3. Miscanthus Biomass in Insulation Panels

Due to the parenchyma content of *Miscanthus* and the accompanying increased porosity compared to woody biomass, inherent thermal insulation properties have been postulated [67,94]. In this context, insulating particleboards have been evaluated for different technical aspects.

El Hage et al. [95] evaluated the potential of a flame retarding chitosan binder for a *Miscanthus* and recycled textile fiber biocomposite. The chitosan binder was developed with different aluminum trihydroxide filler contents while the biocomposite composition was varied in *Miscanthus* to the textile fiber ratio. The thermal conductivities were reported to vary between 69–90 mW*m^{-1} K^{-1} where a higher textile content (0–100%) increased the thermal conductivity by increasing the density and decreasing the porosity. Despite higher densities (250 kg m^{-3}) compared to conventional insulation materials and slightly increased thermal conductivity values (λ values) the chitosan bound biocomposites were still considered as insulation material.

The fire rating Euroclass E could be obtained by a combination of chitosan improved by addition of anorganic filler. The authors therefore concluded that there was a potential of the flame retarding insulation material. The fire behavior of chitosan was reported as interesting and further improved by anorganic filler integration, such that the Euroclass E fire rating is obtained, and an overall potential of the system was concluded.

Eschenhagen et al. [94] produced and compared insulation panels from sunflower stalks and *Miscanthus* × *giganteus* by testing different natural based binder mixtures. The mechanical values were tested in Youngś modulus and Youngś bending modulus, and the thermal insulation properties were evaluated. The binder systems tested spanned binder to water ratios from 10–40%, and three binders based on starch, casein, and gelatin. Due to the low integrity of the formed panels, only two binder systems with *Miscanthus* (starch, casein) were used in structural testing and three for the sunflower compounds. Further integrity problems limited the tested boards. From the *Miscanthus* two starch based boards (20%, 30%) and two casein based boards (30%, 40%) were tested. The sunflower stalk boards were tested with starch (20%), casein (20%, 30%, 40%) and gelatine based binders (30%). The thermal conductivity and thermal resistance were compared for 20% binder systems in the *Miscanthus*/starch and sunflower/casein systems, as shown in Table 3.

Based on the combination of mechanical and thermal properties, the feasibility of *Miscanthus* based insulation boards is concluded to be possible; however, characterizations of the durability in physical and biological aspects, as well as further determination of the standard insulation properties are suggested.

Table 2. An overviewof different projects describing *Miscanthus* based board or insulation materials.

Process/Layer	Added Binder	Pre-Treatments	Question/Variable	Author
Multilayer	MDI	-	Feasibility	Tröger et al. [34,85]
Single layer	PF	-	Process variables	Park et al. [54]
Single layer	MDI	-	Feasibility	Balducci et al. [55]
Single layer	MDI	-	Process variables	Klimek et al. [89]
Hot press	-	Steam Explosion	Process variables	Velásquez et al. [91,92]
Hot Press	Exogen Lignin	Steam Explosion	Feasibility	Velásquez et al. [86]
Hot press	-	-	Process variables	Moll et al. [93]
Single layer	Chitosan	-	Feasibility	El Hage et al. [95]
Single layer	starch/casein/gelatin	-	Feasibility	Eschenhagen et al. [94]

Table 3. Thermal conductivity λ and thermal resistance R, according to temperature T, for composites panels with 20% binder content [94].

T (°C)	*Miscanthus*/Starch (20%) λ (mW m^{-1} K^{-1})	R (m^2 K W^{-1})	Sunflower/Casein (20%) λ (mW m^{-1} K^{-1})	R (m^2 K W^{-1})
10	57.02	1.070	65.24	0.680
25	61.27	0.992	70.42	0.631
40	67.55	0.900	77.42	0.573

Note. Reprinted from "Investigation of Miscanthus and Sunflower Stalk Fiber-Reinforced Composites for Insulation Applications" by Arne Eschenhagen et al., Advances in Civil Engineering, Volume 2019, p. 6.

4.4. Particleboards: Summary

For the production of particle boards, both adhesive and binderless systems are possible. However, the binding agent needs to be compatible with the chemical environment given by the *Miscanthus* feedstock, as well as the chosen processing conditions. In a binderless system the technical performance is strongly influenced by both the process of board production as well as the pre-treatment methods and comminution of the biomass. While the influence of the production parameters is quantified, the physical and chemical parameters, leading to improved board performance, have not been quantified yet. Several factors influencing the bond strength reside in the surface properties of the particles and the low structural integrity of the parenchyma. A separation of the parenchyma and an analysis of the comminution method on the mechanical performance may be advisable. Differences in the chemical composition and morphology of various *Miscanthus* genotypes may be expected to cause variations in mechanical parameters under similar processing conditions.

5. Concrete Systems

5.1. Miscanthus Based Concrete

Concrete production is responsible for around 6% of the global annual CO_2 emissions. Addition of biomass into concrete would reduce CO_2 generation [96] and sequester carbon in building materials. With political development in the European Union, the thermal conductivity of concrete needs to be improved, in order to reduce the energy demand in buildings. The reduction of the energy demand for concrete can also be affected by the reduction of energy demanding resources, such as steel or glass fiber in concrete [53]. *Miscanthus* fibers have a tensile strength of 373 N mm^{-2} [97] and a compressive strength of 56.9 N mm^{-2} [97] and could act as reinforcement, if a good fiber to matrix bond can be established [53,59,67].

Furthermore, *Miscanthus* biomass is silicate rich, as 74% of the ash is composed of silica [98] and porous parenchyma, which are both considered to pose potential benefits in a cementitious matrix [22]. The parenchyma content and the concordant pore structure are expected to reduce the thermal conductivity of the concrete [22,67,99].

Insertion of *Miscanthus* into concrete reduces the density of the composite material through addition of the lighter biomass. Both effects of density reduction and pore introduction are common to both thermal and acoustic insulation materials, such that improved acoustic insulation properties are expected [37]. Employment of *Miscanthus* in concrete is thus researched for several applications, such as porous admixtures [22,36,37], as reinforcement [53,100], and as alternatives to other bioadmixtures [59].

5.2. Miscanthus Compatibility with Concrete

Portland cement is the most common type and also the main type of binder considered in the different studies. The following section will cover the common compatibility issues between biomass and Portland cement. The compatibility of the binder and the biomass should have a key role in the mechanical properties of the produced concrete. The setting reaction of Portland cement is a sequence of crystalline systems that hydrate and redevelop [101]. By the amount of water available for hydration, the equilibrium reactions of the respective crystal phases are determined [101]. Excess water may induce phase separations and layer formation, and excessive pores in the concrete [102].

Water shortages reduces the flowability of concrete and thus limit the compaction [103]. The water to cement ratio of the mixture thus becomes a relevant parameter for the overall properties of the matrix. Biomass can both absorb and release water, thereby changing the local water to cement ratio [104]. *Miscanthus* has a high water absorption capacity between 200 and 600% depending on the comminution method and particle size [100,105], and can thus affect the water to cement ratio. The time for water uptake of *Miscanthus* fibers was found to be in the short minute interval [67,100] such that water deprivation effects take place during the early hydration phase of the concrete. Direct treatment the pre-soaking of *Miscanthus* fibers [37,100] or the addition of water to the concrete mixture have been suggested [37,100,104].

Further arising problems include particle swelling with water uptake and shrinking with drying, or particle degradation in alkaline media, which may leave excessive voids and decouple fibers from the cement binder [53,100,104]. Different strategies to limit the water absorption have been attempted. Physical processes that densify the fiber and close pores, include the hornification by cycled wetting and forced drying of *Miscanthus* [100] or the encapsulation of *Miscanthus* by mineral or organic agents that seal the particle by a non-permeable or hydrophobic layer [37,100].

Organic extractives can delay or inhibit the setting process and ultimately decrease the mechanical properties of the formed concrete [104]. Influencing biomass constituents such as sugars, lignins, and organic acids are suspected to complexate calcium ions and thus slow the equilibrium formation by competition, or disturb the equilibrium by adsorption [59]. Equal inhibiting effects may be caused by absorption of Ca^{2+} in the biomass.

Different pre-treatments to leach the available organic constituents of *Miscanthus* have been carried out. The range spans extractions with hot water [100], as well as leaching and silanization of *Miscanthus* in different chemical environments [104], to the use of saccharification residues with a supposedly reduced amount of extractable sugars [59]. Portland cement forms an alkaline environment, when the hydration reaction occurs [101]. Biomasses can buffer the pH changes by ion exchange capacities, release/reaction of organic acids, or by a degradation reaction with an alkaline solution and the subsequent release of fragmentation products [106].

5.3. Various Miscanthus Particle Influences on Concrete Properties

Pude et al. [36] produced concrete samples from chopped culm pieces with a water to cement (w/c) ratio of 0.8 to determine the influence of the used genotype on pressure stability. Four different genotypes were used: *M.* × *giganteus*, *M. sacchariflorus*, *M. sinensis*, and *M. 'Robustus'* and they displayed variations in pressure stability, depending on the genotype and harvesting year. *M. sinensis* and *M. 'Robustus'* showed the lowest compressibility values (0.41 and 0.28 N mm^{-2}, respectively) and were hence concluded as inadequate for cement applications.

A strong influence of the batch is displayed in the pressure stability differences between the two years. The varieties *M. sacchariflorus*, *M. sinensis* and *M. 'Robustus'* displayed a stability reduction to roughly 25% of the 2001 values while *M.* × *giganteus* did not vary, essentially (0.74 and 0.75 N mm^{-2}). Growing period related quality parameters influenced by the year's climate or plant stresses thus have a strong influence in the pressure stability of concrete and need to be identified [36]. The water to concrete ratio applied in this study is significantly higher than the suggested ratios for Portland cement (0.5) and may have contributed to the low strength values [100]. The high water uptake of the culm pieces is described by Pude et al. as beneficial to the strength due to saturation with concrete sludge.

Acikel et al. [53] attempted to reinforce concrete of different cement dosages with a w/c ratio of 0.5 by varying the biomass input ratios and different comminution styles. The fibers were ground, cut, embedded as reinforcement, and introduced as mixture. An effect of the biomass loading, the comminution method, and the concrete dosage, was observed in the strength of compression, splitting, and flexural strength, as shown in Table 4.

Table 4. Selected mechanical properties of *Miscanthus* concrete specimens by Acikel et al. [53].

Cement Dosage [kg m^{-3}]	Grinded Fiber Loading	Compression Strength [N mm^{-2}]	Splitting Strenght [N mm^{-2}]	Bending Strength [N mm^{-2}]
300	0%	35	2.7	5.5
300	2%	37	3.0	5.8
300	4%	38	3.3	5.9
350	0%	36	2.9	5.9
350	2%	37	3.3	6.1
350	4%	38	3.6	6.2
400	0%	36	3.2	6.2
400	2%	46	3.5	6.8
400	4%	46	3.9	6.7

Fiber loading of ground *Miscanthus* (2% and 4%) improved the strength compared to the reference samples. Increasing the cement dosages displayed higher base values. The increase for compressive strength is reported as 9% to 25%. The strength increase at a high cement dosage with increasing fiber load appears to reach a limiting value at a high cement dosage of 46 N mm^{-2}, as shown in the Table 4. The splitting and bending strength are reported to increase by 4% to 8%, where the bending strength also appears to reach a final value, as can be seen in Table 4. For the cut fibers, the strength parameters did display a reduction that was explained by the smooth plant surface and an insufficient bond to the concrete matrix. Furthermore, crystallization effects were observed on the smooth surface of the biomass, indicating a phase separation [53].

Le Ngoc et al. [59] employed *Miscanthus* residues (*Miscanthus* × *giganteus*, at harvesting time in November, during the second year of cultivation) of two different saccharification pre-treatments in cement mortar with w/c of 0.46. The two biomass pre-treatments were dilute heated sulphuric acid and an aqueous ammonia treatment intended to reduce the inhibitory effects caused by lignocellulosic biomass in cement. The biomass was added as a water saturated mass and displayed an increased outflow speed in the composites, from 3s28 s in neat cement paste to 1s94-2s5 s for the residues and raw *Miscanthus*. However, the polysaccharides and lignin contents of both pretreated biomasses were found to be increased, and the setting of the concrete was delayed. The effect could be limited by the addition of CaCl employed as a setting accelerator.

While the flexural strength appeared unaltered (≈3.0 N mm^{-2}), the compressive strength was reported to decrease. The reduction is 85% against cement (≈66 N mm^{-2}) and by 62% against raw *Miscanthus* cement specimen. The decrease is explained by an increase in the pores of the mineral matrix. Another explanation is a possible modification of the calcium silicate hydrate (C-S-H) crystal phase by the formation of salts between calcium and the organic constituents. Despite of the reduction of the mechanical properties, the values are reported as comparable to other lignocellulosic cementitious compounds.

Boix et al. [104] investigated particle pre-treatment systems consisting of alkaline leaching and silanization protocols and the influence on the concrete specimen. The compression strength of concrete, the sugar amount released from the biomass during concrete exposure and the effect on the setting of concrete were determined. *Miscanthus* particles were leached with NaOH and treated with tetraethyl otrthosilicate (TEOS) emulsions at different pH levels (pH4, pH 6, and pH 10). The compression strength of the concrete increased from 2.2 N mm^{-2} to 11 N mm^{-2} for particle treatment by alkaline leaching, followed by acidic silanization.

A negative correlation between the compression strength and the amount of sugars released into the concrete water was observed, such that the strengthening effect was attributed to the initial basic sugar leaching and silane coating against the degradation in concrete. Fourier transform infrared spetroscopy (FTIR) confirmed the lowest C-S-H inhibition and conductimetry displayed that the setting time for the leached and silanized biomass faster than with pure water. The influence of the treated biomass on the setting of concrete is thus highly complex.

Chen et al. [37] varied *Miscanthus* loading rates and pre-treatment methods for acoustic absorption properties in concrete with a w/c ratio of 0.45. The *Miscanthus* was loaded in volumetric dosages of 10%, 20%, or 30% as different milled fractions and the pre-treatment methods performed included soaking of the fibers and impregnation by cement slurry. The cement mixture was composed of Portland cement and ground granulated blast furnace slag aiming to reduce the alkaline degradation of the biomass.

The compressive strength decreased for increasing fiber loading from 13.4 to 2.26 N mm^{-2} for pre-wetted particles of 0–2 mm against the reference with 55.4 N mm^{-2}. Larger particles with 2–4 mm and *Miscanthus* powder followed the same trend with respective strength decreases of 14.8–5.21 N mm^{-2} and 17.58–3.59 N mm^{-2}. Cement impregnated particles decreased in strength with increasing fiber loading from 23.14 to 10.78 N mm^{-2} for 2–4 mm and 23.69 to 14.59 N mm^{-2}. The smaller trend of decay for the cement impregnated fibers, due to the reduction of leachates through the encapsulation of biomass. The mechanical properties are nonetheless concluded to be improved compared to other bio-based lightweight concretes.

No general trend is observable for the particle size effects over both pre-treatments, except that powder fractions appear to reduce the compressive strength less. The flexural strength of cement impregnated powder samples on the other hand is reported to increase by about 30% compared to pure cement paste. The acoustic absorption coefficients of 2–4 mm pre-wetted *Miscanthus* fibers displayed an increase in the coefficient for low fiber loading with 10% fiber and a shift to higher frequencies with further increased fiber loading. It was concluded that the open pores and voids introduced by the *Miscanthus* significantly enhance the acoustic absorption properties.

Ezechiels [100] designed *Miscanthus* concrete in a master's thesis. Several aspects of concrete mixing with *Miscanthus* feedstock were addressed, and the main findings are described below. The influence of the water dynamic was researched by comparison between pre-saturated water fibers and excess water to saturate fibers in the concrete mixture. It was concluded that no preference for a specific fiber hydration method exists in terms of the concrete compatibility via calorimetry. Hence the water demand of fibers can be treated by the addition of a calculated amount of extra water to the concrete mixture.

The influence of different fiber loadings from 2–10% on the concrete was determined [100]. The mortar workability was found to decrease by increasing the fiber loading and compressive and flexural strength were reported to decrease with fiber content. The strength values decreased about 60% when a maximum loading of 10% fibers was reached.

Different pre-treatments to reduce the water absorption of *Miscanthus* were tested [100]. Next to physical pre-treatment by fiber densification in a hornification process, encapsulation of particles in a water impermeable or hydrophobic matrix (cement, slag and waterglas, lignin, linseed oil, or for example oxydizing oil) were tested. The most efficient reduction of water absorption was 140% by waterglas pre-treatment and 210% by cement slurry. Due to the incomplete inhibition of the water absorption it may be concluded that no full encapsulation has ensued and the pores are still accessible.

5.4. Summary and Conclusions: Miscanthus Concrete

In cementitious*Miscanthus* materials, variations in the mechanical performance are caused by the complex interaction of the biological feedstock with the chemical setting reaction. The introduction of porous biomass decreases the pressure stability but increases the acoustic insulation performance of the material. Reinforcing a concrete matrix requires a good particle to matrix bond that does not get disrupted by particle shrinkage or phase separation around the particles. The reported key issue is the water absorption of the biomass that may be countered by particle treatments or by a calculated amount of excess water within the cement mixture. Organic leachates from the biomass are identified as detrimental to the mechanical properties. Alkaline leaching treatments to reduce the organic leachates have shown an improvement on the mechanical properties. Treatments to reduce the organic leachates have not shown an improvement on the mechanical properties.

The alkaline medium causes biomass degradation into process inhibiting substances; however, the strength of degradation has not yet been quantified. Further investigations should include more effective pre-treatments against water absorption and improved particle to matrix bonds, as well as systematic studies to quantify the magnitude of the strength reducing effects of the organic leachates.

6. Conclusions

This review provides an overview of *Miscanthus* based materials and their conversion from biomass under viewpoints in the scientific community. This review of *Miscanthus* based materials provides an overview of plant specific conversions from biomass to a product in the scientific community with a focus on construction and building materials. The potential feasibility of *Miscanthus* based material applications has been reported for particleboard and concrete applications, such that persistent CO_2 fixation is possible. While the technical constraints and research needs are currently hampering direct economic applications, key factors for the development of in polymer systems, fiberboard production, and concrete have been identified.

The most important limitations regarding the knowledge or technology to convert *Miscanthus* into technically viable materials are insufficient definitions of a usable source material. A targeted pre-treatment to ensure sufficient particle bonding is the key to obtaining a usable feedstock. Further differences in the source material qualities of the different genotypes should be quantified and ranked for their relevance to the applications.

The main constraints in knowledge or technology of the conversion of *Miscanthus* to technically viable materials are missing definitions of a viable feedstock. The active and goal oriented *Miscanthus* pre-treatment is the key to obtaining a viable homogeneous feedstock for each use. Further differences in the feedstock qualities of the various genotypes should be quantified for the applications. All of the described systems share the bond between the *Miscanthus* particles and the binding system as the main factor for critical functions.

The feasibility of a partial wood replacement for the glued particle boards has been proven. Only MDI glue showed good adhesion, due to the pH-value of the biomass, with the disadvantage of increased costs. The internal bond strength was mainly limited by the parenchyma content; however, can be increased to an acceptable level by increasing the wood content of the boards. Reinforcement of the boards with flax fiber mats led to considerable improvements in MOE and flexural strength. The feasibility of partial wood replacement in adhesive particleboards has been shown. Only MDI glue displayed a good bond due to the pH of the biomass. However, the internal bond strength of the boards was mainly limited by the structural integrity of the *Miscanthus* parenchyma.

The surface area and particle size of hot pressed binderless particleboards have a large influence on the mechanical parameters. A good feedstock can be produced by steam explosion; however, for economic reasons, a substitution of steam exploded raw materials would be desirable. A quantification of the particle parameters obtained by steam explosion may be leading to a substitution by matter of other processes or the valorisation of the residual biomass.

Miscanthus fibers or particles were shown to improve the mechanical performance of polymer systems if compatibility to the matrix was established. Fibers may be compatibilized by maleic anhydride grafts in hydrophobic polymers thereby adding costs during pre-treatment. PHBV may be used without further grafting, however, is not a high volume polymer. The added particles are preferred with a high aspect ratio, whereby the processing into a matrix blend can cause severe fiber degradation, both by heat and by mechanical perturbation. Therefore, analysis techniques for the produced matrix blends need to be developed and qualitative links to the feedstock will need to be established.

Miscanthus fibers or particles were shown to improve the mechanical performance of polymer systems under certain conditions. The parameters of particle size, mainly in terms of aspect ratios, were identified as key parameters together with the fiber compatibilizer. Additionally, the particle size parameters need to be quantified for feedstock and the produced matrix.

In concrete systems, the water absorption capacity of *Miscanthus* was identified as the most easily treated feedstock parameter. The addition of a known amount of excess water was described as the most economical pathway. Further strength reducing effects like organic extractives and alkaline degradation products may be limited by chemical pre-treatments. Alkaline leaching, followed by silanization, was found as a most effective solution to the drawback of processing steps and material costs. However, further strength reducing effects reside in the introduction of structural voids and further analysis of the quantitative performance is required. In concrete systems, the water absorption capacity of *Miscanthus* was identified as a relevant feedstock parameter. Different treatments have been attempted in the literature. However, there are further strength reducing effects. Structural voids are introduced via the biomass as well as influencing organic extractives and alkaline degradation products. Further analysis of the quantitative performance influence is required.

Author Contributions: L.M. mainly contributed to the manuscript as well as writing and original draft preparation; G.V. conceptualization; C.W. performed writing–review and editing; R.P. performed conceptualization and supervision; R.P. project administration. All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by OP EFRE NRW (EFRE-0500034).

Conflicts of Interest: The authors declare no conflict of interest.

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