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FEASIBILITY FOR ENERGY RECOVERY FROM CEREAL CROP RESIDUES

by

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ABSTRACT

Feasibility for Energy Recovery from Cereal Crop Residues

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Solid waste management and the depletion of fossil fuel reserves are two critical and unrelated problems requiring resolution. An approach to the solution of these two problems by conversion of solid organic wastes into useful forms of energy was investigated. Canada is fortunate to possess rich natural resources including fossil fuels, however, there is a concern expressed through the wide-spread "energy crisis" that shortages will be encountered in the immediate future. Canada produces about 99.0×10^9 lb (44.9×10^9 kg) of cereal crop residues annually which should not be overlooked as a potential energy source. Much of this residue is considered as waste material which creates problems of disposal and affects on the environment. This quality of residues has a potential energy equivalent to about 593.4×10^{12} Btu (149.5×10^{12} kcal).

Oat straw was chosen as a representative cereal crop residue for investigating the feasibility of energy recovery by pyrolysis and anaerobic fermentation. A significant volume of gas production was achieved with both systems. Gas production from the pyrolysis process was 1.43 cu ft/lb (0.09 litre/gm) of straw and 1.78 cu ft/lb (0.11 litre/gm) of straw at the corresponding temperature ranges of 65 to 600°F (18 to 316°C) and 65 to 700°F (18 to 371°C). The gas contained from 25 to 30% CH_4, and 32 to 48% CO_2. The gas production through anaerobic digestion at a temperature of 95°F (35°C) was about 6.57 cu ft/lb (0.41 litre/gm) of dry matter for the batch feeding system and about 6.01 cu ft/lb

(0.38 litre/gm) of dry matter for the continuous feeding system. The composition of gas was approximately 52 to 56% CH_4, and 44 to 48% CO_2.

Problems of materials handling of straw involving collection, concentration and transportation for the delivery of large quantity volumes to supply large pyrolysis or anaerobic processing plants must be solved. Straw should be delivered in a form that will facilitate pyrolysis or anaerobic energy production processes. The economics of pyrolysis and anaerobic digestion for energy recovery from crop residues has been unfavourable to date. However, the extraction of useful energy from cereal crop residues is technically feasible and merits serious investigation.

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LIST OF SYMBOLS

abs = absolute
ave = average
bu = bushel
Btu = British thermal unit
°C = degree Celsius
cal = calorie
Can $ = Canadian dollar
cm = centimeter
cu ft = cubic foot
cu m = cubic meter
°F = degree Fahrenheit
ft = foot
gal = gallon
gm = gram
hp = horse power
hr = hour
kcal = kilocalorie
kg = kilogram
km = kilometer
kwh = kilowatt hour
lb = pound
m = meter
min = minute
mg = milligram
ml = millilitre
mton = metric ton

ppm	=	parts per million
psi	=	pounds per square inch
psia	=	pounds per square inch absolute
Ref	=	reference
SCFM	=	standard cubic feet per minute
sec	=	second
sq cm	=	square centimeter
temp	=	temperature
U.S. $	=	United States dollar
vol	=	volume
VS	=	volatile solid

CHAPTER I

INTRODUCTION

1.1 General

Energy is ncessary to provide power for all forms of work. Not only our body, but also our life-support systems, agriculture and industry, require energy. If energy is withdrawn from agriculture and industry, our life-support systems cease to function (33, 54). Energy consumption can be used as a measure of the progress of civilization which can be applied to industry and the economy in general. In any society, as the development of civilization progresses, energy consumption increases. Conversely, if the society does not have enough energy, civilization as we have known it will be halted (64). David Cass-Beggs (8), in an address to an international biomass energy conference, stated that "energy use and civilization are a reaction that goes both ways".

Scientific American (14) shows that the annual growth in energy demand per capita in the United States is at the rate of about one percent while in India the rate of increase is about one third of the United States rate. Data presented for 1970 show that United States energy consumption was about 220 kwh/day/capita while in India it was about nine kwh/day/capita. McGinnis (44) estimated that annual energy consumption in Canada in 1970 was about 4,939.5 x 10^{12} Btu or approximately 184 kwh/day/capita.

An improved standard of living demands increased consumption which is a combination of two factors; the energy used per capita and the number of people. A pressing problem facing society is that the relationship of man and energy may become a critical problem in the near future. Then, "the question nowadays is not how we shall live, but indeed if we are going to live at all for very much longer" (Harney, Disch, 1971, p. xvii) (64). The need for solving the energy problem is apparent (8, 61, 64).

1.2 The Problems

1.2.1 The Coming Shortage of Some Fossil Fuels

The energy crisis has become a dominant issue during the past few years (33). The current world energy shortage has stimulated a search for alternative sources of energy, since fossil fuel reserves are being depleted rapidly (14). It is not an objective of this thesis to present statistics of the world's energy situation. It is not a matter of how long the primary energy sources will last, but rather it is a matter of fact that reserves have specific quantity limits, and that energy fuels can not be recycled. "When they are gone, they are gone" (72). The energy crisis has become a reality and the question arises as to what other sources of energy can be tapped to supply the requirements after the fossil fuels are gone (14, 15, 33, 44).

Various alternative energy sources including solar, tidal, geothermal and nuclear will be investigated thoroughly in the immediate future. A further source may be energy from agricultural production or "biomass energy" which is a renewable resource that offers the possibility of providing an alternative energy source (14, 43).

1.2.2 Increase in Solid Wastes and Associated Problems

It is understood that solid wastes refer to the wastes arising from household, industrial and agricultural sources. In the past, solid wastes were commonly disposed by means of open burning or open dumping.

At present, the situation has changed and solid waste disposal is becoming a problem of considerable magnitude both with respect to disposal methods and to economic constraints. This problems arises from the increase in total quantity of waste produced through population increase and per capita increase in waste produced because of changes in the standard of living (53, 61). Riddle (53) estimated that total solid waste produced in Canada to be about 160 million pounds (73 million kilograms) per day or eight pounds (3.6 kilograms) per capita per day, of which 100 million pounds (45 million kilograms) is from households while the remaining arises from industrial and agricultural sources.

Wastes from agricultural sources are primarily organic. Two kinds of agricultural wastes which are considered here as potential sources of energy are agricultural plant wastes (crop residue) and animal wastes (manure) (33, 70). Both sources have been increasing the total quantity of wastes. The increase in animal waste has resulted from the increase of animal feedlots while the increase in crop residue has resulted from increased acreage under production combined with greater efficiency in unit productivity, e.g., irrigation, fertilization, and the influence of mechanization, etc. (12, 70).

In past years, agricultural wastes presented no problem, since it was disposed of on the land as a fertilizer. Today, because of the volume of waste generated in confinement areas, disposal on land is a problem and an overall management scheme must be considered for waste handling (46). We are now considering waste not so much as material to be eliminated, but rather as a resource (61). Once we begin to use it, it will no longer be called waste (70).

Downing (12) has calculated that the ratio of energy output to energy input is very favorable for agricultural production. He concluded that "the utilization of either net crop residue or animal wastes as a fuel source could produce more energy than required for all agriculture production requirements". Therefore, the present problem is not only a matter of disposal technique, but it includes processing for recovery and utilization of useful components in these agricultural wastes.

1.3 Objective

The objective of this thesis is to evaluate the technical and economic feasibility of recovering energy from cereal crop residues.

1.4 Conceptual Approach

Organic material or agricultural waste may be converted into a useful energy by direct combustion for thermal energy or biological or chemical processes for storable chemical energy. The choice of conversion method depends on the physical nature of material, particularly the water content (47). The first step toward meeting the objective was to complete a literature review. In addition, the development of small-scale experiments on pyrolysis and anaerobic processes is included. The major concentration in this thesis is directed to pyrolysis.

Anaerobic digestion studies have been undertaken by many institutions. Few of these institutions have set up experiments to see if anaerobic digestion could be applied to crop residues. Pyrolysis was chosen for investigation since this process has been successfully used to recover energy from organic material in times and places of restricted energy supply. For example, gas producer plants making use of coal were used for road transport in Europe during World War II. Pyrolysis may prove viable as a process for energy recovery from straw.

CHAPTER II

QUANTITY OF RESIDUE AVAILABLE

2.1 General

The discusion in this thesis is related to residues from cereal crops only. Several definitions follow:

Cereal: "A cereal may be defined as any grass grown for its edible grain. The term may refer either to the plant as a whole or to the grain itself" (30).

Grain: "Grain is a collective term for the fruit of cereals" (30).

The principle cereals refer to wheat, corn, rice, barley, oats, rye, sorghum and millet (29). However, the six great cereals of the world are considered to be wheat rye, barley, corn, oats and rice (30). The discussion in this thesis will deal with these six cereals only.

2.2 Grain-straw Ratio

The quantity of crop residue can be computed as a function of crop production and may be determined by the use of the grain to straw ratio. For cereals, Kipps (30) explained that the ratio of grain to straw is not constant and varies with such factors as the variety, thickness of planting, and productivity of the soil. However, he concluded that the ratio of grain to straw may be given as follows:

Barley produces 1 pound of grain to 1 pound of straw (1:1).

Wheat produces 1 pound of grain to 1.5 pounds of straw (1:1.5).

Oats produces 1 pound of grain to 2 pounds of straw (1:2).

Rye produces 1 pound of grain to 2 pounds of straw (1:2).

Corn produces 1 pound of grain to 1 pound of stover (1:1).

For rice, the ratio of grain to straw was given in a report from the International Rice Research Institute, Los Banos, Laguna, The Phillippines. Chandler (9) stated that the grain-straw ratio was affected by a number of factors such as nitrogen applications, percent of sunshine, and varieties of rice. In general, the traditional rice plant of the tropics has a grain-straw ratio between 0.3 and 0.6, while the modern rice plant with short stem and erect leaves has a ratio between 0.9 and 1.3. In the first case, the mean value of grain-straw ratio for selected varieties is 0.56 (or 1:1.8). This figure will be used for the discussion throughout this thesis, since it is applicable to the varieties of rice grown in Thailand (see Table 2.9). Therefore,

Rice produces 1 pound of grain to 1.8 pounds of straw (1:1.8).

2.3 Weights per Bushel for Conversion

It is necessary to use conversion factors in estimating quantities of crop residues available. Weights per bushel for the principle cereals as taken from Grain Crops, published by the Commonwealth Secretariat (20), are given in Table 2.1.

2.4 Limits for the Study

The scope of study in this thesis was defined by the criteria following:

2.4.1 Cereal crops were to include wheat, barley, oats, rye, grain corn, and rice.

2.4.2 The acreage and production of cereal crops, except rice were limited to the total acreage and production in Canada, Manitoba and Crop District No. 3 in Manitoba. The agricultural areas of Manitoba and Crop District No. 3 are shown in Figure 2.1.

2.4.3 Statistics used for crop residue estimates are average grain production values for the year 1968, 1969, and 1970 in Canada, Manitoba and Crop District No. 3.

2.4.4 The acreage and production of rice was taken for Thailand, since rice was almost negligible in Canadian production statistics, for the years noted in section 2.4.3 and since Thailand is the homeland of the author.

2.5 Production

The quantity of cereal crop residue is a function of production and is estimated by using the ratio of grain to straw. Table 2.2 contains the average yield and production in Canada, Manitoba and Crop District No. 3. Statistics for Canada were taken from the 1971 and 1972 Canada Yearbooks (68, 69) and for Manitoba from the 1968, 1969 and 1970 Yearbooks of Manitoba Agriculture (78). The figures for rice were taken from a record of Thailand (3) compiled by the Rice Department for 1968 and the Agricultural Extension Department for 1969 and 1970. A summary of the acreage, yields and production of cereal crops in Canada and Thailand is contained in Table 2.4.

Date relating to rye and grain corn in Manitoba were not given for crop districts. Therefore, production quantities for these crops were not considered for Crop District No. 3. Refering to rye, the 1970 Yearbook of Manitoba Agriculture (78) stated that "seventy-eight percent of the total acreage was planted in the western half of the province and about eighteen percent in Crop District No. 3". There was no planted acreage in the year 1968 and 1969. There are no details given for grain corn, since the total planted area in Manitoba was small. Therefore, rye and grain corn production in Crop District No. 3 was considered to be negligible and was not used in estimating the residues available.

The acreage, yield and production of rice in Thailand are given in Table 2.3.

2.6 Estimated Quantity of Residues Available

The estimated quantities of residues available in Canada, Manitoba and Crop Distric No. 3 were determined by using grain to straw ratios and are shown in Tables 2.5, 2.6 and 2.7 respectively. A summary of the amount of residue for each cereal crop is shown in Table 2.8. An estimate of the total quantity of residues available in Canada follows:

	Estimated Quantity of Residue	
	(10^9 lb)	(10^9 kg)
Canada	99.0	44.9
Manitoba	12.3	5.6
Crop Distric No. 3	1.9	0.9

The total cereal crop residue in Manitoba is about 12.4% of that in Canada, while the residue in Crop District No. 3 is about 15.4% of that in Manitoba.

2.7 Discussion and Conclusions

The quantity of residues shown in the proceeding section is the potential quantity of residues derived from the average total production in Canada and Manitoba for 1968 to 1970. However, not all of the potential quantity of residues may be collected for converting into useful energy. Downing (12) estimated that "half of the residue is returned to the soil for the maintenance of the humus content and that straw is used for bedding at the rate of one-half ton/cattle unit housed".

Thus the net quantity of residues available will probably be about half of the potential quantity of residues. Therefore, in the determination of energy available, this factor should be taken into consideration.

TABLE 2.1

Weights per Bushel for Principle Cereals[1]

Cereals	lb/bu
Wheat	60
Barley	48
Oats	32
Rye	56
Corn	56
Paddy (rough rice)	45

[1] Grain Crops, London: The Commonwealth Secretariat, 1972, p. v.

TABLE 2.2

Acreage, Yields, and Production of Cereal Crops in Canada[1], Manitoba[2], and Crop District No. 3 of Manitoba[2] for the Period 1968-1970

No.	Cereal	Area[3] in 1000 Acres			Yield in bushel/acre			Production[3] in 1000 bushels		
		Canada	Manitoba	District 3	Canada	Manitoba	District 3	Canada	Manitoba	District 3
1.	Wheat									
	1968	29,422	3,400	595	22.1	26.8	27.3	649,844	91,000	16,216
	1969	24,968	2,500	395	27.4	25.6	18.5	684,276	64,000	7,309
	1970	12,484	1,400	297	26.6	21.8	19.4	331,519	30,500	5,774
	Average	22,291	2,433	429	25.4	24.7	21.7	555,213	61,833	9,766
2.	Oats									
	1968	7,556	1,580	320	48.0	51.3	55.1	362,516	81,000	17,627
	1969	7,655	1,530	291	48.5	45.1	38.6	371,387	69,000	11,238
	1970	7,149	1,260	203	51.5	42.1	39.1	367,850	53,000	7,933
	Average	7,453	1,457	271	49.3	46.2	44.3	367,251	67,667	12,266
3.	Barley									
	1968	8,836	1,170	211	36.8	36.8	35.7	325,373	43,000	7,542
	1969	9,535	1,200	217	39.7	35.0	25.9	378,383	42,000	5,625
	1970	10,043	1,500	275	41.4	34.0	29.8	415,704	51,000	8,191
	Average	9,471	1,290	234	39.3	35.3	30.5	373,153	45,333	7,119
4.	Rye									
	1968	679	120	*	19.2	20.8	*	13,019	2,500	*
	1969	927	183	*	17.8	18.3	**	16,493	3,358	*
	1970	1,015	194	*	22.1	21.5	*	22,427	4,177	*
	Average	874	166	*	19.7	20.2	*	17,313	3,345	*
5.	Grain corn									
	1968	958	2.5	*	84.7	40.0	*	81,168	100	*
	1969	978	3.0	*	75.1	33.3	*	73,426	100	*
	1970	1,197	3.5	*	84.3	50.0	*	100,925	175	*
	Average	1,044	3.0	*	81.4	41.1	*	85,173	125	*

[1]1971 and 1972 Canada Yearbooks, Statistics Canada
[2]1968, 1969 and 1970 Yearbooks of Manitoba Agriculture
[3]Rounded figures are used
*No data available

TABLE 2.3

Acreage, Yields and Production of Cereal Crops in Thailand[1]

for the period 1968-1970

No.	Cereal	Area[2] in (1000)		Yield			Production[2] in (1000)		
		Rais	Acres	kg/rai	lb/acre	bu/acre	kg	lb	bu
1.	Rice								
	1968	39,602	15,841	261	1,438.1	32.2	10,336,122	22,780,942	506,912
	1969	45,285	18,114	295	1,625.5	36.1	13,359,075	29,444,307	653,915
	1970	44,569	17,828	300	1,653.0	36.7	13,370,700	29,469,684	654,288
	Average	43,152	17,261	285	1,572.2	34.9	12,355,299	27,231,644	605,038

[1] Rice Department for 1968
Agricultural Extension Department for 1969, 1970

[2] Rounded figures are used

1 Acre = 2.5 Rais
1 kg = 2.204 lb
1 bu (of paddy) = 45 lb

TABLE 2.4

A Summary of Acreage, Yields, and Production of Cereal Crops in Canada and Thailand

No.	Cereal	Area in 1000 acres			Yield in bushel/acre			Production in 1000 bushels		
		Canada	Manitoba	District 3	Canada	Manitoba	District 3	Canada	Manitoba	District 3
1.	Wheat	22,291	2,433	429	25.4	24.7	21.7	555,213	61,833	9,766
2.	Oats	7,453	1,457	271	49.3	46.2	44.3	367,251	67,667	12,266
3.	Barley	9,471	1,290	234	39.3	35.3	30.5	373,153	45,333	7,119
4.	Rye	874	166	*	19.7	20.2	*	17,313	3,345	*
5.	Grain corn	1,044	3	*	81.4	41.1	*	85,173	125	*
		Thailand	-	-	Thailand	-	-	Thailand	-	-
6.	Rice	17,261	-	-	34.9	-	-	605,083	-	-

* not available

TABLE 2.5

The Quantity of Cereal Crop Residues Available in Canada and Thailand

No.	Description	Unit	Cereal Crops					
			Wheat[1]	Oats[1]	Barley[1]	Rye[1]	Grain Corn[1]	Rice[2]
1.	Acreage	10^3 acres	22,291	7,453	9,471	874	1,044	17,261
2.	Yield (by volume)	bu/acre	25.4	49.3	39.3	19.7	81.4	34.9
3.	Production	10^3 bu	555,213	367,251	373,153	17,313	85,173	605,038
4.	Weight/bushel	lb/bu	60	32	48	56	56	45
5.	Grain: straw ratio	lb/lb	1:1.5	1:2	1:1	1:2	1:1	1:1.8
6.	Yield (by weight)	lb/acre	1,524.0	1,577.6	1,886.4	1,103.2	4,558.4	1,572.2*
7.	Straw per unit area	lb/acre	2,286.0	3,155.2	1,866.4	2,206.4	4,558.4	2,830.0
8.	Total amount of straw	10^6 lb	50,957.2	23,515.7	17,866.1	1,928.4	4,759.0	48,848.6

[1]Cereal crops in Canada (excluding Newfoundland)

[2]Cereal crops in Thailand

*Figure from Table 2.3

TABLE 2.6

The Quantity of Cereal Crop Residues Available in Manitoba

No.	Description	Unit	Cereal Crops					
			Wheat	Oats	Barley	Rye	Grain Corn	Rice
1.	Acreage	10^3 acres	2,433	1,457	1,290	166	3.0	*
2.	Yield (by volume)	bu/acre	24.7	46.2	35.3	20.2	41.1	*
3.	Production	10^3 bu	61,833	67,667	45,333	3,345	125	*
4.	Weight/bushel	lb/bu	60	32	48	56	56	*
5.	Grain: straw ratio	lb/lb	1:1.5	1:2	1:1	1:2	1:1	*
6.	Yield (by weight)	lb/acre	1,482.0	1,478.4	1,694.4	1,131.2	2,301.6	*
7.	Straw per unit area	lb/acre	2,223.0	2,956.8	1,694.4	2,262.4	2,301.6	*
8.	Total amount of straw	10^6 lb	5,408.6	4,308.1	2,185.8	375.6	6.9	*

* not available

TABLE 2.7

The Quantity of Cereal Crop Residues Available in Crop District No. 3 of Manitoba

No.	Description	Unit	Cereal Crops					
			Wheat	Oats	Barley	Rye	Grain Corn	Rice
1.	Acreage	10^3 acres	429	271	234	*	*	*
2.	Yield (by volume)	bu/acre	21.7	44.3	30.5	*	*	*
3.	Production	10^3 bu	9,766	12,266	7,119	*	*	*
4.	Weight/bushel	lb/bu	60	32	48	*	*	*
5.	Grain: straw ratio	lb/lb	1:1.5	1:2	1:1	*	*	*
6.	Yield by weight	lb/acre	1,302.0	1,417.6	1,464.0	*	*	*
7.	Straw per unit area	lb/acre	1,953.0	2,835.2	1,464.0	*	*	*
8.	Total amount of straw	10^6 lb	837.8	768.3	342.6	*	*	*

* not available

TABLE 2.8

A Summary of the Total Quantity of Cereal Crop Residues Available

No.	Cereal	Unit	Location		
			Canada	Manitoba	District 3
1.	Wheat	10^6 lb	50,957.2	5,408.6	837.8
2.	Oats	"	23,515.7	4,308.1	768.3
3.	Barley	"	17,866.1	2,185.8	342.6
4.	Rye	"	1,928.4	375.6	*
5.	Grain corn	"	4,759.0	6.9	*
	Total	"	99,026.4	12,285.0	1,948.7
			Thailand	-	-
6.	Rice	"	48,848.6	-	-

* not available

TABLE 2.9

Grain-Straw Ratio for Selected Rice Varieties[1]

Class	Variety	Grain-Straw Ratio
Highly nitrogen responsive	IR 8	1.15
	Chianung 242	1.14
	Taichung Native 1	1.20
	Tainan 3	1.23
	IR 5	0.95
	Mean	1.13
Low or negatively responsive to nitrogen	Hung	0.60
	Peta	0.60
	Nang Mong S_4*	0.49
	Puang Nahk 16*	0.40
	H-4	0.58
	Sigadis	0.69
	Mean	0.56

[1]Robert F. Chandler, Jr., International Rice Research Institute, Los Baños, Laguna, The Philippines.
*Varieties of rice in Thailand.