Detailed Analysis of Wheat Straw Node and Internode for their Prospective Efficient Utilisation

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Key words: Wheat straw, node and internode, physicochemical characterisation, surface chemical distribution

Abstract

In order to efficiently utilise wheat straw, the systematic examination of their cell wall components, chemical structures, morphology and relation to the physicochemical and mechanical properties is necessary. Detailing of node and internode signifies their different features and characteristics which can ultimately lead to their separated processing for enhanced efficiency and higher added-value bio-refinery. In this study, distinct variations were found amongst characteristics of node and internode, inner and outer surface. It was revealed that node has more extractives, Klason lignin and ash content than internode, higher contents of extractives and ash in the node are related to the thicker epidermis tissue. Hot-water followed by mild steam pre-treatment was used to examine the effects on the characteristics of wheat straw. The results showed: 1) reduced level of waxes and Si (weight %) from the outer surface, and 2) significantly lower ($P < 0.05$) extractives content in both internode and node.

1. Introduction

Straw is a potential material for the production of bio-products and can present a novel source for the eco-building products such as agricultural compressed fibreboards and bio-composites. Significant studies in the past decade have been carried out to cover a range of applications for wheat straw [1-10]. Wheat straw is made up of mainly cellulose, hemicellulose and lignin similar to wood, although it contains less lignocellulose cells with higher amounts of ash and extractive. Wheat straw efficient exploitation for bio-refinery needs the complete characterisation of material science to cover different angles of attributes by detailing the node and internode. It is important to

note that not all parts of the agricultural residues are valuable in certain bio-refinery pathways and the undesirable parts must be removed [11,12]. Chemical processors and biofuels for instance, need the higher cellulose and hemicellulose parts of biomass. Through differentiation of the details of straw stem, i.e. node and internode, an efficient strategy can be envisaged to optimise the bio-refinery outcome. Controlling the compositional variability of wheat straw is impossible due to their natural source which differs based on the location, growth environment and so on, but it is certainly valuable to screen/monitor the variability and consequently select the specific processing technology for the bio-refinery pathway. In light of the above mentioned point, this research attempts to comprehensively study the internode and node, with inner and outer surface profiles, and track the changes induced by the environmentally combinational pre-treatment. The delivery of a collective wheat straw material science leads to the upgrading of bio-refinery processes, i.e. bio-energy production and bio-product developments, such as bio-composites. The pre-treatment is an essential step to overcome associated issues with wheat straw for bio-refinery pathways intended, for instance to overcome the issues with the surface impeding the good bonding quality, when it comes to the production of straw composite boards.

2. Raw material with analytical characterisation procedures

2.1 Wheat straw

Triticum aestivum L. – wheat straw, was collected in summer from Dixon Brothers Porters Farm, United Kingdom (East of England). The bales were kept in an ambient room temperature for air-dryness. Wheat straw is constituted from internodes, nodes, leaves, chaffs and rachis. The stem of a wheat straw is hollow except for the intermediate growth sections, i.e. nodes which are interconnected via internodes. For different surface characterisation, the node and internode were cut in half longitudinally to expose the outer and inner profiles.

2.2 Pre-treatment

Node and internode samples were additionally selected for pre-treatment to investigate the influence of the pre-treatment on different attributes of the material science and improve their potential

pathway for further bio-refinery. The pre-treatment consisted of the following steps: first the samples were placed in a pressure cooker with straw to water ratio of 1:20 (by weight) and a water initial temperature of 100˚C (i.e. boiling). After sealing the pressure cooker to maintain a pressure of approximately 0.1 MPa, the internal temperature increased to a maximum of 106 ± 1˚C with advancing of time and pressure. The duration of this stage of pre-treatment was 30 minutes.

In the second stage, the straws were taken from the hot water and placed in a mesh basket positioned above hot water inside the pressure cooker, so that the steam at 100˚C goes through the straws for another 30 minutes. This completed the environmentally friendly combinational pre-treatment of hot water followed by steam (H+S).

2.3 Tensile test

Three batches were chosen for the tensile testing from the pre-treated and untreated (UN) straws, and from each batch, twenty individual straws were randomly chosen and tested. Therefore, in total for each, pre-treated and UN straw, sixty samples were tested. To reduce the discrepancy of the result, the second node and internode from the root of wheat straw was selected within a length of 60 mm. The straw's nodes and internodes were oven dried for 24 hours at 100˚C before the testing, to ensure that the different moisture contents do not influence the mechanical strength as previously observed [13]. The 60 mm length of straws was checked thoroughly by microscope for small longitudinal or cross-sectional cuts/defects. The rate used for testing was 5 mm/min using an Instron 2670 series testing machine. Cross sectional area of each sample was carefully measured using a digital caliper.

The tensile failure stress σ, of each sample was gathered by using Equation 1.

$$\sigma = \frac{F_t}{A} \quad (1)$$

Where F_t is the tension force at failure and A is the wall area of the test sample at the failure cross section.

2.4 Chemical analysis and morphology

The straw samples for chemical analysis were made according to NREL/TP-510-42620 [14]. Moreover, surface chemical distributions (ATR-FTIR) and elemental composition (SEM-EDX) of straws were also examined. Six repetitions were carried out for the wet chemistry (i.e. Klason lignin and extractives content), ten repetitions for surface chemistry (i.e. surface chemical distributions and elemental composition) and the ash content. Table 1 shows the details of each analytical tool/technique chosen.

"Table 1 here"

Attenuated total reflectance-FTIR spectra were recorded on a PerkinElmer Spectrum one Spectrometer. This technique was selected because it permits analysis of the surfaces to a penetrating depth of 0.5-3.0 μm. Wheat straw node and internode were cut in half longitudinally and placed on an ATR equipped with 3× bounce diamond crystal with an incident angle of 45˚ used. In addition to ATR-FTIR, for surface elemental composition analysis, energy dispersive X-ray spectra (SEM-EDX) were obtained using an INCA Energy 400 microanalysis system (Oxford instruments, England). The elements detected were quantitatively analysed using the database of standard samples programmed in the software. Optical microscopy and gun-scanning electron microscopy were both used to assess the morphology of node and internode.

3. Results and discussions

3.1 Surface chemical functional distribution

The surface chemical functional groups for the node and internode, with the respective, inner and outer surface profiles are illustrated in Fig.1. Table 2 presents the functional groups where the features of different surfaces are compared. In Fig.1 it is observed that there are higher intensity of waxes on the outer surface of the node, reflected by high intensity of 2850 and 2920 cm^{-1} band. The hydrophilic affinity of the inner surface of both the node and internode is reflected by the wide and intense bands in the 3200-3600 cm^{-1} area (Fig. 1a and b), this could be due to the -OH groups

present in their main components. It is noteworthy that this characteristic of inner surface could mean that a better interface is achieved when water-based resins are used for straw products/composites.

Remarkably, some bands were observed in node but were absent in internode and vice versa, specifically: 2955, 720 and 790 cm^{-1} in node and 985 cm^{-1} in internode, this observation will be interpreted in later part of the paper in connection with wet chemistry examinations.

The bands assigned to cellulose at 897cm^{-1} (asymmetric out-of-phase ring stretch in the C1-O-C4 glycosidic linkage), 1372 cm^{-1} (C-H bending), 1429 cm^{-1} (C-H wagging), and 2900 cm^{-1} (C-H stretching) can be selected for quantitative indices evaluation of the cellulose crystallinity [18]. The lower order index (LOI) and total crystallinity index (TCI) are gathered based on FTIR spectra [19] with the following ratios: TCI (ratio of bands height:$\frac{H1372}{H2900}$) and LOI ($\frac{H1429}{H897}$). Higher values of TCI and LOI translates into higher crystallinity of cellulose [20,21]. LOI increased by 15% in internode and by 11% in node for H+S pre-treated straws. Moreover, for H+S pre-treated straws, TCI also increased by 24% in internode and by 9% in node. The variation in the cellulose crystalline structure is evident in different anatomical parts, and improvements in the cellulose crystallinity of H+S pre-treated straws means a greater stability to the cellulose chain [22], therefore, increase in the mechanical properties such as tensile strength of straw strands.

"Fig. 1 here"

"Table 2 here"

3.2 Tensile strength

Tensile strength is chosen to be investigated in this paper as it can govern the mechanical performance of straw composites. A quantitative comparison is designed for the evaluation of the effects of the pre-treatment on the tensile strength of node and internode, shown in Fig. 2. The tensile test results have been verified and show a reliable trend as their coefficient of variance (CV %) for 60 samples ranges from 4.2 to 10%. In the pre-treatment process, it is vital that the fibre

structure of straw is not weakened, or else, the mechanical performance of the straw composite will not be satisfactory. The H+S pre-treated straws showed significant increase ($P < 0.05$) of 35% in the tensile strength of internodes and 62% in nodes. The tensile strength of wheat straw node has not been investigated in literature to the best of authors' knowledge. Interestingly, as evident in Fig. 2, the tensile strength of node is significantly lower than internode. This could be related to their morphological properties. In the stem of wheat straw, the node acts as a joint, to provide the connections for the internodes, hence, it does not possess the long stretched longitudinal microfibrils which on the other hand, are the most contributing factor for superior tensile performance of internodes. The node core morphology shown in Fig. 3b (ii), illustrates the compact area occupied by bubbled shape cells, where, the weakest link in node is its core, justifying the lower tensile strength (see Fig. 2). The enhanced tensile strength of H+S pre-treated straws can be due to the higher crystallinity and more ordered structure of cellulose as previously emphasised [4]. Even though, comparison to other literatures may not be correct, as the origin of straws can influence their characteristics, however, it was found that wheat straw fibres pre-treated via pressurised steam pre-treatment (1MPa for 10 mins) had a tensile strength of 74 MPa [28], that is weaker compared to the H+S pre-treated straws (89 MPa) reported herein.

"Fig. 2 here"

3.3 Extractives content

The extractives constitute a heterogeneous set of substances in wheat straw with low molecular weight compounds. The core extractives of wheat straw are sterol esters, resin acids, waxes, fatty acids, triglycerides, fatty alcohols, sterols and a range of phenolic compounds [29,30]. Ethanol was used to investigate the lipophilic extractives which can be extracted from wheat straw with organic solvents such as ethanol and acetone [31].

By looking at Fig. 4a, it is evident that the extractives content in nodes are higher than in internodes for all the cases examined, for example in (hot-water) HW extraction, the node has 10 to 15%

higher extractives than internode. This can be related to the sharp band at 720 cm^{-1}, only seen in node outer surface (Fig. 1b), being characteristic of the methylene (CH_2) in-plane deformations rocking [23], and indicating the presence of lipophilic extractives. The difference of extractives content between the node and internode is a confirmation for the results of surface chemical distribution. This feature of higher node's extractives content would be constructive for the selection and process of wheat straw for composites application, as the higher extractives content can have an impeding effect on the optimised interfacial bonding quality between the straw and the water-based resins.

A comparison of the extractive yields between HW and the ethanol (ET) extraction shows that HW is a stronger medium of extracting extractives from wheat straw than ET. 10% and 13% higher yields of extractives have been observed for the UN internode and the node respectively. Interestingly, the yield of extractives through HW extraction increases more dramatically for the H+S pre-treated straws by 32% and 27% for internode and node respectively, in comparison to ET extraction. This signifies the dependency of extractives yield on the solvent used for extraction.

3.3.1 Impact of pre-treatment on the extractives content

The extractives in biomass (wood and/or straw) can lead to pitch problems during pulping and papermaking. Sterols and waxes do not from soluble soap in alkaline conditions, i.e. kraft pulping, and therefore, they will be deposited and source pitch problems. The build-up of these extractives can be led to issues for pulp and paper manufacturers [31], such as technical (reduce the paper strength by interfering with hydrogen bonding during sheet formation) and economic concerns (reduce paper machine efficiency and increase energy consumptions). Removing/weakening the extractives previous to pulping through a pre-treatment of biomass is beneficial for improving the efficiency the bio-refinery pathway.

Condensed tannins and phenolics have been shown to be released form the cell structure of wheat straw by the hot water pre-treatment [32]. Fig. 4a illustrates the lower contents of extractives in H+S

pre-treated straws for both HW and ET extraction. HW extraction for H+S straws compared to UN straws has been reduced by 55% and 52%, while, ET extraction has been reduced by 66% and 60% in internode and node respectively. The impact of the H+S pre-treatment on the partial deletion of extractives is also confirmed in the surface chemical functional distribution, as previously observed (Fig. 1). The sharp band at 1739 cm^{-1} on the outer surface of node and internode of UN straws can be assigned to the carboxyl groups in the acids and esters of acetic, ferulic, *p*-coumeric and uronic acids, which have been recognised as core elements of extractives [1]. The intensity of this band is diminished after the H+S pre-treatment as evident in Fig. 1. Equally, the strong bands at 2850 and 2920 cm^{-1} diminish in intensity for the H+S pre-treated straws. These bands link to the symmetric and asymmetric stretching of the CH_2-group respectively, which cover the majority of the aliphatic parts of waxes [25]. In light of the aforementioned, a conclusion is gathered that the extractives in particular waxes (an important group of the lipophilic extractives) have been diminished from node and internode by H+S pre-treatment. Eliminating the wax can be beneficial for wheat straw feedstock, as it facilitates the penetration of pulping chemicals into straw. The H+S pre-treatment of wheat straw has been shown to be a suitable process for dissolution/diminishing of the lipophilic extractives. The removal of nonpolar hydrophobic extractives from wheat straw can, not only improve the wettability which is helpful for composite applications [4], but also, facilitate the papermaking by decreasing the pitch problems and enhancing paper strength [30].

3.4 Klason lignin content

It is shown in Fig. 4b that there is no substantial difference in Klason lignin (KL) content between the HW and ET extracted straws. KL content, however, for HW extracted straws are marginally lower than those of ET extracted straws. The lowest KL content is for HW extracted internode of untreated straws (22%) and the highest is for ET extracted node of H+S pre-treated straws (28%). Generally, the node yielded higher KL content compared to internode, for both untreated and H+S samples, by 15% and 5% respectively, for HW extraction and by 13% and 5% for ET extraction.

The greater KL content of node can be clarified in relation to the crystallinity index calculation via X-ray diffraction. In our previous investigation on the same wheat straws, the crystallinity index of node and internode were found to be 35% and 45% respectively [3], this can be an indication of node having more amorphous parts than internode, which is reflected by the higher KL content in the node.

3.4.1 Impact of pre-treatment on the Klason lignin content

The impact of the H+S pre-treatment on the KL content can be seen from Fig. 4b, where there is only a minor upsurge in comparison to untreated straws. The H+S pre-treatment increases the KL content by 18% and 8% for internode and node, respectively, in the case of HW extraction. Similarly, the ET extracted H+S straws; experience an increase in KL content by 12% and 5% in internode and node respectively. The small increase in the amount of KL content for H+S straws can be because of the part deduction of hemicellulose, as high temperature pre-treatments have been proved to remove hemicellulose [33]. Moreover, in chemical functional group distribution (Fig. 1a), it was shown that the lignin bands, particularly at 1510 cm^{-1}, i.e. aromatic ring stretch, are intensified in the case of H+S pre-treated samples. The lignin can be released and re-deposited on the surface as a result of similar pre-treatments to H+S, for instance in the case of hydrothermal pre-treatment of wheat straw [34,35] and for the case of steam explosion pre-treatment of aspen wood [36].

3.5 Ash content

Ash content is examined in two forms, i) structural ash and ii) extractable ash. Structural ash is inorganic material that is bound in the physical structure of the biomass whereas extractable ash is inorganic material that can be removed by extraction [37] (in this study by HW and ET).

It is observed in Fig. 5 that the node of wheat straw contains more ash, in both pre-treated and untreated non-extracted samples, i.e. the node of H+S pre-treated straws has an ash content of 3.3% compared to the H+S internode of 1.6%, the same values for UN samples are 5.3% and 3.2% (see Fig. 5).

In Fig. 4c it can also be seen that for both HW and ET extractions, the node has higher ash content than internode. The higher ash contents of the node can cause problems for the pulping and therefore, removal of nodes prior to pulping will upgrade straw quality as a feedstock. Separation of nodes during collection and storage steps would require modifications of harvesting equipment, or digital image processing [38] or alternatively focus could be on pulping systems [39].

In Fig. 4c it is observed that HW extracted samples have less ash remaining than ET extracted samples. In comparison to ET extracted samples, HW extracted ash contents are lower by 40% and 32% in UN, and by 13% and 33% in H+S for internode and node respectively.

3.5.1 Impact of pre-treatment on the ash content

The impacts of the pre-treatment on the ash content of wheat straw can present a tremendous opportunity for further successful bio-refinery pathways. Silica constitutes more than 90% of the wheat straw's ash content [40]. Fig. 5 illustrates a substantial reduction in the ash content of H+S pre-treated straws compared to UN, which is valuable for the composite application as silica inhibits the good quality interfacial bonding [41]. In Fig. 5, it can be seen that for non-extracted H+S straws, the ash content has been reduced by 50% in internode and 38% in node, since 3.2% of UN ash content has been reduced to 1.6% for H+S, and from 5.3% (UN) to 3.3% (H+S), respectively.

In our previous investigation on the same wheat straws [4], the residual weight calculated based on thermogravimetric analysis (TGA) for untreated straws was higher in comparison to H+S pre-treated straws, i.e. 11% in UN reduced to 4% in the case of internode and 8% in UN reduced to 5% in the case of node, which further approves the partial elimination of ash after the H+S pre-treatment [42]. Because of the partial removal of extractives and hemicellulose, the H+S pre-treated straws have higher thermal stability and lower ignition residue.

"Fig. 4 here"

"Fig. 5 here"

3.6 Surface elemental composition

In Table 3 the elemental composition of wheat straw node and internode with their inner and outer surfaces are tabulated. The elements detected were analysed quantitatively with the use of database of standard samples programmed in the software. The majority of the wheat straw consists of a large amount of carbon (C) and oxygen (O), and a small amount of silicon (Si).

Higher amounts of Si weight percentage were found on the outer surface of internode than the inner surface. For untreated straws the internode outer surface had a 5.8% Si weight percentage compared to the inner surface of only 0.8%. On the other hand, the Si weight percentage in H+S internode compared to UN straws was significantly reduced ($P < 0.05$) by 83% and 100% in outer and inner surface respectively. Similarly, the reduction of Si content (weight %) was seen in nodes of H+S pre-treated straws compared to UN, from 2.8 to 0.8% in the outer surface and 0.7 to 0% in the inner surface. The results here for Si weight percentage reduction due to the H+S pre-treatment is reinforced by the substantial reduction of the ash content in H+S pre-treated straws compared to untreated ones as aforementioned in the previous section.

When investigating the nodes and internodes, outer to inner surface, it is gathered that more silicon (in the form of silica) is mainly found on the outer surface (i.e. epidermis tissue) of wheat straw. Results for chemical functional groups distribution (Fig.1a and b) further echo this judgment, where the bands of 790 cm^{-1} (Si–C stretching vibration [43]) and 985 cm^{-1} (Si–O stretching vibration [43]) are only observed on the outer surfaces of node and internode, respectively.

In Table 3, it is noticed that the O/C ratio for wheat straw in all locations (anatomical and surfaces) indicates the presence of carbohydrate rich surfaces, as the theoretical O/C ratio of cellulose is reported 0.83 and that of lignin is 0.33 [44].

"Table 3 here"

3.7 Morphology

The epidermis tissue which is on the outermost ring of the wheat straw stem is a cellulose-rich dense layer with a high concentration of silica. This dense layer of epidermal cells provides added mechanical strength to the wheat straw stem. Underneath the epidermis in the internode, a loose layer containing parenchyma and vascular bundles is observed in Fig. 3a, while, the node has a completely different cross sectional morphology, as shown in Fig. 3b. The node possesses a dense zone with closely packed bubbled shaped cells in the middle and elliptical shaped rings well-arranged in a circle, occupying the node core. This morphological difference could indicate the more recalcitrance structure of node compared to the internode, whereby it translates into different physicochemical responses to the pre-treatments and the subsequent enzymatic digestibility [45]. Heterogeneous morphology counts as one of the important properties of substrate that impacts the enzyme action and activity.

"Fig. 3 here"

The higher content of extractives and ash in nodes than internode (see Fig 4a and Fig. 5) can be related to their morphological characteristics. The thicker epidermis tissue in the nodes i.e. higher content of epidermal cells is mostly composed of the suberized cells and silica cells [46], therefore, the ash and extractives contents in the nodes are relatively higher than in the internodes. The epidermis tissue thickness is about 200 μm in the node (Fig 3b (ii)) and about 45 μm (Fig. 3a) in the internode. The H+S pre-treatment impact on the morphological characteristics, as investigated in Fig. 6, apart from a colour change from bright yellow into lighter shade yellow observed during experimentation, is the alterations made to the microstructure. The node's morphology was not subject to a substantial change after the H+S pre-treatment. Conversely, an expansion of parenchyma, (i.e. larger and deeper), in H+S pre-treated internode is observed in Fig. 6a, in comparison to the UN internode as shown in Fig. 6b, that shows a fairly compact zone, arranged closely with smaller circumferences of ellipsoidal honeycomb cells. The expansion of cells could be valuable when it

301 comes to composites production where the resins overflow into the expanded cells, forming
302 effective entanglement between the straw particles upon solidification. Moreover, the expanded
303 microstructure can enable the access of the chemical agents and lead to easier fibrillation of wheat
304 straw for further ethanol process or other bio-refinery pathways of main components of wheat straw,
305 i.e. hemicellulose and lignin.

306 **"Fig. 6 here"**

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310 **Tables**

311 **Table 1** - Methods and purpose of investigation for analysis of wheat straw node and internode

Parameters investigated	**Methods**	**Determination**
Extractives content	Extracted using two solvents, hot-water (HW) and ethanol (ET), in a soxhlet method for 24 hours following *NREL/TP-510-42619* [15].	i) Examine the different extractives between node and internode, ii) Identify efficient extraction solvent.
Acid insoluble lignin/Klason lignin (KL)	Determined according to *NREL/TP-510-42618* [16]. KL determinations were corrected for their relative ash content.	i) Inspect the KL yield in node and internode, ii) The effects of pre-treatment on KL content.
Ash content	According to *NREL/TP-510-42622* [17], the residue after combustion of the organic matter at a temperature of 525±25˚C.	i) Classify the ash content of node and internode, ii) The effects of pre-treatment on ash content, iii) Quantify both structural (non-extracted) and extractable ash content.
Surface chemistry	ATR-FTIR spectra were recorded on a PerkinElmer Spectrum one Spectrometer, operated under the following conditions: 4000–650 cm^{-1} range; 4 cm^{-1} resolution; 16 scans.	i) Interpret different surface functionalities in node and internode, ii) Track the changes to the surface chemical distribution after pre-treatment.
Surface elemental	The EDX-SEM spectra were obtained using an INCA Energy 400 microanalysis system.	i) Check the consistency of surface elemental components,

composition		ii) Evaluate the efficiency of pre-treatment in surface modification.
Profile morphology	Investigated using optical microscopy (OM) and field emission gun-scanning electron microscopy (FEG-SEM, Zeiss Supra 35 VP).	i) Differentiation of node and internode, ii) The correlation of morphology and surface chemical characteristics, iii) Changes to morphology induced by pre-treatment.

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317 **Table 2 -** Surface functional groups chemical distribution of node and internode

Wavenumber (cm^{-1})	**Bands assignment**	**Remarks**	**Refs.**
720	Methylene CH_2 in-plane deformation rocking	Just seen in the node outer surface	23
790	Si-C stretching vibration		
985	Si-O stretching vibration	Just seen in the internode outer surface	
1160	C-O-C antisymmetric bridge in hemicellulose and cellulose	Sharper in the internode than the 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 the internode of H+S pre-treated straws	24
1739	Carboxyl groups	High intensities in the internode and the node outer surfaces.	1
2850 & 2920	Symmetric & asymmetric stretching of CH_2 in aliphatic fraction of waxes	Sharper in the node than the internode and outer than inner surface	25
2955	Asymmetric stretching of CH_3 in fatty acids	Just seen in the untreated node	26

3200-3600	OH stretching of hydroxyl groups	Higher intensity in the node and internode of the inner surface than the outer surface	[27]

318 **Table 3 -** Surface elemental composition of node and internode based on EDX-SEM analysis

Profile Surface	**Sample**	**ID**	**Percentage %**			**O/C**
			C	**O**	**Si**	
Inner	Internode	UN	54.1 (2)	45 (1)	0.8 (4)	0.83
		H+S	53.5 (3)	46.4 (7)	0 (1)	0.87
	Node	UN	54.1 (9)	45.6 (7)	0.7 (6)	0.84
		H+S	53.5 (5)	46.2 (4)	0 (1)	0.86
Outer	Internode	UN	51.3 (2)	43.4 (5)	5.8 (2)	0.84
		H+S	54.4 (7)	44.5 (3)	1.0 (3)	0.82
	Node	UN	53.7 (3)	43.5 (8)	2.8 (2)	0.81
		H+S	54.5 (2)	44.6 (1)	0.8 (4)	0.82

319 *values in () are Coefficient of Variance %

320 **Figures**

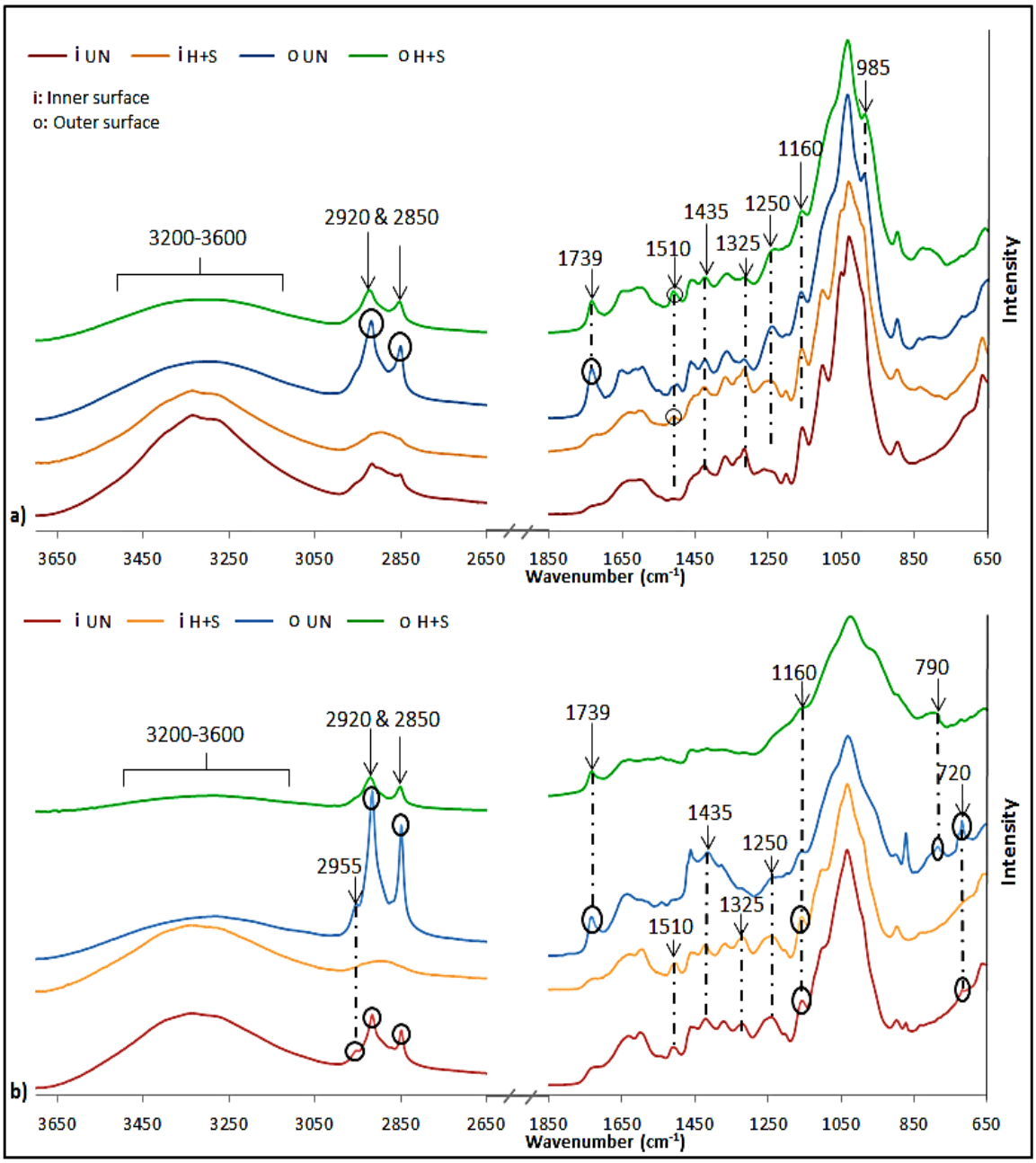


Fig. 1 - ATR-FTIR spectra of a) Internode and b) node of untreated (UN) and pre-treated (H+S) inner and outer surface (Print in colour or see online version for colours)

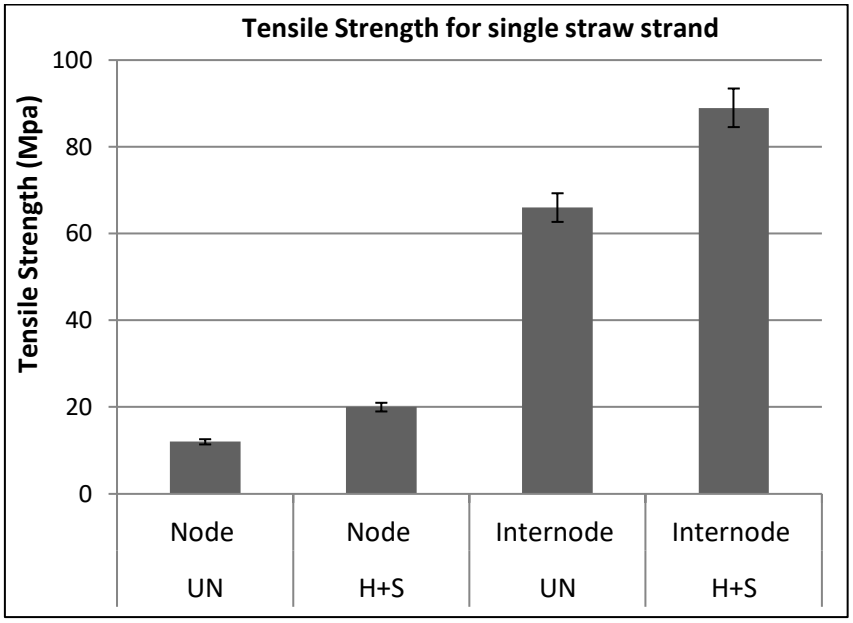
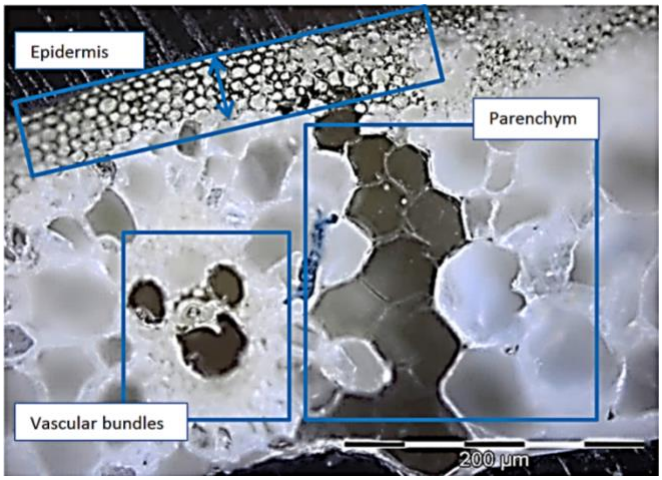
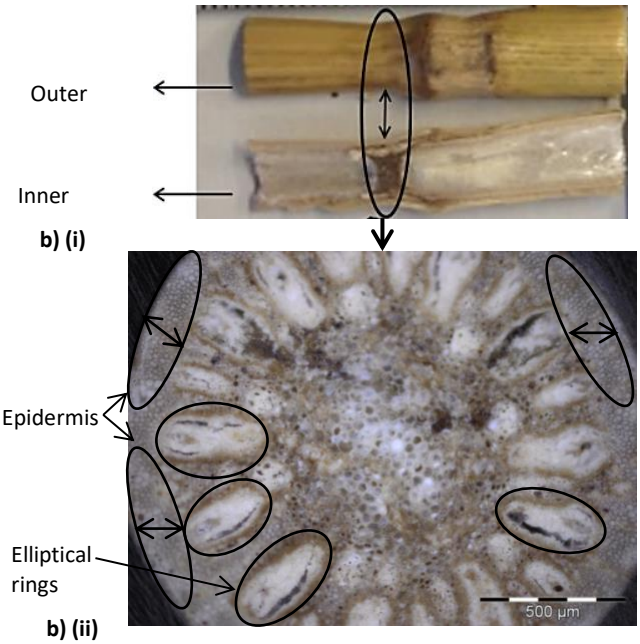


Fig. 2 – Tensile strength of untreated (UN) and pre-treated (H+S) node and internode



a)



b) (ii)

Fig. 3 – a) Cross section of internode; b) (i) Transverse view of node outer and inner surface, and b) (ii) Cross section view of node

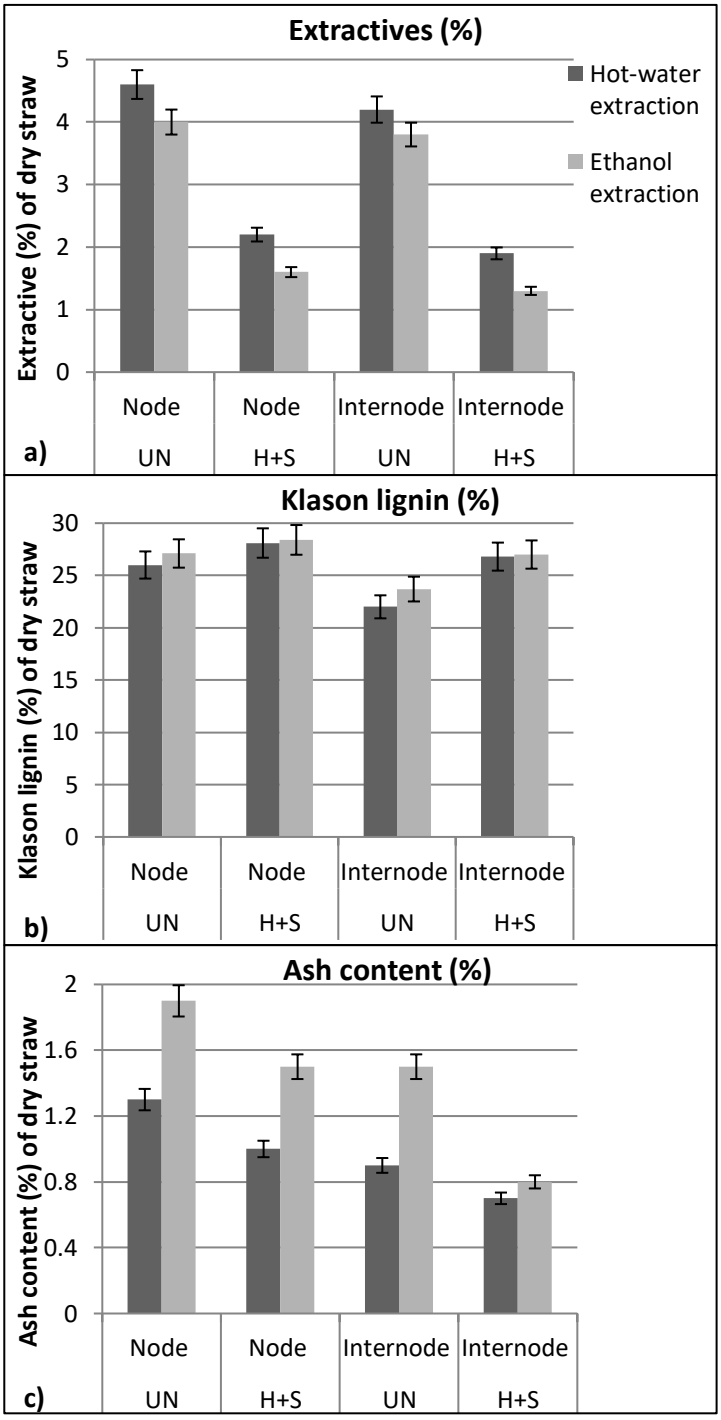


Fig. 4 – Chemical analysis of untreated (UN) and pre-treated (H+S) wheat straw (% dry straw); a) extractives content, b) Klason lignin content and c) ash content of samples with hot-water and ethanol extractions

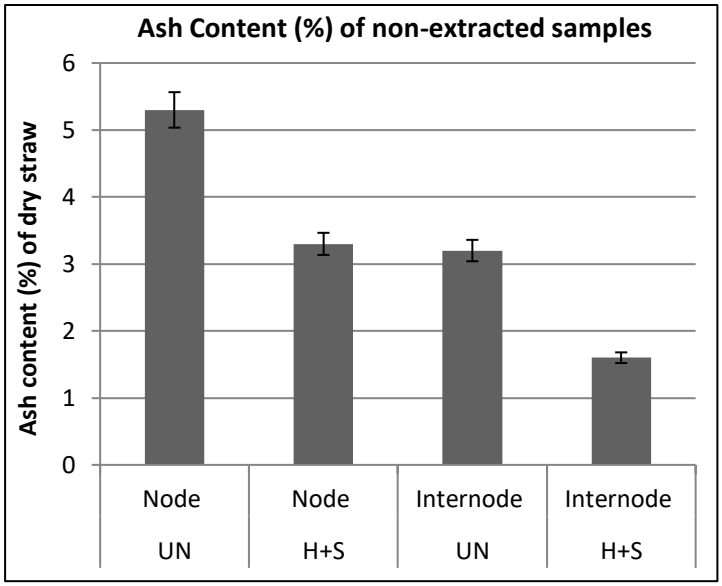


Fig. 5 – Ash content percentage of non-extracted dry wheat straw for untreated (UN) and pre-treated (H+S) samples

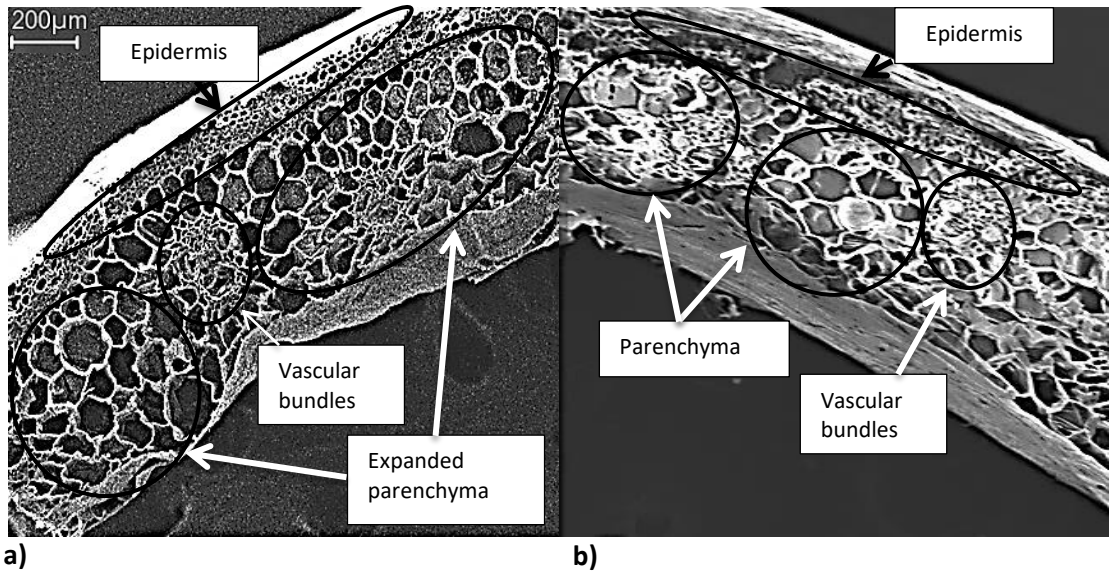


Fig. 6- SEM micrographs for cross sections of a) pre-treated internode and b) untreated internode

399 **TOC Graphic**

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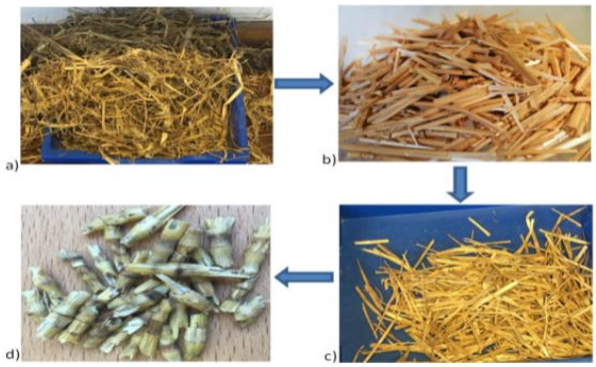

406 **Graphic Abstract:** Segregation of node and internode for efficient and smart utilisation of straw

407 biomass in bio-refinery

408 (This is to confirm that the TOC Graphic is original and was created by the corresponding author

409 using images taken by corresponding author.)

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