About Wheat Straw …

Wheat - a grass that is cultivated throughout the world.
Second or third in worldwide production after corn (maize), depending on the year.
Two major forms of wheat: winter wheat and summer wheat.
Leading source of vegetable protein in human food [14].

The wheat straw cell wall is a natural composite composed of cellulose microfibrils in an amorphous matrix of hemicellulose and lignin [9, p.17]
The cellulose microfibrillar crystals are about 20nm in diameter and 150-200nm in length [10]

Wheat straw is one of the most abundant renewable resources. [11]
About 1.9 x 10^9 tons of wheat straw were annually produced world-wide, along with 6.2 x 10^8 tons of wheat production [11].

Annual Global Production of wheat lands	690	Tg	[32]
Annual Global Production of wheat	223	Tha	[32]

Uses of Wheat Straw

Use	Comment	Link
Animal bedding	Absorbs about 300% of its weight in moisture	[link]
soil fertilizer replacement (high N):	$0.01-$0.02/lb	
fuel liquid/bioethanol		
methane production		
erosion control		
livestock bedding		
mushroom compost substrate		
activated carbon	for filtration	
animal feed		
solid core interior (home) door fillers		
low cost building panels walls (load/non-bearing), floors and ceilings (Romania)		
biosorbent/metal ion removal (e.g., Cr)-wastewater		
biofiller		
fuel log (replacing coal)		

Estimate of crop residues in Ontario (OMAFRA, 2006)

Crop	Area (000) acres	Estimated annual production (AP) (000) tons	Estimated Crop Residues (CR) (000) tons	Estimated heat value from crop (10^6 MJ)	Source
Wheat	1231	1674 @136(	753 @45% of AP	13560	[8, p. 41]

Item	Density	Units		Energy Density	Units	Source
bulk density of loose wheat straw	18	kg/m3				[3]
	40	kg/m3				[34]
baled biomass, large round bales, hard core	190-240	kg/m3		3.4-4.5		[3]
	120	kg/m3				[34]
Ground biomass (i.e., hammermill)	200	kg/m3		3.6		[3]
briquettes	350	kg/m3		6.4		[3]
cubes	400	kg/m3		7.3		[3]
pucks	480-640	kg/m3		8.6-12.0		[3]
pellets	550-700	kg/m3		9.8-14.0		[3]
torrefied pellets	800	kg/m3		15		[3]
bio-oil	1200	kg/m3		20		[3]

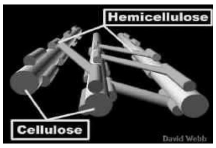
Physical Content of Wheat	Mass Percent	Units	Source
Internodes	68.5	%	[4, p. 2-3]
Leaves-sheaths	20.3	%	[4, p. 2-3]
Leaves-blades	5.5	%	[4, p. 2-3]
Nodes and Fines	4.2	%	[4, p. 2-3]
Grain and Debris	1.5	%	[4, p. 2-3]

Chemical composition of wheat straw			Source	Internode [%]	Node [%]	Leaf [%]	Source	Comments
Cellulose	**35-45**	%	**[33, p. 1904]**					(C6H10O5)n a long chain polysaccahride carbohydrate
holocellulose	58.5-72.9	%	[4, p. 2-1]					
alpha-cellulose	33-40	%	[4, p. 2-1]					
hemicellulose	25-32	%	[4, p. 2-1]					Rich in 5-carbon sugars (pentoses.)
lignin	16-23	%	[4, p. 2-1]		23.22	17.48	[4, p. 2-3]	Total lignin=Klason lignin + soluble lignin. One of the most organic compounds on earth after cellulose and chitin. lignin yields more energy when burned than cellulose [31]
ash	4-10	%	[4, p. 2-1]			56.95	[4, p. 2-3]	
lipids	1-2	%	[33, p. 1904]. Of lipids: fattry acids 25%, free fatty alcohols (ca. 20%), high molecular weight esters of long-chain fatty acids esterfied to long-chain fatty alcohols.					Lipids can be used to produce high value waxes, used in cosmetics and personal care products. Lipds canbe extracted with acetone in a Soxhlet apparatus after 8h.
silica and silicates	2.0-5.5		[4, p. 2-1]	5.93		12.06	[4, p. 2-3]	
EtOH-Benzene extr.	2.9-5.8	%	[4, p. 2-1]					
Fibers	38-42	%	[4, p. 2-1]					Consist of the celluloses
Fiber length (mm)				1.73	0.82		[4, p. 2-3]	

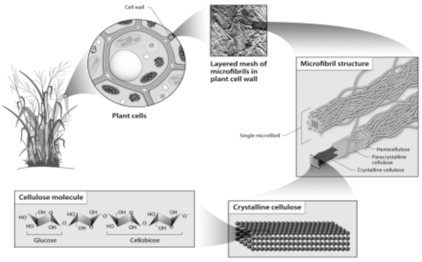
Item	Internode [%]	Node [%]	Leaf [%]	Source	Comments
Straw Fractions - Hand Harvested Madsen (%)	48	6	46	[4, p. 2-5]	
Straw Fractions - Baled Madsen, estimated (%)	80	11	9	[4, p. 2-5]	

Item	Internode	Node	Leaf	Whole	Source	Comments
Mass (%)	49	6	45		[4, p. 2-5]	
NAFL (mm)	0.61	0.28	0.35	0.48	[4, p. 2-5]	
WAFL (mm)	1.2	0.65	0.79	1.04	[4, p. 2-5]	
Fines (%)	51.3	51.4	49	51.3	[4, p. 2-5]	

NAFL=Numerical Average Fiber Length
WAFL=Weighted Average Fiber Length



Source: http://www.biologie.uni-hamburg.de/b-online/library/webb/BOT311/PlantCellWalls00/CellWallHemiLab_small.jpg



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Item	Gross Amount	Units	Source	Detection Limit [ppm]	Internode [ppm]	Node [ppm]	Leaf [ppm]	Source	Comments
Chemical Components									
Aluminum (Al)				20	<20-20	<20-20	40-100	[1]	
Boron (B)				20	<20	<20	<20-30	[1]	
Barium (Ba)				1	28-83	39-97	47-86	[1]	
Calcium (Ca)				10	1130-3300	2200-3470	5950-8230	[1]	
Chromium(Cr)				1	<1	<1	<1-3	[1]	
Copper (Cu)				2	3-5	22-68	4-6	[1]	
Iron (Fe)				5	21-87	22-68	88-175	[1]	
Potassium (K)				1000	13000-34000	20000-65000	920-1710	[1]	K= primary micronutrient.
Magnesium (Mg)				10	500-2970	930-2770	2000-2790	[1]	
Maganese (Mn)				0.5	10.4-25.1	9.3-27.2	34.9-128	[1]	
Molybdenum (Mo)				1	<1-2	1-2	<1-1	[1]	
Sodium (Na)				50	60-260	20-1570	50-130	[1]	
Phosphorus (P)				20	330-1030	350-1020	920-1710	[1]	P= primary micronutrient.
Tin (Sn)				5	<5-6	<5-7	<5-7	[1]	
Strontium (Sr)				0.5	5.8-15.9	9.6-18.8	22.1-37.8	[1]	
Zinc (Zn)				1	7-24	12-25	15-24	[1]	

Proximate Analysis (Wheat Straw)							**Comments**
Volatiles	69	m%	[2, p.6]	75.27	m%	[5, p. 1561]	
Fixed Carbon	23	m%	[2, p.6]	17.71	m%	[5, p. 1561]	
Ash	8	m%	[2, p.6]	7.02	m%	[5, p. 1561]	Biosolid ash from combustion be reduced by adding lime (CaO) [18, p. 12]. [Miscanthus, switchgrass] delayed harvest in spring can reduce ash content, largely by reducing potassium K [19, p.?].

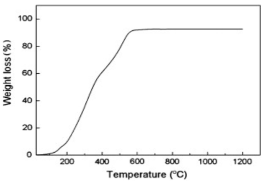
Ultimate Analysis (dry biomass)	Qty	Unit	Source	Qty	Source	Comments
C	45.7	m%	[2, p.7]			
H	5.7	m%	[2, p.7]			
O	43.3	m%	[2, p.7]			
N	0.5	m%	[2, p.7]			Nitrous oxides (NOx) emissions will be proportional to the N2 content. N= primary micronutrient.
S	0.3	m%	[2, p.7]			S=secondary micronutrient.
Cl	0.7	m%	[2, p.7]	0.1%-0.6%	[6]	Most chlorine released as Hcl in the gas phase [2, p.9]. Higher risk of dioxin formation [6]. 90% of Cl can be removed by complete immersion in water in < 2 min, [27, p. 41]. K, Na, Cl can be "...removed... by spraying water over the top of a 30 cm
K				0.7%-0.8%	[6]	

Lower Heat Value (LHV)	Qty	Unit	Source
Wheat Straw (dry)	7680	BTU/lb	[13, p.5]
Wheat Straw (dry)	17.86	MJ/kg	[13, p.5]
Wheat Straw (20% m.c.)	5908	BTU/lb	[13, p.5]
Wheat Straw (20% m.c.)	13.74	MJ/kg	[13, p.5]

High Heat Value (HHV, dry biomass)			Source			Source
Experimental	17100	kJ/kg	[2, p.8]	19100	kJ/kg	[20, p. 35]

Ash Content (dry biomass)									
K2O	2.2	%	[2, p.9]	25.6	wt-%-ash	[5, p. 1561]	16.9	wt-%-ash	[21]
CaO	0.3	%	[2, p.9]	6.14	wt-%-ash	[5, p. 1561]	7.3	wt-%-ash	[21]
SiO2	3.6	%	[2, p.9]	55.32	wt-%-ash	[5, p. 1561]	59.9	wt-%-ash	[21]
Cl	0.7	%	[2, p.9]						the chlorine content in agrobiomass like straws is lower than in dry years."
P2O5	0.2	%	[2, p.9]				2.3	wt-%-ash	[21]
Fe2O3	<0.1	%	[2, p.9]				0.5	wt-%-ash	[21]
MgO	0.1	%	[2, p.9]	1.06	wt-%-ash	[5, p. 1561]	1.8	wt-%-ash	[21]
NA2O				1.71	wt-%-ash	[5, p. 1561]	0.4	wt-%-ash	[21]
Al2O3				1.71	wt-%-ash	[5, p. 1561]	0.8	wt-%-ash	[21]
Other				1.71	wt-%-ash	[5, p. 1561]	10.1	wt-%-ash	[21]

Omtec WSBF Grade	Size (Mesh/um)	Nominal Avg Length	OMTEC Application
WSBF-TH (chopped straw)		5+ mm	
WSBF-15 (large fibers,#2)	>16 mesh	3.5 mm	Fuel Pucks
WSBF-25 (medium fibers, #1)	16 – 35 mesh	2 mm	Automotive Plastic
WSBF-35 (fine fibers,#3)	< 35 mesh	0.75 mm	Automotive Plastic
WSBF-45 (dust)		< 0.1 mm	Fuel Pucks



Weight loss–temperature curve of wheat straw [29]

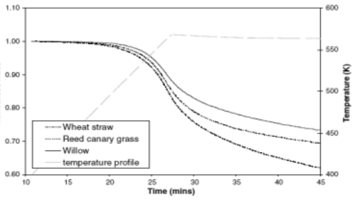


Fig. 2. Mass loss of wheat straw, reed canary grass and willow during torrefaction at 563 K.

Mass loss of wheat straw, reed canary grass, and willow during torrefaction at 563K (290 C) [30, p. 847]

Pyrolysis Stages

Temperature	Process (overlap)	Major Produ	Heat	Source
< 200C	Drying	H20	IN	[12, p. 11]
230C-250C	Depolymerization	Acetic acid, Methanol, CO2, CO	IN	[12, p. 11]
250C-280C	Torrefaction	Extractives, CO2, CO	IN	[12, p. 11]
200C - 350C	decomposition of hemicellulose starts at temperatures above 473 K (200C) and full devolatisation will occur by 623 K (350C) with the major products being H2O, CO2, CO, and char, as well as traces or low molecular weight organics			[30, p. 847]
280C-500C	Devolatilization	Organics, Tars, CO2, CO	OUT	[12, p. 11]
<500C	25%-75% of chlorine released			[27, p.40]
500C-700C	Dissociation/ Carbonization	CO,H2	IN	[12, p. 11]
650-750C	Normal operation of catalytic converter			
>700C	Gasification	H2, CO	IN	[12, p. 11]
>700C	Remaining chlroine released			[27, p.40]
700C-900C	PAHs formed, total yield increasing with temperature and residence time in the furnace. At higher temperatures, they are thermally decomposed.			[6, p. 561]

5 Phases of Combustion [6]	Comments	Source
Initial smouldering (I)	Methoxyphenols from the lignin of the fuels released at high concentrations.	[6]
Early flaming (II)		
Late flaming (III)		
After-flame smouldering (IV)	released high concentrations of compounds that are hazardous to health and the environment	[6]
Final glowing (V)		

Concentrations of compounds in smoke from Wheat Straw pellets during the different combustion stages:

No.of analyses	**5**		**5**		**5**		**6**		**6**						
	CAS	Carcinogenic?	**Initial smouldering (I)**		**Early flaming (II)**		**Late flaming (III)**		**After-flame smouldering (IV)**		**Final glowing (V)**		**Source**	**Notes**	**Link**
			conc.	s.d.	conc.	s.d.	conc.	s.d.	conc.	s.d.	conc.	s.d.	[6]		
Carbon dioxide			6100	1700	120000	20000	110000	20000	28000	4000	21000	2000	[6]		
Carbon monoxide			630	300	220	140	270	110	3100	400	2200	400	[6]		
Methane			11	5	5.5	3.2	6.5	2.4	750	470	13	9	[6]	colorless, odorless; Low concentrations are not harmful.	link
Ethane			7.5	3.8	1.2	0.9	1.8	0.6	300	190	0.4	0.5	[6]	May cause central nervous system depression. Causes adverse cardiovascular effects.	link
Ethene (ethylene)	74-85-1		7.5	3.4	13	8	5.5	1.9	100	70	0.4	0.4	[6]	Colorless. Not carcinogenic.	

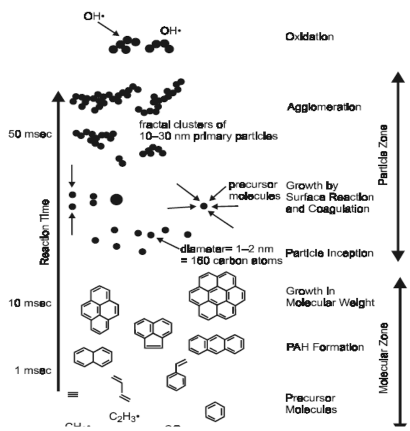
Propane			2.8	1.5	0.3	0.4	0.5	0.2	76	54	<0.03		[6]	Colourless gas. Odourless. EXTREMELY FLAMMABLE GAS.Low concentrations are not harmful. Not a carcinogen.	link
Propene (propylene)			5.9	2.9	2.2	1.4	1.2	0.4	98	66	0.04	0.07	[6]	May cause central nervous system depression. Not carcinogenic.	link
Ethyne			1.2	0.5	4.3	2.6	0.9	0.6	2	1.6	0.5	0.1	[6]		
1,3-Butadiene			1.4	0.6	0.04	0.01	0.06	0.04	12	9	<0.03		[6]		
Benzene			1	0.4	0.8	0.4	0.5	0.1	30	18	1.4	1	[6]	Carcinogenic to humans. CARCINOGEN. Known to cause: cancer of the blood or blood system. Clear colourless liquid. Aromatic odour. HIGHLY FLAMMABLE LIQUID AND VAPOUR.	link
Methylbenzene			1.5	0.7	0.2	0.2	0.5	0.2	46	30	0.2	0.2	[6]		
Naphthalene			0.2	0.1	0.3	0.3	0.2	0.1	8	2	0.4	0.2	[6]	polycyclic aromatic hydrocarbons	
Furan C4H4O			5.2	2.4	0.9	0.5	0.2	0.2	6.6	3.1	<0.03		[6]	Decomposition products of the polysaccharides of the fuels (mainly cellulose, hemicellulose and starches). Toxic and may be carcinogenic [28].	
2,5-Dimethylfuran ((CH3)2C4H2O)			1	1	1	1	0.6	0.3	2	1	<0.03		[6]		
2-Furaldehyde			50	30	10	10	3	1	0.4	0.3	0.5	0.2	[6]		
5-Hydroxymethyl-2-furaldehyde			3	1	20	10	2	1	o0.03	o0.03			[6]		
Benzofuran			0.5	0.2	0.6	0.2	0.2	0.1	3	2	0.04	0.02	[6]		
1,6-Anhydroglucose			2	1	20	10	1	1	2	1	0.2	0.1	[6]		
Phenol			20	10	10	10	7	6	100	100	0.3	0.1	[6]		
GuH (guaiacol)			30	10	9	5	2	1	7	10	0.2	0.1	[6]		
GuCH3			7	3	10	10	2	2	4	5	0.1	0	[6]		
GuCH2CH3			10	10	10	10	1	1	5	8	0.08	0.03	[6]		
GuCH==CH2			200	100	20	10	0.9	0.5	4	5	0.5	0.3	[6]		
GuCH==CHCH3 (E)			50	30	30	20	1	0.5	5	7	0.2	0.1	[6]		
GuCHO			20	10	100	100	9	5	4	3	1	0.4	[6]		
GuCH==CHCHO			6	3	3	3	0.7	0.3	<0.03	0.3	0.2		[6]		
SyH (syringol)			100	100	200	200	3	1	20	30	1	1	[6]		
SyCH3			8	5	20	10	0.7	0.3	5	8	0.1	0.1	[6]		
SyCH2CH3			10	10	20	10	0.8	0.3	2	3	0.1	0.1	[6]		
SyCHQCH2			20	10	3	1	<0.03	<0.03	0.05	0.04			[6]		
SyCHQCHCH3 (E)			8	6	9	5	<0.03	2	2	0.01	0.03		[6]		
SyCHO			5	3	10	10	2	1	<0.03	0.2	0.1		[6]		
Sum_of_organic compounds			600	500	50	2000	20						[6]		

Gu: 4-hydroxy-3-methoxyphenyl
Sy: 4-hydroxy-3,5-dimethoxyphenyl

Thermal degradation:
TBD

Non-organic combustion products		
NOx		Formed by: 1) thermal Nox formed from atmospheric oxygen above 1300C, 2) prompt Nox formed at the flame front, and 3) fuel-NOX formed from ele
H2O		
CO2		excess CO2 can also be injurious, with chloroplast disruption and chlorosis often observed above 1000 µmol CO2 mol–1 [22]
CO		
SOx		

Particulate Matter (PM)		Aerosol defined as suspension of particles in the range 0.001um and 100um. PM= total mass of particles and droplets.
PM20		~20,000
PM10		PM10= Particulate Matter < 10um
PM2.5	[23]	Emission factors (EF) of wheat straw is 7.6 +/- 4.1 g/kg, It also indicates that 12.1-24.2% of N in biomass is released as nitrogen-based trace gases and 1
	[24]	Efs from high and low combustion efficiency (CE) wheat stubble burns were 0.8+/-0.4 and 4.7+/-0.4 g kg-1, respectively, and decreased with increasing CE.
PM1	[26]	alkali transformation causes high emissions of PM1, peaking in the 200um-300um range



Schematic picture of soot formation Source: H. Bockhorn, Soot Formation in Combustion (vol. 59 in Series in Chemical Physics, Springer-Verlag, Berlin, 1994.)

Biomass combustion equation

$CH_{1.44}O_{0.66} + 1.03\ O_2 = 0.72\ H_2O + CO_2$ (+Heat)

Note: $CH_{1.44}O_{0.66}$ is the approximate chemical equation for the combustible portion of biomass

Sintered or fused deposits due to alkalis: Volatile alkali (0.34 kJ/GJ)sufficiently lower the fusion temperature of the ash [16]

Minimum and maximum cost of biomass supply (20 to 100km distance) including granulation (pelleting):

Operations	Low		High		Source
	Cost ($/t)	Energy (GJ/t)	Cost ($/t)	Energy (GJ/t)	
Collection	19.69	0.319	23.72	0.339	[7, p.27]
Transport	6.06	0.271	23.72	0.339	[7, p.27]
Granulation (pellet)	20.53	0.471	30.85	0.821	[7, p.27]
Granulation (grind)	5.65	0.096	5.65	0.096	[7, p.27]
Total	46.28	1.006	78.29	1.509	[7, p.27]

Calculations of the net yield:

Crop	Yield grain (bu/ac)	Dry grain (t/ha)	Straw/grain ratio	Gross yield (t/ha)	Max fraction removed for soil fertility k1	Fraction machine can remove k2	Estimate of losses from harvest to biorefinery	Net yield (t/ha)	Source
Wheat Straw	60	3.5	1.3	4.6	0.5	0.75	0.2	1.822	[7, p. 9]

Sources:
[1] MST MEP, p. 97
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