Wheat straw bio-refinery for agricultural waste valorisation

Seyed Hamidreza Ghaffar*

[a] Department of Civil & Environmental Engineering, Brunel University London, Uxbridge, Middlesex, UB8 3PH, UK

*Corresponding author email: seyed.ghaffar@brunel.ac.uk; ORCID: https://orcid.org/0000-0002-4694-9508

Abstract

This study justifies strategies for new concept of agricultural waste management prior to bio-refinery, based on comprehensive material science investigations. Efficient pre-treatments on the extraction, separation and fractionation of agricultural waste in conjunction with understanding the details of microstructure and properties can be essential for high efficiency bio-refinery. The information in this study shall serve as valuable and fundamental basis for researchers and industries in the sector of straw biomass bio-refinery. In order to achieve the maximum efficiency possible in agricultural waste valorisation, it is crucial to understand that not all parts of the straw are equally valuable and can be treated in a same bio-refinery process. In our studies, wheat straw stem that is composed of nodes and internodes has shown to have distinct properties and characteristics. Separation of these anatomical parts before bio-refinery process presents a unique area for future research investment as it can lead to higher performance of the intended product. For example, node has higher extractives and ash content that proved to be a diminishing factor for bio-composites or bio-energy production.

Key words: 1) Material characterisation; 2) Sustainable materials; 3) Biomass conversion.

1. Introduction

Life cycle efficiency improvements can be made by recycling and remanufacturing of waste or manufacturing by-products. This practice is directly linked to the circular economy that is becoming increasingly significant as a research area in the UK and worldwide. In 2017, humankind caused 32 billion metric tons of carbon dioxide to be released to the atmosphere, which was additional to naturally sourced emissions (1). Despite the billions of dollars invested in research, the total quantity of global greenhouse gas emitted per year, has continued its inexorable rise.

Valorisation can be defined as the environmentally friendly, industrially feasible and sustainable conversion of agricultural waste to energy and other useful materials (2). The focus should be on the successful transition of laboratory scale to pilot and full scale demonstrations of bio-refinery of agricultural waste into multiple products and by-products such as biofuels, bio-products, fertilisers, heat and/or electricity (3–7). Advances in technologies such as biotechnology, process chemistry, and engineering are leading to the concept of bio-refining (8). In a bio-refinery, agricultural waste can be valorised in an integrated manner and thereby it can maximise the economic value and reduce the waste streams produced (9). Wheat straw biomass conversion processes are appealing to the industries and extension to future scenarios is easy for the public to envision. Fundamental research has historically been focused on wheat straw biomass conversion to fuels, chemicals and materials (10–15), however, limited sum of these efforts have been successfully translated into commercial practice.

A successful utilisation of wheat straw requires comprehensive understanding of the following points: 1) structure; 2) chemistry; 3) morphology, and 4) how these characteristics are changed by a given pre-treatment and processing. Scientific investigation giving accurate database on the characteristics and composition of wheat straw agricultural waste is a basic requirement for any scheme in conversion and valorisation. Therefore, this paper will present the characteristics of wheat straw and discuss anatomical component for a selective bio-refinery strategy contributing to efficacy of the valorisation concept.

2. Wheat straw main constituents

Wheat straw is a polymeric composite with cell walls made up of cellulose (linear and crystalline), hemicellulose (branched non-cellulosic and non-crystalline hetero-polysaccharides) and lignin (branched non-crystalline) (16). Lignin is primarily a structural material to add strength and rigidity to cell walls (17,18). Lignin acts as a matrix together with hemicelluloses for the cellulose microfibrials which are formed by ordered polymer chains that contain tightly packed, crystalline regions, represented in Figure 1.

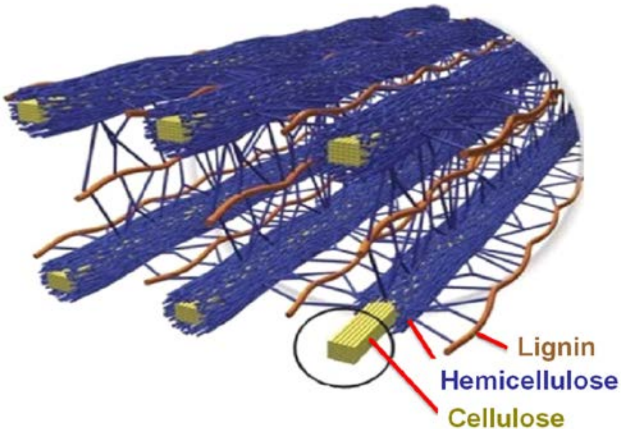

Figure 1 – Cellulose strands surrounded by hemicellulose and lignin (19)

Cellulose is made from a long chain of glucose molecules that are linked to each other mainly by β (1→4) glycosidic bonds. Cellulose has a simple structure, which makes it biodegradable. Hemicellulose is a polysaccharide macromolecule from different sugars and it is different to cellulose in that it is not chemically homogeneous and has lower molecular weight. Hemicellulose has branches with short lateral chains containing several sugars, whereas cellulose has hydrolysable oligomers (16). Apart from the three main groups of organic mixtures, straw comprises several other organic compounds such as extractives, proteins, wax that protects the epidermis of the straw, sugars, salts and insoluble ash including silica. Wheat straw contains 35 – 40% cellulose, 20 – 35% hemicellulose, and around 20% lignin (20). The small lignin percentage in wheat straw makes it a good raw materials for production of bioethanol (21).

2.1 Anatomical and microstructure variations

On a mass basis, wheat straw has 57 ± 10% of internodes, 10 ± 2% of nodes, 18 ± 3% of leaves, 9 ± 4% chaffs and 6 ± 2% rachis (13) (see Figure 2). The composition of the chemical elements changes between and within anatomical parts of wheat straw. Wheat straw's internodes have concentric rings leaving a lumen in the centre. The outermost ring contains a dense layer, which is cellulose-rich, called the epidermis. Epidermis has a concentration of silica on the surface.

Underneath the epidermis, there is a loose layer, which contains parenchyma and vascular bundles (22).

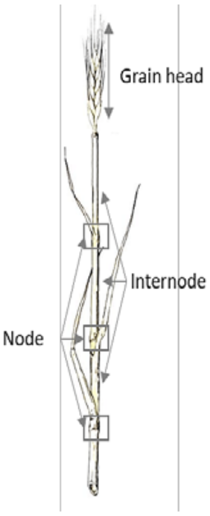

Figure 2 – Wheat straw with nodes (N) and internodes (IN)

For the experimental work, the leaves were separated from the stem, and then the stems were grouped and cleaned. The internodes were grouped and nodes were carefully cut and separated. When investigating the node's morphology along the longitudinal direction, interesting results were revealed. By taking cross-section images after grinding small layers with smooth abrasive paper moving upwards to wheat grain, the 3D image as illustrated in Figure 3 was achieved. The morphological investigation began from the internode instantly before the node and then pass in the node core zone, which continues forward to where the brown elliptical rings get smaller and the beginning of the upper internode exposes. The brownish elliptical rings get smaller and smaller until they are fade. This is the start of the hollow upper internode.

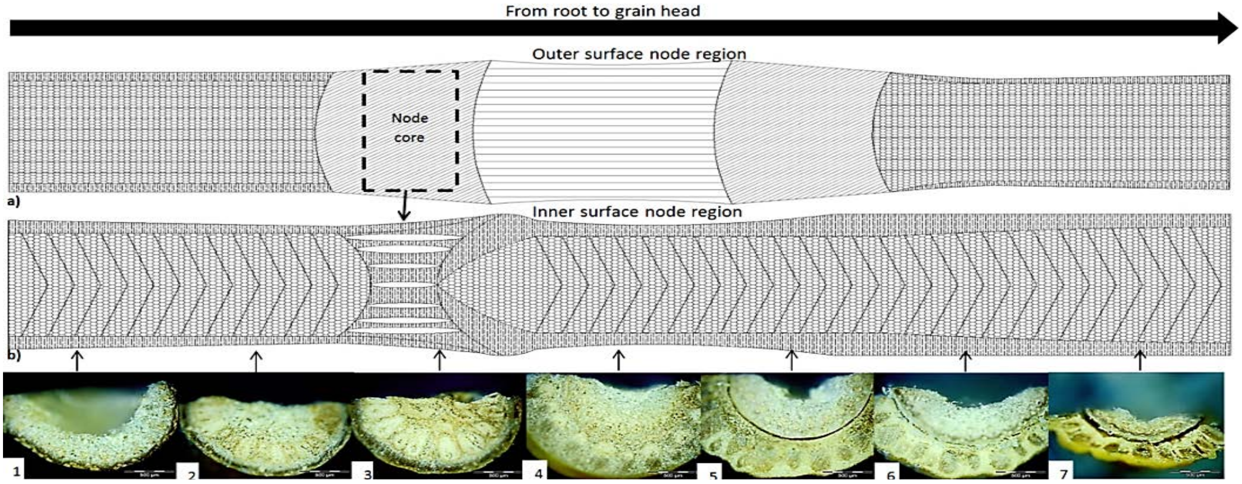

Figure 3 – Node outer (a) and inner (b) surface longitudinal view and the corresponding images to the position in the node shown by the arrows

Unlike node, the longitudinal microstructure of internode was found to be consistent. The outer surface of the straw internode contains wax and inorganic substances, and then follows a region with fibre bundles (vascular bundles) integrated in a region of parenchyma and vessel elements. The epidermis is a complex tissue with bubble-shaped polygonal short and long cell types, as shown in Figure 4. The epidermis is thin, but has dense and thick-walled cells with an outer wall coated with a waxy film of cutin cuticle (22).

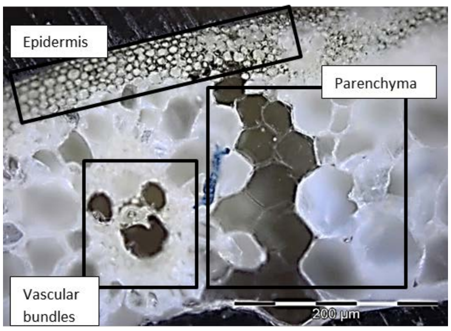

Figure 4 – Optical microscopy image of internode cross-section

2.2 Elemental and cell wall composition of wheat straw

There are distinct differences amongst the physicochemical characteristics and cell wall components of node and internode, making them appropriate or deficient for a specific bio-refinery pathway. The energy dispersive X-ray spectra were attained using an INCA Energy 400 microanalysis system. The chemical elements detected were analysed using the database of standard samples. The elemental ratio of all elements detected was automatically calculated from their normalised peak areas. For quantitative element analyses, the recorded EDAX results were analysed by using Oxford INCA Version 4.02. The bulk structure of the wheat straw consisted of carbohydrates and lignin with a considerable amount of carbon (C) and oxygen (O), and a trace amount of silicon (Si) weight percentage (Table 1). The outer surface of internode has considerably higher Si weight percentage than the inner surface, i.e. 5.8% compared to 0.8%. More silicon (in the form of silica) is located mainly on the outer surface (epidermis) of wheat straw.

Table 1 Node and internode profile elemental composition based on EDAX-SEM analysis

Profile Surface	Sample	Percentage % C	Percentage % O	Percentage % Si	O/C
Inner	Internode	54.1 (2)	45 (1)	0.8 (4)	0.83
	Node	54.1 (9)	45.6 (7)	0.7 (6)	0.84
Outer	Internode	51.3 (2)	43.4 (5)	5.8 (2)	0.84
	Node	53.7 (3)	43.5 (8)	2.8 (2)	0.81

* Values in () are Coefficient of Variance %

The assessment of cell wall composition in straw biomass is usually conducted on milled samples of the whole stem, without separating node and internode. The cell wall composition of the internode may be rather different from that of the node. Table 2 shows the main chemical components of wheat straw investigated following the NREL/TP-510-42620. Wheat straw node yielded slightly higher extractives and ash content than internode, which can be related to their microstructure, i.e. higher ash and extractives content in the node are explained by thicker epidermis tissue. The extractives are a heterogeneous group of substances including resin acids, sterol esters, waxes, triglycerides, fatty acids, sterols, fatty alcohols and a selection of phenolic compounds (23). As shown in Table 2, the extractives in nodes are higher than in internodes, for both hot-water extraction and ethanol extraction. The results also showed that the node contains more ash, in both non-extracted samples (structural ash) and extracted samples through hot water and ethanol.

Table 2 **Extractives and ash content of wheat straw (% dry straw)**

Sample	**Hot-water extraction**		**Ethanol extraction**		**Non-extracted samples**
	Extractives (%)	**Ash content (%)**	**Extractives (%)**	**Ash content (%)**	**Ash content (%)**
Internode	4.2 (4)	0.9 (8)	3.8 (9)	1.5 (2)	3.2 (2)
Node	4.6 (5)	1.3 (7)	4.0 (7)	1.9 (3)	5.3 (4)

* Values in () are coefficient of variance %

2.3 Characterization of surface chemical distribution

Fig. 5 shows surface chemical distributions of wheat straw node and internode, inner and outer surfaces. Table 3 summarises the characteristics of surface profiles in node and internode. The intensity of 2850 and 2920 cm^{-1} is much higher in a node (Fig. 5), which is ascribed to the higher intensity of waxes on the surface. Moreover, by comparing inner to outer surface, it is observed that the broad and more intense band in the 3200-3600 cm^{-1} region, reflects the hydrophilic tendency of the inner surface of both node and internode. In wheat straw, some chemical bonds are present in node, but absent in internode and vice versa, i.e. 2955, 720 and 790 cm^{-1} in node and 985 cm^{-1} in internode.

Table 3 **Band assignments and observed differences between node and internode**

Wavenumber (cm^{-1})	**Bands assignment**	**Observations**	**Ref.**
720	Methylene CH_2 in-plane deformation rocking	Only detectable in node outer surface	(24)
790	Si-C stretching vibration		
985	Si-O stretching vibration	Only detectable in outer surface of internode	
1160	C-O-C antisymmetric bridge in hemicellulose and cellulose	Sharper in internode than node	

1435	C=O methoxyl group in lignin	Sharper in internode inner surface than outer surface	
1510	C=C lignin aromatic ring stretch	Sharper in internode of treated straws	(25)
1739	Carboxyl groups	High intensities in internode and node outer surfaces.	(26)
2850 & 2920	Symmetric & asymmetric stretching of CH_2 in aliphatic fraction of waxes	Sharper in node than internode and outer than inner surface	(27)
2955	Asymmetric stretching of CH_3 in fatty acids	Only detectable in node untreated	(28)
3200-3600	OH stretching vibration of hydroxyl groups	Higher intensity for the inner surface compared to outer surface, both in node and internode	(29)

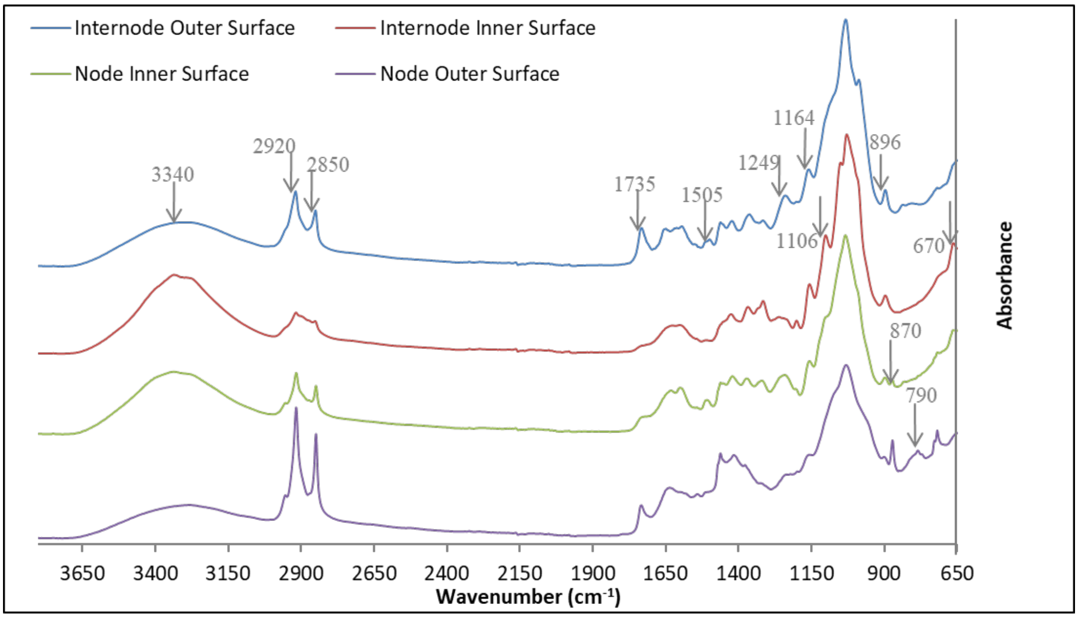

Figure 5 – ATR-FTIR spectra of wheat straw internode and node outer and inner surface

3. Strategies for valorisation of wheat straw

Without an appropriate strategy for disposal of agricultural waste, many aspects of the environment may be negatively affected (30). The most abundantly available, cheap and renewable raw materials for bioethanol production is lignocellulosic biomass due to its high cellulosic content. Wheat straw is a potential source of feedstock for biofuel production that does not compete with food (31).

Lignocellulosic materials from agriculture waste biomass are the largest sources of hexose (C-6) and pentose (C-5) sugars with a potential for the production of biofuels, chemicals and other by-products. For bioethanol/biofuel production, the three main steps include pre-treatment, enzymatic hydrolysis and fermentation (21) (see Fig 6).

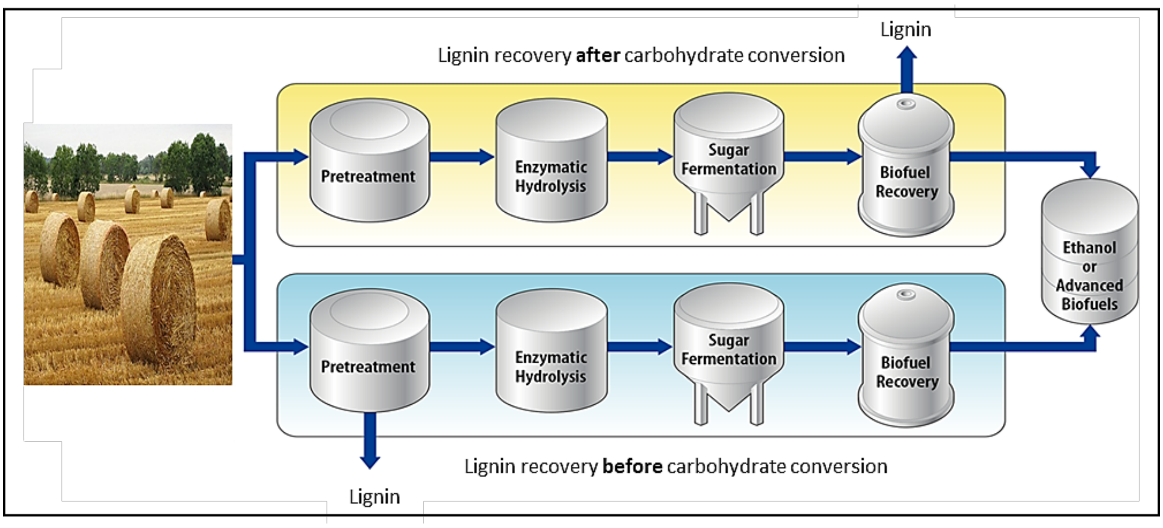

Figure 6 – Agricultural waste valorisation: lignin recovery and bio-energy production

Physical, chemical, physicochemical and biological pre-treatments have been utilised for adding value to wheat straw as agricultural waste. The pre-treatments must be carefully designed and its parameters must be chosen in a way that improves the enzymatic hydrolysis, avoids carbohydrates degradation, prevents formation of inhibitors for the following hydrolysis and fermentation processes, produces high yields of monosaccharides, generates highly hydrolysable cellulose for efficient conversion to chemicals and be economically feasible, e.g. low energy and low cost (32–34).

In an investigation on valorisation of wheat straw, Kaparaju et al. (9) studied the production of bioethanol from cellulose, bio-hydrogen from hemicelluloses and biogas from the waste of bioethanol and bio-hydrogen processes. This is in line with an effective low-cost bio-refinery concept. Some of wheat straw was utilised without any treatment, and some was pre-treated using hydrothermal process. The pre-treated wheat straw yielded liquid fraction hydrolysate that contained hemicelluloses and a solid cellulose fraction. Kaparaju et al. (9) investigation discovered that the production of biogas from wheat straw or production of different biofuels from wheat straw was an energy efficient technology in comparison to mono-fuel generation including bioethanol from hexose sugars fermentation. They also concluded that the integrated waste bio-refinery is more feasible than using individual bio-refinery technology for the generation of single fuel.

Biological pre-treatment weakens the heterogeneous straw biomass with lignin biodegrading microorganisms that can degrade aromatic compounds. A biological process removes substantial amount of lignin, which increases the enzymatic hydrolysis efficiency (35). The important benefits of biological pre-treatments are small energy input, no chemical obligation, environmentally friendly working style. On the other hand, the drawbacks are the slow pre-treatment rate. The introduction of some kind of catalyst is necessary which can accelerate the process and improve the efficiency (36). Combination of biological pre-treatment with mild physical, chemical or mechanical pre-treatments is also one way of improving the slow rate of biological pre-treatment, therefore improving the industrial feasibility (37). Yu et al. (38) showed that pre-treatment of corn stalks with *Irpex lacteus* can modify the lignin structure and facilitate lignin biodegradation and xylan elimination under mild alkaline environment (1.5% NaOH, 30–75˚C for 15–120 min).

Hydrothermal pre-treatment (200˚C for 10 minutes) was the initial stage in the procedure of turning wheat straw into second generation bioethanol (39), where the enzymes were added to the fibre mass (mostly of cellulose and lignin), for bioconversion of cellulose to lower carbohydrates, enabling the fermentation of ethanol in the following stage. Pre-treatment of straw for the production of bioethanol is estimated to account for 33% of the summed cost of bioethanol production (40). Developing an economically suitable processing is therefore the key for bioconversion of straw biomass into bioethanol. The ideal pre-treatment in terms of technical aspects would be to i) expose the cell wall constituents for enzymatic attack, ii) increase the porosity and surface area of the substrate, iii) diminish the cellulose crystallinity and disrupt the heterogeneous structure of lignocellulosic biomass (37).

3.1 Wheat straw as bio-based building product

Buildings under construction and in use generate a disproportionate amount of non-recyclable waste along with around 40% of greenhouse gas emissions. Therefore, the construction industry has seen increasing demands for natural novel eco-innovative products e.g. compressed straw boards. While in the distant past, most buildings were made of bio-sourced, ultimately biodegradable materials: wood, straw, reed, rammed earth or adobe; today, there is a tendency to regard these as primitive: either insufficiently durable, too weak to withstand forces of nature or loads in use over time. This is not necessarily an accurate perception. In the case of straw, its life in a building is indefinite; provided that it is kept dry (41). It is the emergent understanding of the potential durability of straw and its self-evident modest structural capability that has prompted research that aims to reinstate it as a viable building material for modern building construction. As the growth of straw, converts airborne CO_2 into carbon by photosynthesis, its incorporation into the fabric of a long-lived building after suitable processing would fit in with two pressing policy objectives referred to above. Firstly, that of achieving a "closed-loop" cycle of growth, material use and ultimate safe return to nature and, secondly, ensuring the effective capture and long-term storage of atmospheric CO_2.

Our developed and demonstrated pilot results, where an environmentally friendly pre-treatment was employed, which led to an improved interface between resins and the micro porous surface of straw. The results showed that chemical functionalities of various surface profiles (i.e. when cut longitudinally in half, inner and outer) altered the bonding performance, i.e. extractive, aliphatic fraction of waxes, and silica concentrated on the outer surface, inhibited the bonding quality which translates into an inefficient stress transfer under load. The pre-treatment ($P < 0.05$) however, could significantly: (i) modify the surface of straw with the partial removal of extractives, waxes, and silica which made it more hydrophilic and more compatible with water based resins, (ii) cause the microcellular structure of straw to expand and hence induce the mechanical entanglement on a micro level upon resin solidification. Therefore, these pilot results have given us the motivation to upscale the pre-treatment. So far, manufacture of bio-composites, whether for use in vehicles or in construction, has been held back due to their non-reliable load-bearing capability. Research on bio-composites from straw by-products has been focused on utilising them in small particle and/or short fibre form (42), as fillers in plastic composites, while, as proposed herein, the mechanical properties of the composites could potentially increase by using longer straw strands. The highly processed products from straw, entailing the extraction of cellulose for papermaking require high-energy inputs and pose significant negative environmental impacts and a cost penalty arising from the need to treat large quantities of complex effluents. The other product stream is straw as bales with almost no processing, however, straw bales underutilise the inherent properties of straw, where structural performance tends to be affected by compaction and in humid climates decay is caused by internal condensation.

Our research has revealed that the micro-architecture of straw nodes is very different from that of the internode (43). It is much less structurally competent and distributions of node and soluble starch from nodes have been found to deteriorate the performance of the straw strand/stem when these are reconfigured into a bio-composite material. We found out this is due to node's morphology and surface chemical functional groups (Ghaffar, Fan and McVicar, 2017). Moreover, the values of tensile strengths of wheat straw internodes are in the range of 66-89MPa, whereas the node showed a tensile strength in the range of 12-20MPa (43), further proving the fact that node would act as a defect in bio-composites.

4. Challenges and perspectives of agricultural waste valorisation

There is a lack of effective utilization of wheat straw for further bio-refinery and bioconversion to value added products. The complex chemical structure of straw biomass has various mechanisms for resisting attacks on their structural sugars from microorganisms, these include: 1) the epidermal tissue, particularly the cuticle and waxes, 2) the arrangement and density of the vascular bundles, 3) the relative amount of sclerenchymatous (thick wall) tissue, 5) the heterogeneity of cell wall constituent (45). To overcome the biomass recalcitrance and thus, producing cost-competitive bio-products from straw biomass, the new findings of the fundamental properties of straw material sciences need to be integrated into the conversion processes.

The main challenge is to demonstrate the feasibility of one novel technology chain aimed at valorising several types of agricultural wastes by converting them into an array of valuable bio-based products (e.g. bioplastics, bio-composites and bio-energy), while also minimising any residual or consequent waste requiring disposal. There are needs within different fronts, including but not limited to: (i) technical development and product innovation, (ii) increasing the bio-based product market demand and (iii) gathering sufficient and accurate information about specific variations in straw biomass properties, which is not straightforward.

The change from a linear economy towards a circular economy is essential and therefore the selective and optimised bio-refinery of agricultural waste can be the vision to promote a shift from the consumption of fossil reserves to renewable resources, leading to mitigation of greenhouse gases emissions and their impact on climate change. Collaborative projects between farmers, research institutes, industrial beneficiaries and policy makers are vital for the success in valorisation of agricultural wastes. The strategies for these types of activities should aim to reduce the carbon footprint of bio-based products, promote the creation of new job and market opportunities, and lead towards expanded bio-economy, greatly needed for future environmental and economic sustainability.

5. Conclusions

Utilisation of agricultural waste as raw materials positively affects environmental and socio-economic aspects by not only generating additional income to the farmers, but also generating cost-effective high performing bio-products. Our research contributed to comprehensive understanding of wheat straw biomass (*Triticum aestivum* L.) by: 1) examining and revealing the morphology of node and internode with a 3D model of node and its core (22). 2) analysing different physicochemical properties of node and internode and their surface profile functionalisation (43,46,47). 3) developing an environmentally friendly pre-treatment for surface modification and optimisation of interfacial bonding (48). 4) studying the interfacial bonding and developing a physical model of failure mechanisms in straw composite (48). The complicated heterogeneous characteristics of straw, makes their comprehensive analysis essential prior to bioconversion process. It is worth emphasising that straw biomass's chemical composition can vary with species, location, storage time, harvest, stage of maturity, environmental conditions and anatomical parts, i.e. node and internode.

References

1. Rich N. Losing Earth: The Decade We Almost Stopped Climate Change - The New York Times. New York Times Magazine [Internet]. 2018; Available from: https://www.nytimes.com/interactive/2018/08/01/magazine/climate-change-losing-earth.html
2. Nzihou A. Toward the valorization of waste and biomass. Waste and Biomass Valorization. 2010;1(1):3–7.
3. Nizami AS, Rehan M, Waqas M, Naqvi M, Ouda OKM, Shahzad K, et al. Waste biorefineries: Enabling circular economies in developing countries. Vol. 241, Bioresource Technology. 2017. p. 1101–17.
4. Venkata Mohan S, Nikhil GN, Chiranjeevi P, Nagendranatha Reddy C, Rohit M V.,

Kumar AN, et al. Waste biorefinery models towards sustainable circular bioeconomy: Critical review and future perspectives. Vol. 215, Bioresource Technology. 2016. p. 2–12.

5. Zhang M, Xie L, Yin Z, Khanal SK, Zhou Q. Biorefinery approach for cassava-based industrial wastes: Current status and opportunities. Vol. 215, Bioresource Technology. 2016. p. 50–62.
6. Aristizábal M V, García V CA, Cardona A CA. Integrated Production of Different Types of Bioenergy from Oil Palm Through Biorefinery Concept. Waste and Biomass Valorization. 2016;7(4):737–45.
7. De Pretto C, Giordano R de LC, Tardioli PW, Costa CBB. Possibilities for Producing Energy, Fuels, and Chemicals from Soybean: A Biorefinery Concept. Vol. 9, Waste and Biomass Valorization. 2018. p. 1703–30.
8. Asada C, Sasaki C, Suzuki A, Nakamura Y. Total Biorefinery Process of Lignocellulosic Waste Using Steam Explosion Followed by Water and Acetone Extractions. Waste and Biomass Valorization. 2018;9(12):2423–32.
9. Kaparaju P, Serrano M, Thomsen AB, Kongjan P, Angelidaki I. Bioethanol, biohydrogen and biogas production from wheat straw in a biorefinery concept. Bioresour Technol [Internet]. 2009 May [cited 2015 Aug 28];100(9):2562–8. Available from: http://www.ncbi.nlm.nih.gov/pubmed/19135361
10. López-Abelairas M, Álvarez Pallín M, Salvachúa D, Lú-Chau T, Martínez MJ, Lema JM. Optimisation of the biological pretreatment of wheat straw with white-rot fungi for ethanol production. Bioprocess Biosyst Eng [Internet]. 2013 Sep [cited 2015 Nov 29];36(9):1251–60. Available from: http://www.ncbi.nlm.nih.gov/pubmed/23232963
11. Stelte W, Clemons C, Holm JK, Ahrenfeldt J, Henriksen UB, Sanadi AR. Fuel Pellets from Wheat Straw: The Effect of Lignin Glass Transition and Surface Waxes on Pelletizing Properties. Bioenergy Res. 2012;5(2):450–8.
12. Petrik SŠ, Kádár Z, Márová I. Utilization of hydrothermally pretreated wheat straw for production of bioethanol and carotene-enriched biomass. Bioresour Technol. 2013;133:370–7.
13. Motte JC, Escudi?? R, Beaufils N, Steyer JP, Bernet N, Delgen??s JP, et al.

Morphological structures of wheat straw strongly impacts its anaerobic digestion. Ind Crops Prod. 2014;52:695–701.

14. Kaparaju P, Serrano M, Thomsen AB, Kongjan P, Angelidaki I. Bioethanol, biohydrogen and biogas production from wheat straw in a biorefinery concept. Bioresour Technol [Internet]. 2009 May [cited 2016 Mar 20];100(9):2562–8. Available from: http://www.sciencedirect.com/science/article/pii/S096085240800967X

15. Halvarsson S, Edlund H, Norgren M. Properties of medium-density fibreboard (MDF) based on wheat straw and melamine modified urea formaldehyde (UMF) resin. Ind Crops Prod [Internet]. 2008 Jul [cited 2016 Apr 28];28(1):37–46. Available from: http://www.sciencedirect.com/science/article/pii/S0926669008000095

16. Ghaffar SH. Straw fibre-based construction materials. Advanced High Strength Natural Fibre Composites in Construction. 2016.

17. Akin DE. R. B. Degradation of polysaccharides and lignin by ruminal bacteria and fungi. Appl Environ Microbiol. 1988;54:1117–25.

18. Baurhoo B, Ruiz-Feria CA, Zhao X. Purified lignin: Nutritional and health impacts on farm animals—A review. Anim Feed Sci Technol [Internet]. 2008;144(3–4):175–84. Available from: http://www.sciencedirect.com/science/article/pii/S0377840107004300

19. Doherty WOS, Mousavioun P, Fellows CM. Value-adding to cellulosic ethanol: Lignin polymers. Vol. 33, Industrial Crops and Products. 2011. p. 259–76.

20. Sun R, Lawther JM, Banks WB. Fractional and structural characterization of wheat straw hemicelluloses. Carbohydr Polym. 1996;29(4):325–31.

21. Irfan M, Asghar U, Nadeem M, Nelofer R, Syed Q, Shakir HA, et al. Statistical Optimization of Saccharification of Alkali Pretreated Wheat Straw for Bioethanol Production. Waste and Biomass Valorization. 2016;7(6):1389–96.

22. Ghaffar SH, Fan M. Revealing the morphology and chemical distribution of nodes in wheat straw. Biomass and Bioenergy. 2015;77:123–34.

23. Sun RC, Tompkinson J. Comparative study of organic solvent and water-soluble lipophilic extractives from wheat straw I: yield and chemical composition. J Wood Sci [Internet]. 2003 Feb 1 [cited 2015 Dec 2];49(1):47–52. Available from: http://link.springer.com/10.1007/s100860300008

24. Jiang H, Zhang Y, Wang X. Effect of lipases on the surface properties of wheat straw. Ind Crops Prod [Internet]. 2009 Sep [cited 2015 Nov 15];30(2):304–10. Available from: http://www.sciencedirect.com/science/article/pii/S0926669009000879

25. Xiao B, Sun XF, Sun R. Chemical, structural, and thermal characterizations of alkali-soluble lignins and hemicelluloses, and cellulose from maize stems, rye straw, and rice straw. Polym Degrad Stab. 2001;74(2):307–19.

26. Alemdar A, Sain M. Isolation and characterization of nanofibers from agricultural residues - Wheat straw and soy hulls. Bioresour Technol. 2008;99:1664–71.

27. Merk S, Blume A, Riederer M. Phase behaviour and crystallinity of plant cuticular waxes studied by Fourier transform infrared spectroscopy. Planta. 1998;204(1):44–53.

28. Dodson J. Wheat straw ash and its use as a silica source [Internet]. University of York; 2011 [cited 2016 Jan 14]. Available from: http://etheses.whiterose.ac.uk/1931/2/J_Dodson_PhD_thesis.pdf

29. Stelte W, Nielsen NPK, Hansen HO, Dahl J, Shang L, Sanadi AR. Reprint of: Pelletizing properties of torrefied wheat straw. Biomass and Bioenergy [Internet]. 2013;53:105–12. Available from: http://dx.doi.org/10.1016/j.biombioe.2013.03.012

30. Ismaiel MMS, Ahmed AESI, Sobhy S. Enhancement of Wheat Cultivars (Triticum aestivum L.) by Cellulase-Treated Plant Wastes. Waste and Biomass Valorization. 2017;1–8.

31. Tishler Y, Samach A, Rogachev I, Elbaum R, Levy AA. Analysis of Wheat Straw Biodiversity for Use as a Feedstock for Biofuel Production. Bioenergy Res. 2015;8(4):1831–9.

32. Arenas P, López A, Moeller G, León E. Current Pretreatments of Lignocellulosic Residues in the Production of Bioethanol. Waste and Biomass Valorization [Internet]. 2017;8(1):161–81. Available from: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85001850045&doi=10.1007%2Fs12649-016-9559-4&partnerID=40&md5=88cb52502ea9bb63015dff560029741f

33. Sun Y, Cheng J. Hydrolysis of lignocellulosic materials for ethanol production: A review. Vol. 83, Bioresource Technology. 2002. p. 1–11.

34. Mosier N, Wyman C, Dale B, Elander R, Lee YY, Holtzapple M, et al. Features of

promising technologies for pretreatment of lignocellulosic biomass. Vol. 96, Bioresource Technology. 2005. p. 673–86.

35. Zhang X, Yu H, Huang H, Liu Y. Evaluation of biological pretreatment with white rot fungi for the enzymatic hydrolysis of bamboo culms. Int Biodeterior Biodegrad. 2007;60(3):159–64.

36. Van Dyk JS, Pletschke BI. A review of lignocellulose bioconversion using enzymatic hydrolysis and synergistic cooperation between enzymes-Factors affecting enzymes, conversion and synergy. Vol. 30, Biotechnology Advances. 2012. p. 1458–80.

37. Talebnia F, Karakashev D, Angelidaki I. Production of bioethanol from wheat straw: An overview on pretreatment, hydrolysis and fermentation. Bioresour Technol [Internet]. 2010;101(13):4744–53. Available from: http://dx.doi.org/10.1016/j.biortech.2009.11.080

38. Yu H, Du W, Zhang J, Ma F, Zhang X, Zhong W. Fungal treatment of cornstalks enhances the delignification and xylan loss during mild alkaline pretreatment and enzymatic digestibility of glucan. Bioresour Technol. 2010;101(17):6728–34.

39. Petrik S, Kádár Z, Márová I. Utilization of hydrothermally pretreated wheat straw for production of bioethanol and carotene-enriched biomass. Bioresour Technol [Internet]. 2013 Apr [cited 2015 Nov 29];133:370–7. Available from: http://www.ncbi.nlm.nih.gov/pubmed/23434815

40. Ibrahim HAH. Pretreatment of straw for bioethanol production. In: Energy Procedia. 2012. p. 542–51.

41. Walker P, Thomson A, Maskell D. Straw bale construction. In: Nonconventional and Vernacular Construction Materials [Internet]. 2016. p. 127–55. Available from: http://linkinghub.elsevier.com/retrieve/pii/B9780081000380000068

42. Halvarsson S, Edlund H, Norgren M. Manufacture of non-resin wheat straw fibreboards. Ind Crops Prod. 2009;29(2–3):437–45.

43. Ghaffar SH, Fan M. Differential behaviour of nodes and internodes of wheat straw with various pre-treatments. Biomass and Bioenergy. 2015;83:373–82.

44. Ghaffar SH, Fan M, McVicar B. Interfacial properties with bonding and failure mechanisms of wheat straw node and internode. Compos Part A Appl Sci Manuf. 2017;99.

45. Himmel ME, Ding SY, Johnson DK, Adney WS, Nimlos MR, Brady JW, et al. Biomass recalcitrance: Engineering plants and enzymes for biofuels production. Science. 2007.

46. Ghaffar SH, Fan M. An aggregated understanding of physicochemical properties and surface functionalities of wheat straw node and internode. Ind Crops Prod. 2017;95.

47. Ghaffar SH, Fan M, Zhou Y, Abo Madyan O. Detailed Analysis of Wheat Straw Node and Internode for Their Prospective Efficient Utilization. J Agric Food Chem. 2017;65(41).

48. Ghaffar SH, Fan M, McVicar B. Interfacial properties with bonding and failure mechanisms of wheat straw node and internode. Compos Part A Appl Sci Manuf. 2017;99:102–12.