Linking Energy Crop Production to Conversion : The Case of Herbaceous Lignocellulosic Crops to Ethanol[1]

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ABSTRACT

Herbaceous energy crops represent an opportunity to supplement fuel supplies and, most importantly, liquid transportation fuels. While corn grain is currently the best feedstock for ethanol in the United States, in the long run lignocellulosic crops are a better choice. Lignocellulosic crops are composed primarily of cellulose, hemicellulose, nonstructural carbohydrates, lignin, protein, and ash. Lignocellulosic crop characteristics, such as whether they are annual or perennial, summer or winter, thick or thin stemmed, their degree of stress tolerance, and their specific chemical composition, are important factors affecting the production, transportation, and conversion processes used to produce ethanol.

INTRODUCTION

The current rate of fossil fuel use could result in shortages and/or higher prices of oil and natural gas as soon as the 1990s. To mitigate the effects of liquid and gaseous fuel shortages and/or price rises, development of alternative ways to produce these fuels would be prudent. Agriculture in the developed world has the ability to supply more food than is required, and this has resulted in the need for subsidies to support the farm economy. Many energy products, including ethanol, electricity, steam, heat, synthetic natural gas, and diesel fuel, can be produced from crops and crop residues. Energy markets are large and can readily absorb much energy crop production. But energy will only be produced from agricultural products if it can be sold at prices competitive with conventional fuels like oil, natural gas, coal, and electricity and can provide producers of energy crops with adequate returns. In the United States, the use of agricultural products for energy is limited to a few special cases. Currently, the only well-developed biomass energy industry ferments the starch in corn *(Zea mays)* to ethanol. Also, some residues and wastes, such as sugar cane *(Saccharum officinarum)* bagasse, are burned to generate steam and electricity.

Energy crops are a long-term solution to agricultural problems in the United States, with the potential to diversify agricultural product markets, improve the profitability of agriculture, and reduce soil erosion. Using crops for energy is possible with existing technology, but few uses are economically feasible today. Crops, cropping systems, and the technologies for turning agricultural commodities into energy all require further development to improve their competitiveness with fossil fuels.

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The United States Department of Energy has recognized this and is funding research on producing energy crops and on converting them to energy [1-4].

The choice of crop type (i.e. sugar, grain, forage, oilseed, hydrocarbon) to grow for energy depends upon many factors, including the choice of available technologies for converting the crop into energy and the type of energy desired. Over 60% of the use of petroleum products in the United States is accounted for by transportation. Substitutes are not readily available for these transportation fuels; thus, the transportation sector is greatly affected by supply disruptions or oil price changes. Because of these factors, plus the fact that liquid fuels are relatively expensive fuels, the conversion of energy crops to a liquid fuel, ethanol, will be the focus of this paper.

BACKGROUND

Crops are composed primarily of carbohydrates, lignin, protein, ash (inorganics), and vegetable oil. Carbohydrates can be divided into nonstructural (i.e., contained within the cell) -- sugar and starch -- and structural (i.e., part of the cell wall) -- cellulose and hemicellulose. Starch is a polymer of six-carbon sugars which is easily broken down (hydrolyzed) into the simple six-carbon sugar glucose. Cellulose is also a polymer of the six-carbon sugar glucose but is more difficult than starch to hydrolyze. Hemicellulose is a polymer of mostly five- but also some six-carbon sugars and is easier than cellulose but harder than starch to hydrolyze. For energy purposes the carbohydrates, lignin, and vegetable oil are of primary interest. In the ethanol production process, it is the carbohydrates that are converted into ethanol.

In the United States, the best crop to use as an ethanol feedstock is currently corn. Corn and other grains are primarily starch. Using available commercial conversion technology, about 387 l/mg of ethanol can be obtained from corn (or about 2.3 kg of dry matter per litre of ethanol), and with an improvement in technology to allow the hemicellulosic portion also to be converted efficiently to ethanol, close to 447 l/mg of ethanol can be obtained from corn (or about 2.0 kg or dry matter per litre of ethanol). Even during the early 1980s when energy prices were much higher than at present, ethanol from corn was economically viable only with government subsidies. There are opportunities to reduce the costs of water removal during the conversion process, but given the relatively high cost of corn as an ethanol feedstock, only a marginal decrease in the cost of producing ethanol from corn is possible.

In the longer run, forage-type crops, specifically grasses, appear to be better choices than grains for ethanol production. These crops are referred to in this paper as lignocellulosic crops, because they are made up primarily of cellulose, hemicellulose, and lignin.The focus is on grasses because they appear to be a better choice than legumes as an energy crop because of their higher yield potential and higher carbohydrate fraction. The advantage of lignocellulosic crops over grains such as corn lies in their relatively low delivered cost (production plus transportation), estimated to be US$33 to US$44 per dry megagram in the year 2000, to a conversion facility [1]. The delivered cost of corn is in the range US$65 to US$110 per dry megagram, although the lower end of this range represents the currently depressed price for corn, which is low by historical standards. Although lignocellulosic crops have a significant cost advantage on a per unit mass basis over grain crops, the conversion technology to take advantage of this price differential (i.e., to convert the cellulosic and hemicellulosic components efficiently into ethanol) is still being developed. There are, however, many considerations that must be taken into account to effectively integrate the energy crop production-transportation-conversion system and allow for competitively priced ethanol from lignocellulosic crops.

CHARACTERISTICS OF LIGNOCELLULOSIC CROPS

A number of characteristics of lignocellulosic crops are important for the production, transportation, and conversion processes and, ultimately, to the production of a competitively priced fuel. Species may be annual or perennial, summer or winter, thick or thin stemmed, have varying chemical composition, and have varying tolerances to wetness or drought.

Land and climatic characteristics have a large impact on the choice of appropriate species. For large-scale production of energy crops, large farmland areas with adequate rainfall are required.

Much farmable land is characterized by potential erosion problems from either water or wind. Depending upon the severity of the problem, it may not be feasible to till some land annually. On this type of land it is desirable to grow perennial crops because they protect the soil from erosion. Also, perennial crops are more suitable than annual crops for land characterized by wetness because they have fewer machinery needs, a result of infrequent establishment and low weed control.

There are two basic harvesting-handling systems for lignocellulosic crops: high moisture (e.g., silage, 40-80% moisture content) and low moisture (e.g., hay, 10-20% moisture content). A potential advantage of the low-moisture system is its low transportation cost relative to the high-moisture system [to move 1 kg of dry matter at 10% moisture (or 1.11 kg on a wet basis) versus 1 kg of dry matter at 70% moisture (or 3.33 kg on a wet basis) requires that only one-third as much matter be moved for the same amount of usable energy]. Thin-stemmed species [e.g., switchgrass *(Panicum virgatum)*, bermudagrass *(Cynodon dactylon)*, reed canarygrass *(Phalaris arundinacea)*, weeping lovegrass *(Eragrostis curvula)*] are amenable to field drying to a low moisture content and are currently harvested as hay in conventional forage systems. In regions with high labour costs, large, round bales appear to be the best low-moisture system because of their low labour requirements and ability to be stored outside, although there may be an advantage in providing some type of inexpensive cover for the bales, such as plastic, to reduce storage losses. During harvest and storage it is primarily the nonstructural carbohydrates that are lost. The cellulose and hemicellulose are unaffected during drying. Leaf shatter can be a major source of dry matter loss during harvesting. Because leaves are relatively high in nonstructural carbohydrates, losses of nonstructural carbohydrates are greater than those of cellulose and hemicellulose during harvesting [5].

Thick-stemmed species [e.g., sweet sorghum and forage sorghum *(Sorghum bicolor)*, sorghum × sudangrass *(S. bicolor × S. sudanensis)*, napier grass *(Pennisetum purpureum)*, kale *(Brassica oleracial)*] may require a high-moisture system because they are difficult to field dry to a low moisture content, and artificial drying is too expensive for a low-cost bulk commodity such as biomass energy. If ensilage is used, low-cost ensiling methods such as trench, bunker, or stack silos must be used. However, storage losses can be high for these methods, from 18 to 34% for six months of storage [6]. During the ensiling process, the ensiled material undergoes changes. In the fermentation stage of ensiling, nonstructural carbohydrates are fermented and some hemicellulose, 10 to 55%, is hydrolyzed providing mainly five carbon sugars which are then fermented. Fermentation in ensiling produces mainly lactic and acetic acid. Cellulose is relatively unaffected by the ensiling process. The acid produced by fermentation lowers the pH until finally the pH is low enough for bacterial action to stop and a stable storage environment is provided. The buffering action of the protein in lignocellulosic crops resists the lowering of pH. However, lignocellulosic energy crops would not be high in protein. A low nonstructural carbohydrate content may mean that insufficient sugars are available for fermentation and thus there may be problems creating a stable storage environment [5]. Based on our interpretation of the information presented in references [5,7,8] and the need for low-cost bulk storage, a crop is best stored with a cover in a trench, bunker, or stack silo and at about 70% moisture. Data presented in ref. [8] indicate that dry matter losses will be 13% for covered trench, bunker, or stack silo. Some carbohydrates will be lost to lactic and acetic acids, but the addition of acids to lower the pH, instead of allowing fermentation to produce acids to lower the pH, would reduce this loss.

Coble and Egg [9] discuss the ensilage of sorghum for the production of methane by anaerobic digestion. They indicate that ensilage can also be used for ethanol production if enzymes or yeasts are added. The added yeasts and enzymes allow the sugars that are converted into lactic and acetic acids under normal ensilage conditions to be converted into ethanol instead.

A possible alternative to ensilage for thick-stemmed species would be to (1) use a crushing or crimping device to speed drying and reduce moisture to a low enough level, or (2) allow the crop to dry on the stalk and then be harvested so that the crop may be baled and stored as large, round bales of hay.

If there are economies of scale in biomass conversion facilities, low-moisture harvest-handling systems, because of their lower transportation costs, can be used to better exploit these economies of scale. This advantage, though, may be somewhat offset by the higher yields that have been found in currently ongoing research with some of the thick-stemmed species, in particular sweet sorghum, although some of the thin-stemmed perennial species have not had the opportunity take advantage of well-established stands [1].

Most lignocellulosic crops are grown during the summer and harvested in late summer or early fall. However, a conversion facility needs to run year-round to be most economical. Year-round operation makes growing winter crops on a double-crop basis or growing cool-season perennial grasses for harvest during the spring attractive options.

Growing both winter and summer crops has several advantages. By growing winter crops, the time during the year in which fresh supplies are available for conversion is lengthened, and storage requirements are reduced. If a winter crop can be double cropped with a summer crop (this largely depends on a long enough growing season and the availability of adequate moisture), the winter cover produced will reduce soil erosion and improve the economics of energy crop production by utilizing factors of production that would otherwise be unused during the winter (e.g., land, machinery). Winter cropping also allows a greater quantity of biomass to be supplied within a fixed distance from a conversion facility, thus reducing average transportation costs.

For perennial crops, harvesting and fertilizer are two of the largest costs, while for annual crops, planting costs, in addition to harvesting and fertilizer, are important. In regions where land rents are relatively high, land cost can be a significant fraction of total costs. Research with some species, such as bermudagrass [10] and sorghum × sudangrass [11, 12], indicates that substantial yield gains can be achieved if the grass is cut less frequently than one would for optimal forage production. One cut of sorghum × sudangrass gave 30% and 150% yield advantages in Virginia [11] and in Ohio [12] respectively, over two cuts of sorghum in a year (Fig. 1). In other regions, differences in growing season length may lead to higher yields with two cuts instead of one cut. Less frequent harvesting results in lower nutrient concentrations (e.g., nitrogen, phosphorus, potassium); therefore, less replacement fertilizer is required for each tonne of crop harvested. Less frequent harvesting also results in lower per tonne labour and machinery requirements. Without feed-quality constraints, harvest scheduling for energy crops can be more flexible than for forages for livestock feed, making it easier to avoid scheduling problems related to weather, labour, and machinery. It may also be possible to use a piece of harvest machinery on more hectares by spreading out harvesting over time, thus increasing machinery utilization. There are, however, limits to how infrequently a crop should be harvested. At some point, plants stop accumulating dry matter and shift dry matter from leaves and stems to seeds. For energy crop production, it is more advantageous to continue to accumulate biomass, in particular carbohydrates, than to have the shift in dry matter occur.

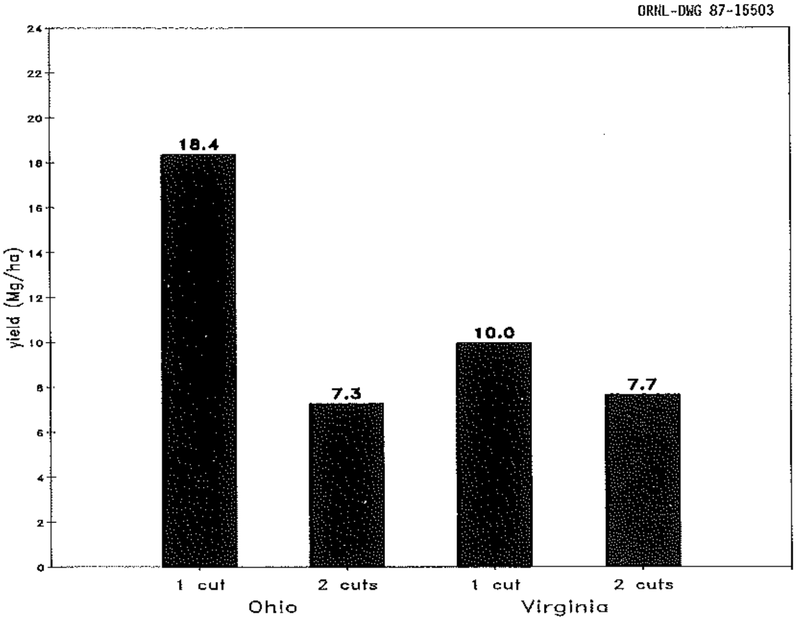

Fig. 1. One cut yields more than two cuts per year of sorghum × sudangrass.

COMPOSITION OF LIGNOCELLULOSIC CROPS

The objectives of growing forage crops for energy as opposed to livestock feed are different. The carbohydrate fraction is of primary interest when the intended use is conversion to ethanol. Residual lignin can be (1) burned to provide energy for the conversion process, (2) burned and used to generate electricity, (3) converted to chemicals, or (4) with advances in research, possibly made into a useful liquid fuel. High protein, mineral, and vitamin content, which are important for livestock feed, are not needed for energy purposes, and, in fact, minimizing their value as energy is even less than that for livestock feed. Crops produced for energy must be managed differently from those produced for livestock feed, even if the same species is used for both purposes.

The chemical composition of the energy crop being processed at a conversion facility can have a great impact on the economics of the conversion process. While gains can be made in reducing the cost of producing energy crops, it also seems possible (as has been done with forage crops for livestock feed [13,14]) to optimize the composition of the energy crop for a particular conversion process. This is one of the paths upon which research has focused in the production of methane gas from napier grass and sorghum in Florida and Texas [15].

A diagram of one possible configuration of an ethanol facility is shown in Fig. 2. This configuration is adapted from Fig. 5 in ref. [16]. After a discussion with the author of ref. [16] the figure was modified so that cellulose hydrolysis and fermentation are combined [simultaneous saccharification and fermentation (SSF)], and the output of the xylose fermentation step is combined with the cellulose stream before the SSF step, not the distillation step, and thus reflects a more efficient ethanol plant configuration. The delivered feedstock is reduced in size and is then subjected to pretreatment (sometimes called prehydrolysis) in which the lignin-hemicellulose structure is broken down, the lignin is separated, and the hemicellulose and nonstructural carbohydrates are hydrolyzed (i.e., the

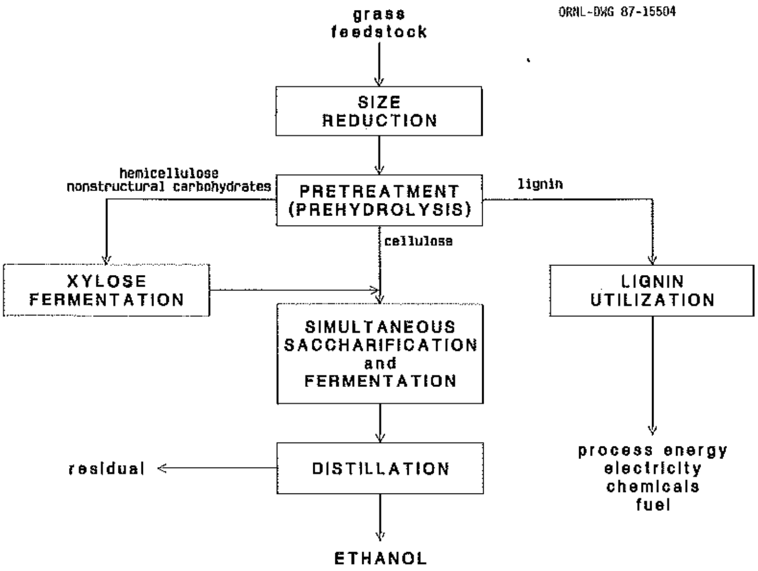

Fig. 2. The conversion of a grass feedstock into ethanol (adapted from Fig. 5, ref. [15]).

polymers of sugars broken down). The xylose in the hemicellulose/nonstructural carbohydrate fraction is fermented to ethanol, and the ethanol from the xylose and the residual, containing some glucose, sucrose, fructose, and other carbohydrates, is fed into the SSF stage. The cellulose that remains after the pretreatment stage is enzymatically hydrolyzed in the SSF stage to yield glucose. The glucose from the hemicellulose/nonstructural carbohydrate stream and from the cellulose is fermented simultaneously as the cellulose is being hydrolyzed. The ethanol is distilled off, and a residual consisting of nonfermented carbohydrates, other organic material, ash, and protein remains. This residual can be subjected to anaerobic digestion to clean up the organic matter, turning it into methane gas.

The chemical composition data presented in the text that follows come from research on energy cropping being conducted at Purdue University [17]. The data presented are for grasses, which have a quite different chemical composition than legumes. Average composition data for sweet sorghum, which is high in nonstructural carbohydrates (both sugar and starch), and switchgrass, which is low in nonstructural carbohydrates, are presented in Fig. 3. Currently available fermentation technology works well for nonstructural carbohydrates, but these make up less than 25% of grasses (on a dry matter basis) and are more typically less than 10%. To make use of the cellulose and hemicellulose, they must be hydrolyzed, either with acids or enzymes, prior to fermentation to ethanol. Cellulose can also be fermented with present commercial technology, but the hydrolysis of cellulose is not as efficient as for nonstructural carbohydrates. Cellulose makes up from 24 to 36% of grasses. The five-carbon sugar xylose in the hemicellulose can be fermented, although not as efficiently as glucose, but efficiency can be expected to increase as research continues [18]. Hemicellulose makes up between 20 and 34% of grasses, and in some cases hemicellulose is more abundant than cellulose.

Lignin makes up between 5 and 10% of grasses. Although it impedes the conversion process, lignin might prove to be a source of chemicals or liquid fuel. At present, in the ethanol production process, lignin appears best suited for combustion for heat or electricity production. Inorganics constitute about 10% of the dry matter of grasses, and, while small quantities may be useful for ethanol

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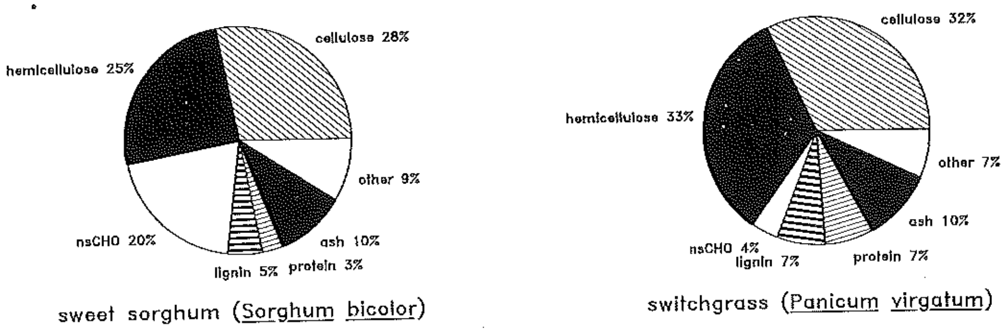

nsCHO = nonstructural carbohydrates

Fig. 3. The approximate composition of sweet sorghum *(Sorghum bicolor)* and switchgrass *(Panicum virgatum)*.

production, they are not useful as ethanol feedstocks, and their accumulation in lignocellulose is best minimized. Some inorganics, such as calcium (if acid is used for hydrolysis), can inhibit the hydrolysis process. Inorganics are best returned to the ground where they can be utilized as nutrients for plant growth. Proteins are nitrogen compounds. In case of energy crops, as opposed to forage crops, protein accumulation should be minimized. Protein can be more than 20% of forage crops [19] but can be kept to less than 5% in mature grasses. Minimizing protein accumulation leads to better nitrogen fertilizer utilization, and nitrogen fertilizers are a major cost of crop production. Infrequent harvest helps minimize protein accumulation. Vegetable oil, at 2%, is only a minor component of lignocellulosic crops.

The outputs and energy flows of the ethanol conversion process depend upon the composition of the feedstock, the configuration of the conversion process, and the technology incorporated into the conversion process. Both energy crops and conversion technologies are still under development, and it is beyond the scope of this paper to propose an optimal combination of feedstock and conversion system or to discuss material and energy flows in detail for any given configuration. As an example, however, assume that switchgrass is the feedstock. This switchgrass has the composition indicated in Fig. 3, and the hemicellulose is 69% xylose and 13% glucose. Nonstructural carbohydrates are lost quickly once plant material is harvested, so assume that 50% of the nonstructural carbohydrates shown in Fig. 3 never reach the conversion system. Further assumptions for the conversion process, based on research results, include a dilute acid pretreatment that hydrolyzes 85% of the hemicellulose and 100% of the remaining nonstructural carbohydrates; an enzymatic hydrolysis process that hydrolyzes 90% of the cellulose during the SSF stage; xylose fermentation at 70% efficiency; glucose fermentation at 90% efficiency; 99.5% recovery of the ethanol by distillation; and burning of the lignin and unfermented carbohydrates to provide process energy. Energy in excess of process needs is used to generate electricity. Under these assumptions, all process energy needs are met and 310 litres of ethanol and 165 kWh of electricity are produced per Mg of dry feedstock. The process outputs could be changed by changes in either the feedstock composition or in the parameters of the conversion process. Over time, improvements in conversion efficiency as well as feedstock composition can be expected.

For ethanol production, the carbohydrate fraction of lignocellulose is of primary interest. For lignocellulosic fuel crops to be economic, all the carbohydrates -- cellulose, hemicellulose, and non-structural carbohydrates -- must be converted into fuel. From the above discussion, the generalization can be made that more carbohydrates and less of the other components are desirable. Within hemicellulose it would be best, from a conversion point of view, to minimize the number of sugars. From a systems point of view, it is unclear whether it is better to have more nonstructural carbohydrates, cellulose, or hemicellulose. What is optimal for ethanol production may not be optimal for other conversion processes. When contemplating the optimal feedstock composition, one must also consider how changes in composition affect crop production (e.g., yield effects, overwintering ability of perennials, lodging, and storage).

CONCLUSIONS

Energy crops represent an opportunity to diversify the energy resources of the United States and to provide insurance against the interruption of imported energy supplies. Energy crops also provide an alternative market for the output of the agricultural sector which can help provide for its long-term economic viability. Through the use of perennial and double crops, an opportunity also exists to reduce soil erosion significantly.

If lignocellulosic crops are to be used for energy, they must be produced at low cost, and the conversion process must be able to convert as much of the crop to energy as is feasible. Given these constraints, the use of inputs to the crop production process, in particular fertilizers and machinery, must be optimized while at the same time high yields must be achieved. The chemical composition of the crop and the conversion process must be optimized for each other. Harvest frequency should be minimized, from one to three times per year, depending upon a particular species' physiology, to allow low harvest costs, high yields, maximum accumulation of carbohydrates, and minimal accumulation of protein and ash. Minimal accumulation of protein and ash reduces the amount of fertilizers required and also reduces contaminants in the conversion process. Specific tailoring of a crop, through breeding, to a specific conversion process will allow for the most efficient conversion of the crop. No one species will be best because of variances in growing conditions as well as the need to provide year-round supplies of crops to a conversion facility. Much progress has been made in improving forages produced for livestock feed and in the livestock converting the forages into meat and dairy products. It should be possible to duplicate this success in the effort to produce competitively priced energy products from forage lignocellulosic crops.

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