COMMERCIAL USES OF STRAW

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Summary

Straw is a lignocellulosic biomass material and can have many commercial uses for agricultural and industrial applications. Increasing environmental and public health concerns with conventional straw disposal methods, such as open-field burning, have made the alternative uses of straw attractive in many countries. Straw utilization must also allow for proper maintenance of soil organic matter and erosion control. The challenge is developing economically viable options that can produce and market straw products to offset the harvesting and processing costs. The extent of straw utilization is largely influenced by the local availability of competing feedstock sources for animals and biological conversion processes and prices of conventional fuels, such as coal and natural gas, for energy generation. The mostly developed uses of straw include:

- feeding animals,
- producing electrical power and heat via combustion and gasification,
- producing ethanol via microbial fermentation,
- producing methane via anaerobic digestion,
- growing mushrooms,
- manufacturing composite and paper products and building homes and other structures
- controlling soil erosion.

The technologies involved in these different uses vary from simple to very sophisticated. Among many uses, feeding ruminant animals is the most ancient and is now common in areas where there is a short supply of grains and other types of feed. Straw has also been used as cooking fuel, although in low efficiency and high polluting applications. Energy generation either through thermo-chemical conversion processes,

such as combustion, gasification, or pyrolysis, or biological conversion processes, such as ethanol fermentation or anaerobic digestion, has a potential of consuming a large quantity of straw. Technologies continue to be developed to improve the properties of straw and increase the energy yield of straw through physical, chemical, and/or biological means. Favorable local government policy to provide biomass power incentives and regulations directed at improving opportunities for renewable energy and reducing greenhouse gas emissions are usually necessary for increasing the use of straw for electrical power and fuel generation. Production of compost, mushrooms, single-cell protein, and other biological products using solid-state fermentation technologies will have a large impact on the use of straw as the market for such products expands and the biotechnology industry grows. Increase in the use of straw for building construction, paper product manufacturing, and environmental mitigation will be expected in the near future as the supply of conventional structural and fiber materials, such as wood, is dwindling in general throughout the world. Continuing efforts in developing new markets for straw products is important. Straw can become a valuable biomass resource if used properly. In many cases, production of more than one product from straw may be necessary to obtain favorable economics and sustainable operation.

1. Introduction

Straw is a lignocellulosic material produced as a byproduct from agricultural crop production. It is mainly composed of cellulose, hemicellulose, lignin, nitrogenous compounds, and ash. The exact composition of straw varies with the type and variety of straw. The growing, harvesting, and collection conditions can also affect the make-up of the straw. Generally speaking, straw contains about 35 to 50% cellulose, 15 to 30% hemicellulose, 20 to 30% lignin, and lesser amounts of ash and other components.

Open-field burning is currently the most common and also perhaps the most polluting agronomic practice for straw disposal. This disposal technique, although inexpensive, rapid, and sometimes effective for weed, pest, and disease control in many grain crops, is a controversial practice in many areas of the world. The smoke and various gases including hydrocarbons that are emitted during open burning create public health concerns. The especially high emission rates of fine particulate matter and the consequent effects on visibility and perceived effects on health have been largely responsible for the increasing worldwide regulation or prohibition of agricultural crop residue burning. In many instances, soil incorporation of straw can be employed as a ready alternative. However, off-field utilization may be a preferred approach to limiting the impact of additional field operations, and higher biomass loading in soils, weeds, and diseases. In rice, for example, slow decomposition of straw in temperate soils and carry-over of weed seeds and fungal pathogens has been viewed as a disadvantage of shifting from open burning to soil incorporation of straw. Another disadvantage of soil incorporation of straw is increased methane emission that contributes to global climate change problems. The costs of straw harvest and removal tend to be higher ($60 to $250 per hectare in the United States) than open-field burning ($7 to $12 per hectare) and soil incorporation ($15 to $200 per hectare). However, straw incorporation in many instances is necessary for proper maintenance of soil organic matter and to protect the soil from erosion. Thus, utilization of straw has to be carefully managed and considered as part of the overall agronomic and environmental practice. The challenge for off-field uses where suitable is to develop economically viable options that can produce and market straw products to offset the harvesting and processing costs.

Straw is a valuable renewable biomass resource if used properly. There are many alternative uses of straw. The mostly developed commercial uses include feeding animals, producing electrical power and heat via combustion and gasification, producing ethanol via microbial fermentation, producing methane via anaerobic digestion, growing mushrooms, constructing buildings and manufacturing composite and paper products, and controlling soil erosion. The technologies involved in these different uses vary from simple to very sophisticated. This paper presents an overview of currently available technologies involved in preparing and processing straw for these commercial uses and identifies some future directions for further development.

2. Animal Feeding

Straw has the nutritional characteristics of being rich in energy, low in crude protein, and poor in palatability. It is generally considered to be poor-quality roughage that requires proper pretreatment or supplementation with other nutrients before it can be used as useful feed for ruminant livestock. If straw is used as the primary feed for animals, such as for the maintenance of animals, it must be supplemented with protein, phosphorus, calcium, and possibly certain trace minerals. The feed value of straw varies with the type, variety, and botanical parts of straw. More than half of straw consists of polysaccharides, such as cellulose and hemicellulose. Even though straw contains enough cellulose to make it an excellent source of dietary energy for ruminants, it is a poor-quality feed in its natural state because of low digestibility and protein content, poor palatability, and bulkiness. Major factors that have been identified to influence the biological digestibility of lignocellulosic materials include porosity (accessible surface areas), cellulose fiber crystallinity, lignin content, and hemicellulose content. Various pretreatment processes, including physical, chemical and biological, are available to increase the acceptability of straw to animals, thus increasing daily feed intake, and to enhance the rate and/or extent of digestion, thus increasing the availability of nutrients. These processes include mechanical (chopping, grinding, compressing); other physical (irradiation, heat extrusion); chemical (mainly sodium hydroxide and ammonia); and microbiological (bacterial and fungal). The effects of these pretreatment methods on improving the digestibility of straw are reviewed as follows.

2.1 Physical Treatment

The mechanical process is used mainly for comminution and/or densification of straw. The processes include chopping, grinding and shredding, milling, pelleting, and extrusion. The need for particle size reduction of straw as feed varies with the types of animals. Generally, chopping or grinding help increase the daily intake, especially with young animals, and improves the digestibility of straw. The appropriate particle sizes of straw depend on the type and age of animals. However, feeding diets based on finely milled roughage with or without concentrates can lead to digestive disorders. Effects of pelleting on the nutritive value of straw are not definitive in the literature, although pelleting can be used to good advantage in insuring intake of a complete ration blended prior to densification. Milling is generally considered to be inappropriate in practical animal production because of high processing costs as well as the fact that a high proportion of the extremely fine particles will pass through the rumen too fast without being sufficienly fermented. Feeding straw in the long or coarsely chopped forms is the most common practice at present, even though other processes have demonstrated positive effects.

Heat is often used in combination with other processes such as pelleting or chemical treatment. Heat treatment with steam under pressure, a process called steam explosion, is a highly effective process for increasing the straw digestibility and has received considerable attention for providing the pretreatment of straw and other lignocellulosic materials for biological conversion. It has been commercially used for biochemical production facilities (e.g. ethanol fermentation, see below). Steam explosion of straw for feed production is still under investigation. Irradiation by gamma rays or by high-velocity electrons has been found to be capable of improving the digestibility of straw. However, irradiation is an expensive technology and is not yet practical for commercial operations.

2.2 Chemical Treatment

Chemical treatment of straw is one of the most active areas of animal production research in recent years. The chemicals commonly used include sodium hydroxide (NaOH), calcium hydroxide (CaOH), and ammonia (NH_3). Alkali treatment has been well recognized as an effective method for upgrading the feed value of straw. Researchers believe that alkali treatment could cause saponification or ammoniation of intermolecular ester bonds, which promotes the swelling of fibers beyond water-swollen dimensions and therefore allows for increased enzyme and microbial penetration into the fine structure.

Sodium hydroxide (NaOH) treatment is the most prominent among these chemical treatments. Several treatment methods with NaOH are available. The Beckman process was widely used in the early century for upgrading the feed value of agricultural cellulosic wastes. This process involves soaking straw in a 1.5% NaOH solution at atmospheric temperature and pressure, after which the straw was drained and washed with water to remove alkali. This process was found to be highly effective in increasing the digestibility of straw. The treated straw showed about a two-fold increase in digestibility. However, this process has disadvantages in losses of up to 25% dry matter and use of large volumes of alkali solution and wash water, creating economic and wastewater disposal problems. To alleviate these problems, several dry caustic processes have been developed. With dry treatment methods, the excess alkali is not neutralized and the sodium is not removed before feeding. In-vitro digestibility tests showed that the dry matter digestibility of straw could be increased by about 40%. In practice, 2 to 10% NaOH in straw have been used for straw treatment. Higher pressure and temperature can help increase the effectiveness of treatment. It has been found that the digestibility of straw can be more than doubled upon coupling steam treatment with the addition of NaOH. There has been considerable interest in the use of alkali mixtures, especially NaOH and $Ca(OH)_2$, to reduce the level of sodium in the product.

Ammonia NH_3 is another common chemical used for straw treatment. A study reported that the optimum treatment was with 30% water and 5% ammonia in a closed container for 30 days at room temperature. Under these conditions, the digestibility increased from 29 to 63 percent. Ammonia level, treatment temperature and time all affect the treatment effectiveness. A minimum treatment time of three days at elevated temperatures was necessary to obtain the full value of ammoniation. Ammonia has also been applied with some success to straw on the baler during harvesting. Besides aqueous ammonia, urea and ammonia bicarbonate are other effective sources of ammonia for use in straw treatment. Recently ammonia treatment has been combined with heat treatment, such as steam treatment, to enhance effectiveness. Other chemicals that have been used for straw treatment include $NaClO_2$ and gaseous SO_2. At present, sodium hydroxide and ammonia treatment are considered to be the most effective chemical methods for improving the feed value of straw.

2.3 Biological Treatment

Lignolitic micro-organisms, including bacteria and fungi, and/or their enzymic products, can be used to break down the bonding structure between the polysaccharides (cellulose and hemicellulose) and lignin in the straw, extract and decompose the lignin so as to release polysaccharides and oligomers for better accessibility of ruminant microflora and improve the digestibility of straw. In some cases, reducing the hemicellulose in the straw through fungal treatment can increase the digestibility of cellulose.

The criteria for choosing micro-organisms for upgrading lignocellulosics, such as straw, require that such organisms should have a strong lignin metabolism with a low degradation of cellulose and hemicellulose, and rapid growth and high substrate-colonization ability, and should not produce any metabolites that are toxic to animals. White rot fungi have been widely studied by researchers for biologically upgrading the nutritional value of straw. The white rot fungi are a heterogeneous group of fungi that are capable of producing extracellular phenol oxidases for degrading lignin and are considered to be the only organisms present in nature that can degrade lignocellulosic materials to a substantial degree. Some strains of white rot fungi, such as white pocket rot fungi, are selective in degrading lignin, leaving considerable amounts of cellulose undegraded, and are the desirable fungi for bioconversion of straw to feed. The effectiveness of straw treatment with white rot fungi largely depends on strains of fungi used, type and quality of straw, and treatment conditions . In one study, one hundred and fifteen species with a total of 235 different strains were screened for treatment of wheat straw. Eighty-five species (115 strains) showed good growth, of which 13 species were found to have capacity of increasing the digestibility of wheat straw. Selection of effective strains needs to be based on the results of both laboratory tests and animal feeding trials. Temperature and duration of fermentation strongly influence the rate of lignin degradation. Some strains degrade lignin better at higher temperature and others at lower temperature but most strains grow well at around 30°C. The typical fermentation time varies from 30 to 60 days, depending on the strains used.

The composition and quality of straw is another important factor. Generally, leaves are more digestible than stems because leaves contain higher amounts of protein, cell solubles and lower cell wall compared to stem. However, rice straw differs considerably from other cereal straw, such as barley, wheat and oats in that it has a very high proportion of leaf-stem (60% vs. 40%) and the digestibility of the stem of rice straw is similar to that of leaf or higher than leaf due to a higher content of silica in leaves. Silica has been shown to inhibit digestibility by three percentage units for every one-unit increase in silica content.

Solid-state fermentation is used to grow fungi on straw under controlled environmental conditions with the aim of producing a predictable and high quality feed product. Fungal treatment of straw usually consists of four steps: preparation and pretreatment of straw, inoculation of straw with desired fungi, fermentation and product harvesting. In addition to the types of straw and fungal strains, temperature and duration of fermentation, other factors controlling the course of solid-state fermentation include substrate pretreatment, nutrient (nitrogen) supplementation, oxygen supply to the substrate, and carbon dioxide concentration in the gaseous phase. The nitrogen content of straw is generally below the optimal levels for fungal growth. Substrate pretreatment mainly refers to the sterilization of straw to suppress the growth of indigenous micro-organisms prior to the inoculation of desired fungi strains. Heat or chemicals can be used to provide pretreatment. Fungal treatment of straw for feed value improvement still remains experimental. Large-scale fungal fermentation processes are yet to be developed.

3. Electrical Power and Fuel Generation

The total world production of straw from four principal cereals (barley, corn, rice, and wheat) of approximately 3×10^{12} kg y^{-1} represents a potential electrical power generation of 2.5×10^{15} Wh y^{-1} or an average power generation of 290 GW. This compares with the world total electrical power production of 13×10^{15} Wh y^{-1} from a global generating capacity of 3074 GW and average generation rate of 1500 GW. In practice, energy recovery from straw is likely to be only a small fraction of total potential and not all commercial energy would be recovered as electricity. Seasonality of straw production would also lead to variations in generation rates unless large-scale storage is employed. Straw is burned mainly in developing countries as cooking and heating fuel and for small industries. These are mostly low efficiency, high polluting combustion applications. Use of straw as fuel for power plants has been developed in Europe, particularly Denmark, and is under active investigation elsewhere, but technical constraints and economic considerations have so far prevented widespread use of straw in direct combustion and gasification applications for heat or power generation. Technical and economic constraints have also limited the use of straw in biological conversion technologies, such as ethanol and methane production.”. Competing feedstock sources and low prices of natural gas in most countries make use of straw less appealing. Favorable local government policy to provide biomass power incentives and regulations directed at improving opportunities for renewable energy and reducing greenhouse gas emissions are usually necessary for increasing the use of straw for power and fuel generation. The technologies currently available for converting straw into power and fuel include combustion, gasification, ethanol fermentation, or anaerobic digestion as outlined below.

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Biographical Sketches

Ruihong Zhang teaches and conducts research in the area of agricultural and food waste management and environmental engineering of biological systems. Her research focus areas include treatment and processing of agricultural and food wastes for environmental pollution prevention and resource utilization, air quality control for animal and human environments, development of biological, physical, and chemical processing techniques for organic waste conversion and nutrient management, and control of gaseous and particulate emissions from animal feedlots and food processing facilities. Professor Zhang teaches both undergraduate and graduate courses in Bioenvironmental Engineering. She is a member of several professional societies, including American Society of Agricultural Engineers (ASAE) and American Society of Woman Engineers (ASWE).

Bryan M. Jenkins teaches and performs research in the areas of energy and power, with emphasis on renewable fuels, especially biomass. Research is focused on thermal conversion of biomass for the production of heat, power, and fuels, including both combustion and thermal gasification processes. Work includes studies of inorganic transformations during thermal conversion, emissions from controlled and uncontrolled biomass burning, and system studies for optimal plant design. Prof. Jenkins teaches both graduate and undergraduate courses on energy systems and power and energy conversion, including sections on renewable fuels, system analysis and optimization, fuel cells, engines, electric machines, fluid power, cogeneration, and other technologies. Professor Jenkins was recently presented an Outstanding Achievement Award by the US Department of Energy for exceptional contributions to the development of bioenergy.