PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

EEC Resources and Strategies [and Discussion]

J. Coombs, J. M. Lynch, J. F. Levy and J. A. Gascoigne

Phil. Trans. R. Soc. Lond. A 1987 **321**, 405-422
doi: 10.1098/rsta.1987.0019

Phil. Trans. R. Soc. Lond. A **321**, 405–422 (1987)
Printed in Great Britain

EEC resources and strategies

BY J. COOMBS
BABA Ltd, P.O. Box 7, Southend, Reading RG7 6AZ, U.K.

In common with those of other regions, the major wastes of the European Community (EC) that may be regarded as potential sources of lignocellulose are animal manures, crop and forestry residues, domestic and industrial solid wastes and waste paper. The availability reflects the agricultural policy under the Common Agricultural Policy (CAP) as well as the shortfall in timber production within the EC. Significant regional differences exist due to variations in climate and both agricultural and industrial practices. Of particular importance in future will be policy in respect of land use and/or steps taken to reduce agricultural surpluses.

1. INTRODUCTION

The overall theme of this Meeting is the utilization of lignocellulosic wastes. The aim of this paper is to indicate the various types of residual materials that could become available once conversion processes are perfected, as well as to consider those policies and the legislation that may affect future availability. The complex of cellulose, hemicellulose and lignin, referred to here as lignocellulosic wastes, is not of course a single substance with particular properties but differs widely in composition, size, ash content, water content, seasonal availability and so on.

Because of the diversity of materials that may be described as lignocellulosic wastes, some initial categorization will be attempted, followed by a brief consideration of their basic physical and chemical characteristics. In the first instance, the easiest way to classify such materials is to define where they came from. Such wastes will be derived from agriculture, horticulture, the production of fruit (viticulture, orchards, soft-fruit farms, etc.), forestry, the pulp and paper industry, the wood products industries, the fibre and textile industries, and from commerce and households as domestic solid wastes. Although each grouping contains many different types of materials, in reality each is dominated by only a few major types. For instance, the main products of agriculture will be manures and straws; from forests, bark and thinnings; from the wood industries, shavings, offcuts and sawdust; and from commerce and domestic sources paper and card will be the main products.

Availability of these materials may also be considered from a number of different viewpoints. These range from the initial potential to generate the product, reflecting photosynthetic activity, to a consideration of the amounts of feedstock available, at a commercially viable price, in a suitable form to be considered as the raw material for some conversion process.

The supply of lignocellulosic waste materials will be limited by land availability, choice of crops or forest system, and the efficiency with which the raw material is used for generation of the primary product of interest. In the area of end use, the materials will face competition from two directions. First, they must compete with alternative raw materials, such as oil, gas and coal; and second, the chosen use must represent a cost-effective alternative to other possible actions, which may range from doing nothing other than letting the residues rot in the field, through directed composting, to use as a fuel by direct or indirect combustion. At the same time, the very fact that these materials are classed as wastes can be misleading because there must always be a positive drive to improve efficiencies, by using raw materials in house rather than to face the costs of disposal. In other words, once a use is found for such materials they cease to be wastes and assume a commercial value.

At present, within the European Community (EC) as elsewhere, there is such a large surplus of wastes that to any one who wants to use them supply is not a problem. The main issue at present is to find economically viable routes for the utilization of these materials.

The economics of such use are largely determined by legislation and policy in respect of agricultural prices, tariffs and quotas on imports into the EC, e.g. the sugar and starch régimes, and regulations and controls (and particularly their enforcement) in relation to disposal of noxious or environmentally damaging wastes, or methods of waste disposal. In general, the greater the extent of restrictive legislation on disposal, the greater the negative value of the waste product, and hence the more competitive it becomes as a raw material. However, at present the current options for conversion would appear to be limited to composting, anaerobic digestion or combustion.

To widen the range of alternative processes to meet market needs will require considerable inputs to be made into a directed research programme. As discussed below, the EC has identified several specific lines of interest in this respect and is investing some six million ECU (European Currency Units) in further understanding of the biological breakdown of lignocellulose for the production of fermentation feedstocks. The U.S.A. and Japan have supported similar programmes on a larger scale. At present, in spite of the personal interest of a number of the contributors to this meeting, U.K. public-sector grant support for such research remains low, with Research Councils and groups such as the Biotechnology Unit of the Laboratory of the Government Chemist (Department of Trade and Industry) regarding studies on lignocellulose research as of little importance.

Because the limitations to the use of lignocellulose do not, in the foreseeable future, lie on the supply side, discussions will concentrate on major resources and on systems in which harvesting or collection is achieved as part of the overall process under consideration, rather than on those requiring an additional expenditure of energy. From this point of view, the most interesting materials in terms of potential use as raw material, in biologically based manufacturing processes, are straw, forest residues, waste from wood processing, and the paper and card found in domestic and commercial solid wastes. However, at the same time it must be borne in mind that biological degradation through both aerobic and anaerobic processes are of great importance in the decay or treatment of other wetter and more diffuse wastes, such as manures and green-vegetable matter. Hence, an understanding of the biology of these decay processes is of equal importance to an understanding of the biology of the commercial processes used in the production of chemicals (sugars, lignin, organic acids or alcohols) or fuels (ethanol or biogas).

2. Production base

Almost all lignocellulosic wastes have their origin in plant material. Hence, the total production can be defined in terms of the amount of material formed by photosynthesis within the EC during one year,† less that which is gainfully used in one way or another (Coombs

† Note that the historical data available for the EC vary as the number of member countries has increased. Where the basis is known, this is indicated by the addition in bracket of the number of countries at the time for which the data are applicable.

et al. 1983). In other words, it is a fraction of the total phytomass produced, which in turn can be defined as

$$P = IA\mathscr{E}f,$$

where P is the total phytomass formed, I is the total solar energy intercepted, A is the land area, $\mathscr{E}$ is the efficiency of photosynthesis and f is the fraction of the material harvested (the harvest index). Both the available land area and the level of incident radiation are finite factors that cannot be changed and set the basic level of overall productivity.

Land availability and land-use patterns

The total land area of the various member states of the EC is shown in table 1, which also indicates the current distribution of land used for crop production as compared with forest use.

This demonstrates the domination of France as the major agricultural and forest producer as far as the longer established members of the EC are concerned, as well as the impact on the established status quo resulting from the recent addition of Spain (in particular) and Portugal to the EC.

Table 1. The pattern of land use within the EC (Mha)

(FAO *Yearbook of agricultural production* (1984).)

	total	arable	forest
Belgium–Luxembourg	3.3	0.8	0.7
Denmark	4.3	2.6	0.5
France	54.7	17.4	14.6
Germany	24.9	7.4	7.3
Greece	13.1	2.9	2.6
Ireland	7.0	1.0	0.3
Italy	30.1	9.4	6.4
Netherlands	3.7	0.8	0.3
Portugal	9.2	2.9	3.6
Spain	50.5	15.6	15.6
United Kingdom	24.5	6.9	2.1

Photosynthetic potential

It is now fairly well established that the potential productivity of suitable irrigated and fertilized land, bearing a healthy crop, is proportional to the amount of intercepted light. Obviously, within Europe large differences occur in the level of solar irradiance experienced in any region throughout the year, as well as from one region to another with average mean values in the range 8–20 MJ m^{-2} d^{-1} and a mid-summer maximum of between 27 and 30 MJ m^{-2} d^{-1}. In theory at least, at 1% photosynthetic efficiency annual yields of dry mass of about 40 t ha^{-1} a^{-1} would be expected from crops that possess the C3 pathway of photosynthesis (where some losses occur due to photorespiration) and about twice this from C4 species. In practice, actual yields are significantly lower because of deficiencies in nutrition and availability of water, and attack by pests and disease.

Crop–species characteristics

With the tree species and main crops found in Europe (with the exception of maize) belonging to the group known as C3 species, photosynthetic efficiencies of between 1% and 2% are probably the maximum to be expected. Record crops of dry matter of over 30 t ha^{-1} have been reported for sugar beet and over 25 t ha^{-1} for wheat, and total production of most agricultural products have significantly increased within the EC over the last decade (see for instance the figures for wheat in table 2). This increase partly reflects increased area of planting but also the influence of breeding new varieties with a higher harvest index and higher yield of grain ha^{-1}. Further improvements in the amoint of grain harvested reflect increased technical inputs, including more fertilizer and a wider range of plant-protection chemicals. This has resulted in a linear increase in average yield of around 2.5 t ha^{-1} in 1945 to over 6.4 t ha^{-1} in 1983 (Rexen & Munk 1984).

Although this increase in yield has been associated in part with a decrease in harvest index (expressed as mass of grain over total crop mass) as discussed in more detail in §3, the net effect has also been a significant increase in straw production in the U.K. in particular.

In contrast, the productivity of many of Europe's wooded and forested areas, with the exception of softwood plantations, remains low with average increments of around 2–3 $m^3\ a^{-1}$ for broad-leaf species, but reaching 5–6 $m^3\ a^{-1}$ for softwood plantations.

3. Agricultural residues and wastes

The main classes of crops grown in the EC are cereals, roots and tubers, dry pulses and oilseeds (table 2). Of these, the main sources of usable residues are of course the cereals, with wheat and barley the major crops followed by maize. Grass and various forage legumes grown as pasture for production of hay or used for silage are not included because they will supply little material that can be regarded as wastes in this context. Although large quantities of other green waste arise, they are of less interest because first, they have a higher water content, and second, there are not (in general) mechanisms for their collection and storage on a large scale.

Table 2. The production levels of some of the major crops produced in the EC (Mt)

(FAO *Yearbook of agricultural production* (1984).)

	wheat		barley	beet	potatoes
	1974	1984	1984	1984	1984
Belgium–Luxembourg	0.9	1.3	0.9	5.7	1.7
Denmark	0.6	2.4	6.1	3.2	1.1
France	16.7	32.9	11.5	27.8	6.2
Germany	7.2	10.2	10.3	20.0	7.8
Greece	2.2	2.6	0.8	1.7	1.0
Ireland	0.2	0.7	1.6	1.7	1.0
Italy	9.6	10.0	1.6	11.2	2.6
Netherlands	0.7	1.1	0.2	7.0	6.7
Portugal	0.6	0.5	0.1	0.1	1.1
Spain	4.4	6.0	10.7	9.1	5.9
United Kingdom	5.1	14.9	10.9	8.6	7.4

Straw

It is relatively easy to determine the production of straw on the basis of the recorded figures for production of grain in each country. The ratio of grain to straw approximates to 1:1, but varies considerably from region to region, reflecting differences in climatic factors, varieties grown and the level at which blades are set on cutters. A more detailed analysis for the U.K., based on 1983, is shown in table 3.

Straw is both a resource and a major problem at present. About half of the straw produced

TABLE 3

(MAFF (1984).)

(*a*) Measured straw:grain ratios and estimated straw yields, England and Wales, 1983

cereal	straw:grain ratio	grain yield $t\ ha^{-1}$	straw yield $t\ ha^{-1}$
wheat	0.75	6.40	4.80
winter barley	0.70	5.67	3.97
spring barley	0.60	4.10	2.46
oats	0.65	4.59	2.98

(*b*) Estimated straw production and disposal, England and Wales, 1983 (Mt)

straw	wheat		barley		oats		total	
	Mt	%	Mt	%	Mt	%	Mt	%
baled	3.12	40	4.26	81	0.20	65	7.56	56
burned	4.60	58	0.96	18	0.04	15	5.62	42
incorporated	0.17	2	0.07	1	0	0	0.24	2
total	7.89	100	5.31	100	0.24	100	13.44	100

is burned in the fields, with associated risks due to fires which get out of control and smuts which are borne in the wind and smoke. The problem is so severe that attempts have been made to legislate for the prohibition of burning of straw in the field. Such surplus straw which is equivalent to 1% of U.K. energy requirements, probably represents the most easily utilizable agricultural waste as far as the U.K. and much of Europe is concerned.

A number of other crops have been suggested as possible future sources of fermentable raw materials. These include the Jerusalem artichoke and sweet sorghum, both of which could result in the production of large amounts of fibrous residues and hence contribute to the greater availability of lignocellulose.

4. Forest residues

The EC (12) has a total area under forests and woods of around 222 Mha distributed as shown in table 1. Of this, around 43 Mha can be regarded as proper closed forest (i.e. forest in which the high density of trees results in a canopy with few gaps). However, this is not sufficient to supply the Community with all its wood needs at costs that are competitive with imports. As a result, the EC is a net importer of wood and timber products as indicated by the annual balance of wood use (table 4).

Large amounts of forest products are generated during felling and trimming, debarking and sawing timber during harvest. Part of this is used as fuel. However, large amounts remain within the forest to decay, or are burned on site. Of this residual material, a volume equal to some 25% of the harvest yield should be collectable, indicating a resource of $20\text{–}30 \times 10^6\ m^3$.

TABLE 4. THE PRODUCTION, IMPORTATION AND RECYCLING OF WOOD AND PAPER FOR THE EC (12) (MILLIONS OF CUBIC METRES)

(Ollmann (1985).)

production	115.8
imports	10.0
recycled paper	34.6
exports	4.2
fuelwood	23.9

However, these figures are not as large as they might be, because of the high level of imports of partly processed wood into the Community (table 5). Obviously, if the level of demand stays constant or increases and is met to a greater extent by wood produced within the EC, the amount of by-products generated will also increase.

Table 5. Traded wood products EC (10) (millions of cubic metres)

(Ollmann (1985).)

	import	export
sawn wood	36.9	1.9
panels	10.9	1.4
pulp/waste paper	36.1	2.1
cardboard/paper	37.7	5.2
articles/furniture	4.0	2.7

The U.K. probably has the lowest per capita availability of wooded land area (2 Mha or 9% of the land area) of which 1.4 Mha is coniferous plantations and the remainder is broadleaved high forest and coppice. In addition, there are some 300000 ha of unproductive and scrub woodland. In 1982 some 4.5×10^6 m^3 of British-produced timber were delivered to the wood-processing industries. Of this 110000 m^3 were classified as fuelwood. Considerably less than 10% of the U.K. demand for forest products is met from home production (table 6).

Table 6. U.K. forest industry statistics (1981)

		wood products 10^3 m^3
softwood	total	7437
	imported	7131
	home grown	304
hardwood	total	1101
	imported	950
	home grown	151
pitwood	imported	1164
plywood	imported	509
chipboard	imported	597

The use of paper and pulp in the U.K. is as shown in table 7. This indicates that the U.K. is also dependent on imports for most of the paper and pulp used. Hence, possible lignocellulose wastes from the pulp industry are limited.

Table 7. The use of paper and pulp in the U.K. (thousands of cubic metres)

(CSO (1985).)

wood pulp	1205
waste paper	1834
homegrown pulpwood	479

5. Processing by-products

A wide range of vegetable processing, fruit canning, fermentation and other processes such as the production of vegetable oils generate significant local and seasonal amounts of wastes. However, these usually have disadvantages as feedstocks for any sophisticated process because

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

of their high water content, which makes storage difficult, and in many cases because of their high levels of phenolics, tannins and other secondary metabolites. In general, interest in the biological conversion of such materials is concerned more with the generation of useful products.

Processing of starch from grain does not produce large amounts of lignocellulose wastes, whereas the extraction of sugar from beet produces an approximately equal mass of dry pulp. However, much of this finds use as an animal feed.

Less seasonal and amenable to accumulation and storage are off-cuts and sawdust generated from the volume of raw-wood sawn logs.

6. Wastes from animal husbandry

Animal manures represent a very large source of lignocellulose wastes. Although the total amount of manure produced is not recorded, estimates have been made on the basis of the number of animals raised within the EC (table 8). Obviously, not all the manure is recoverable or needs to be disposed of, but because of the fact that many animals are housed, for part of the year at least, significant quantities require some form of disposal. This is true in particular for those types (cattle, pigs, horses and fowl) listed in table 8, but of much less significance in so far as sheep are concerned because they are seldom housed.

Table 8. Number of farm animals (millions) in the EEC (12) in 1984 (FAO (1984).)

	cattle	pigs	fowl	horses
Belgium–Luxembourg	3.2	5.3	28	0.04
Denmark	2.9	9.0	15	0.05
France	23.6	11.4	185	0.30
Germany	15.6	23.4	75	0.40
Greece	0.8	1.3	37	0.10
Ireland	6.8	1.1	9	0.07
Italy	9.1	9.2	111	0.30
Netherlands	5.5	11.0	90	0.06
Portugal	1.0	3.5	17	0.03
Spain	5.1	12.4	53	0.25
United Kingdom	13.2	8.3	121	0.16

The daily production of organic wastes from typical animals will be (in grams dry organic material) around 250 for pigs, 2500 for cattle, and 20 for an average mature hen (Palz & Chartier (eds) 1980). To these figures can be added the weight of bedding material, which is straw, wood chips or shredded paper. Because of the nature of their diet and digestive system, ruminants give rise to manures that contain high proportions of lignocellulose fibre, totalling over 200 Mt of solid waste annually within the EC. The level of generation of recoverable manure for the U.K. is shown in table 9.

Methods of treatment or disposal of such manures include lagooning followed by disposal to land, aerobic treatment in slurry pits, or to a lesser extent at present anaerobic digestion, which may include separation of the solids for composting before digestion of the liquid portion.

TABLE 9. PRODUCTION OF MANURES IN THE U.K. (DRY MASS/Mt a^{-1})

(ETSU (1984).)

source	mass
dairy cattle	2.67
beef cattle	1.99
pigs	0.98
laying hens	0.53

7. URBAN WASTES

Within the EC as a whole, the annual production of urban wastes is probably around 150 Mt of which about 75% comes from domestic sources. Typical rates of annual waste production may be around 300 kg per head of population with about 30% being paper. Within the U.K. the amount of domestic rubbish produced annually is over 20 Mt and another 36 Mt of solid waste come from commerce and industry.

Development of strategies for the recovery of paper, glass and non-ferrous metals has been slower in Britain than elsewhere in Europe, and most of the refuse goes to landfill sites in former clay quarries and sand and gravel pits. The landfill method has been preferred by local authorities and many private contractors as the cheapest way of getting rid of waste.

8. THE CHEMICAL RESOURCE

The value in processing lignocellulose lies in the possibility of generating monomers from its polymeric constitutents; cellulose, hemicellulose and lignin. Although the exact composition of lignocellulose varies with the sources, in general these compounds are present in approximately equal quantities (table 10).

TABLE 10. TYPICAL COMPOSITION OF POTENTIAL LIGNOCELLULOSIC FEEDSTOCKS (%)

	ash	lignin	cellulose	hemicellulose
softwood	1.7	27–30	35–40	25–30
hardwood	2.0	20–25	45–50	20–25
wheat straw	7.8	15	33	25
waste newspaper	trace	16	61	20

Cellulose

Cellulose molecules are unbranched chains of D-glucose linked by β-1–4 glycosidic bonds. The average number of glucose residues in a cellulose molecule is about 8000. The repeating unit in cellulose is a disaccharide of two glucose units known as cellobiose. Within the plant cell wall, the cellulose molecules are organized into structural units known as microfibrils, which consist of a large number of parallel cellulose chains generally arranged in the form of a crystalline lattice that has regions of less rigid structure and is enclosed by an amorphous region that includes varying amounts of hemicellulose. On hydrolysis by acid, assuming complete conversion and degradation, the only product will be glucose. In contrast, the use of various cellulases will result in glucose, cellobiose and higher oligosaccharides, depending on the source of the enzyme or enzymes.

Hemicellulose

The term hemicellulose, which is based on a historical misconception of the nature of these polysaccharides, is misleading because these compounds are not cellulose precursors as was first thought. They differ from cellulose in chemical composition and structural form. The hemicellulose may be divided into three groups on the basis of their chemical composition. These are the xylans, the mannans and the galactans.

The xylans include all those polysaccharides that are rich in D-xylose (a five-carbon sugar). In hardwoods, the most abundant xylan is a linear chain of xylose units, about 70% of which are acetylated. This type also occurs as a minor constituent in softwoods. Primary cell walls contain another type of xylan in which a backbone of glucose units bears branches of either single xylose units or short chains of fucose, galactose and xylose. The mannans are the main hemicelluloses of softwoods (coniferous woods). Hydrolysis of this type of mannan yields mannose, glucose and galactose in the ratio of 3:1:1. The galactans occur mainly in larches where they replace other types of hemicellulose yielding mainly galactose and some arabinose on hydrolysis.

Lignin

The term lignin covers a group of closely related high molecular mass polymers whose main building unit is a phenylpropane residue. On chemical hydrolysis, which is difficult, lignin will yield varying amounts of vanillin, hydroxybenzaldehyde and syringaldehyde. All three aldehydes occur in lignin from monocotyledons (e.g. cereals), whereas lignin from gymnosperms (firs, pines, etc.) yields mainly vanillin (with an annual commercial production of around 7500 t), and that from dicotyledons (hardwoods) yields both vanillin and syringaldehyde. Lignin could be incorporated into phenol-type polymers. However, the use of materials produced by present pulping routes is restricted by the low chemical activity of the lignin degradation products. It is possible that lignin produced from lignocellulosic residues as a by-product of glucose production by using enzymic methods for hydrolysis of cellulose would be more useful in this respect because less chemical degradation of the lignin would occur. Any such added value associated with the use of lignin would improve the economics of a cellulose-based process.

9. Lignocellulose use

If one is expecting to develop a new biotechnical process that will use such wastes, it is necessary to realize that it will have to compete with existing ways in which they are used or disposed of and, at the same time, will also compete with other non-biological uses as they develop. At present, very large quantities of lignocellulosic wastes are used or processed each year. The major routes of utilization are indicated in table 11, in which the various processes are grouped in two sections. The first column lists those processes that are based on a biological principle, whereas the second column lists non-biological processes.

At present, the greatest volume of such wastes is recycled back to carbon dioxide, through either natural decay or combustion. The former process is of particular importance in maintenance of soil fertility. An extension of this natural process lies in composting of wastes that can range from simple compost heaps in the garden to large-scale automated plants with mechanical shredding, forced air circulation and mechanical mixing.

Large amounts of such wastes are used as feed for ruminants, where again the breakdown

TABLE 11. CURRENT AND POSSIBLE FUTURE USES OR METHODS OF DISPOSAL OF LIGNOCELLULOSIC WASTES

biological processes	competing technologies
in situ decay†	combustion†
composting†	thermochemical conversion
landfill deposition†	catalytic liquefaction
animal feed and SCP	chemical hydrolysis
anaerobic digestion	pulping†
saccharification	reconstitution†

† Present major processes of lignocellulose use or disposal.

depends on the activity of a complex consortium of anaerobic bacteria and protozoa in the rumen. Similar bacteria are involved in the early stages of the degradation of lignocellulosic wastes in both landfill sites and purpose-built anaerobic digesters.

Although considerable research has been carried out on alternative methods of thermochemical treatment, including pyrolysis, gasification and catalytic liquefaction, at present direct combustion remains the major method used to dispose of those wastes with a water content of less than 40–45%, the major non-biological processes being reconstitution of sawdust and chips to form artifical board and the chemical pulping of lignocellulosic materials in paper production. Pulping is of particular interest in the present context because the various processes used all produce large amounts of dilute wastes.

Pulping

Within the EC the major raw material used to produce paper pulp is wood (table 12). However, around 200000 t of straw are used for this purpose. The total pulp production meets less than 50% of the Community's needs. However, only a small fraction of the pulping by-products are used for anything other than process fuel. This suggests that the outlets for by-products of cellulose hydrolysis processes are limited unless new uses can be found for the lignin and pentose sugar fractions.

TABLE 12. PRODUCTION OF PAPER PULP AND ASSOCIATED BY-PRODUCTS IN THE EC (10) (THOUSANDS OF TONNES PER ANNUM)

(Busch (1985).)

	production	consumption
wood pulp	3091	7645
lignin	1500	120
hemicellulose	1000	80
straw pulp	200	200

A large amount of partly degraded lignin is potentially available as lignin sulphonate, from acid sulphite processes, or as Kraft lignin from alkali processes. However, in general this material is used as a fuel in house. Within the EC such residues have been estimated to generate some 39000 TJ of energy annually, as compared with over 121000 TJ derived from this source in the Nordic countries. Lignin sulphonates are used to some extent as chelating agents, tanning agents, surfactants or as constituents of phenol-type resins. Such use would no doubt increase if better-quality lignin degradation products, such as might be produced as by-products of enzymic pulping or cellulose saccharification, were available.

10. Saccharification

A major objective of a considerable amount of research has been the development of methods for the production of a fermentable sugar stream from lignocellulose wastes. The objectives have been either to produce a glucose syrup for consumption or, more generally, to produce a liquid fermentation feed stream that could be used to synthesize bulk chemicals and/or fuel ethanol.

If such objectives are to be realized two requirements must be met. First, the fermentable product must be produced at a price at which it is competitive with the large surpluses of potential fermentation substrates that exist at present in the form of sucrose (beet sugar) and wheat. Second, a substantial market outlet must be found for the product to use a significant amount of the wastes.

As far as organic chemicals are concerned, lignocellulosic wastes could make a significant contribution to their production because over 75% of the organic chemicals manufactured are produced from five primary feedstocks: ethylene, propylene, benzene, toluene and xylene. These are used to produce a wide range of products, the major ones in terms of volume being polymers and resins together, in the U.K., amount to around 1.4 Mt annually. The aromatic compounds might be produced from lignin whereas the low molecular mass aliphatic compounds can be derived from ethanol produced by fermentation of sugar streams generated from the cellulose and/or hemicellulose fractions. However, the use of lignin as a chemical feedstock is unlikely to alter the general economics of large-scale cellulose saccharification plant. Apart from the technical aspects of developing cost-effective processes, the size of the potential chemical markets are relatively small. In the U.K., for instance, in 1984, the largest selling chemical (ethylene) showed sales of nearly 800 kt (CSO 1985), whereas the use of fermentation feedstocks for chemical production were less than 300 kt for Europe as a whole (CEFIC 1985). Estimations of the total demand for chemicals that could be made by fermentation are shown in table 13.

Table 13. Annual production of chemicals that could in theory be made by fermentation (thousands of tonnes)

	EEC	World
ethanol	1000	16000
acetone	217	1659
butanol	466	1400
glycerol	154	414
acetic acid	476	2539
citric acid	150	300
fumaric acid	15	60

Hence, the only significant market would appear to be the production of ethanol, either as a chemical feedstock or for use as an octane enhancer or petrol additive. At present, alcohol derived by fermentation of cane juice is being used for such purposes in Brazil, where it has been shown that although the capital cost of a new plant using ethanol as feedstock to produce polyethylene is lower than that using naphtha, the raw material costs are higher giving a product selling price of around \$590 t^{-1}.

Hence, at present feedstock prices, ethylene from ethanol is more expensive than ethylene from naphtha. This conclusion can be extrapolated to other bulk chemical products that use either sugar or starch as raw material, where the cost of raw material represents between 60 and 80% of the total production costs. Hence, bulk fermentation processes will remain uneconomic unless an alternative raw material can be found. Lignocellulosic wastes and residues could provide such a lower-cost feedstock if an effective low-cost method of hydrolysis could be found.

11. EC legislation

The production, use, import and export of agricultural products within, as well as in and out of, the European Community is covered by a wide range of regulations and agreements (see, for example, Morris *et al.* 1981). These may affect the availability of wastes by:

(i) determining the level of agricultural production through quotas;

(ii) affecting the type of arable wastes available by determining the types of crops planted;

(iii) altering the availability of animal manures through changes in quotas for milk, meat and other related products or through changes in regulations in housing of intensively reared animals;

(iv) changing the amount and type of by-products formed by setting production quotas;

(v) altering the profitability of any proposed scheme by setting prices;

(vi) limiting levels of production of end products;

(vii) controlling the import of competing products;

(viii) restricting the amount of wastes available within the EC by encouraging the import of part-finished products;

(ix) regulating the accumulation and/or discharge of untreated wastes or effluents;

(x) assisting in the development of new methods of waste utilization and treatment through joint research, development and demonstration projects.

It is obviously not possible to deal with all these regulations in detail. However, a brief description of some of these agreements is given below.

Common Agricultural Policy (CAP)

The basic principles of the CAP are laid down in articles 38–47 of the Treaty of Rome. The aims are to increase agricultural productivity, ensure a fair standard of living for agricultural workers, to stabilize markets and to ensure reasonable prices to the consumer. The CAP operates in two ways; it protects the Community market against extremes in world prices and it guarantees a minimum price and a system for buying in when prices fall below these values. Financed from the farm fund, the CAP accounts for over 70% of the Community budget.

The basic form of the CAP was derived at a time when the EC was deficient in many agricultural products. In a way it has been too successful because its operation is based on production rather than market-demand forces and has resulted in large surpluses. In the present context, this has had two effects. First, there are large surpluses of sugar, starch, wine, milk, butter, etc., leading to low-price fermentation feedstocks on the world market, discouraging innovative uses for wastes; and second, attempts to rationalize the CAP may change the amounts and characteristics of the lignocellulosic wastes produced. In particular, a decrease in cereal production and cattle raising may be associated with an increase in production of vegetable-oil crops, fibre crops and short-rotation forestry and/or coppicing.

Lome

The basic objective of the Lome agreements is to provide cooperation between the Community and the ACP (African, Caribbean and Pacific) states, especially with respect to agricultural produce from these regions, most of which enters the EC duty free. These agreements have effects in increasing surpluses of sugar in particular, as well as reducing the amounts of wastes generated within the EC because of the import of semi-finished products.

General Agreement on Tariffs and Trade (GATT)

The GATT is older than the Community, having come into force in 1948 as a multilateral trade treaty with the object of liberalizing world trade. It is subscribed to, at various levels of compliance, by over 120 countries and covers some 80% of world trade. Many of the agreements are highly complex and may effect the development of one sector of trade at the expense of another.

Sugar and starch regulations

The regulations in respect of sugar differ from most under the CAP in that they introduce limited support price quotas and penalties for over production. The basic structure of an A quota linked to consumption, a lower-value B quota of about 25% and a C quota unlimited in size but that may not be sold to intervention, has failed to control production surpluses and has maintained prices well above world prices. In the past, various regulations have provided for production refunds in respect of a number of starch-based products, although such refunds covering food and animal feed products have gradually been phased out. However, in response to pressure from the chemical industry, recent directives provide for the supply of sugar and starch at world prices. The objective of these is to boost the European biotechnology industries.

Isoglucose

The development of an alternative to sucrose, in the form of a mixture of glucose and fructose derived from starch-based glucose syrup, promoted legislation that initially attempted to control production by introduction of a substantial levy that in effect made the process non-profitable within the EC. A ruling by the European Court, that this was unconstitutional, resulted in the subsequent imposition of stringent quotas limiting the production of isoglucose to some 200 $t\ a^{-1}$ in total for all EC states. It is not out of the question that similar attempts might be made to restrict production of other products from lignocellulosic wastes if they substantially undercut the price of sucrose.

Lead in fuel

A number of communications and directives deal with the lead and benzene content of petrol and limit certain gaseous emissions from motor vehicles. The lead directive specifies that from January 1986 member states may require unleaded petrol to be sold and may not prevent its sale; and that from July 1989 states must require unleaded petrol to be sold and the lead content of leaded petrol on sale should not exceed 0.15 $g\ l^{-1}$. An increased availability of oxygenates will obviously be required to meet these objectives, and here the oxygenate market has to develop in a common manner so that particular environmental needs are met, but at the same time motorists are able to drive freely between member states. For oxygenates, the Commission has proposed minimum percentages (by volume) of 3% for methanol, to which 2% cosolvent must be added to avoid phase-separation problems; 7% for ethanol, including any stabilizing agents needed; 5% for isopropyl alcohol; 7% for tertiary butyl alcohol or isobutyl alcohol; and 10% for methyl tertiary butyl ether. There is no technical objection to the use of fermentation ethanol or other products derived from lignocellulose as octane boosters; the choice will therefore depend on price.

Environmental protection and waste recycling

The basic principle of anti-pollution legislation within the EC is that the polluter pays. Much of the legislation relates to toxic and harmful substances, such as chlorinated hydrocarbons and heavy metals. However, as part of the environment programme in 1975, the Community adopted an anti-waste directive designed to encourage the prevention, recycling and processing of waste that requires that governments ensure that waste is disposed of without endangering human health or harming the environment; a waste management committee was set up in 1976. In 1980, recommendations were made demanding greater use of recycled paper and board, as well as government-sponsored promotion programmes to make both governments and the public aware of the benefits in saving on both imported and indigenous resources by using recycled paper.

In the U.K., the high population density and industrial nature of the country, combined with its small size, mean that waste disposal can cause pollution problems and that effective waste disposal is essential. If this can be combined with efficient economic production of heat, power, fuels or chemicals it is of obvious attraction. This is realized by Government, resulting in significant activities in the areas of energy conservation and waste recycling, including a number of research programmes (see §13).

12. Economics

In theory one might expect that the fact that material was waste would make it a low-price raw material. However, this is not always so because the major costs of collection, transport, storage and pretreatment may amount to some £20–25 t^{-1}. At this price the actual cost of cellulose (and hence potentially fermentable glucose) is around £75–100 t^{-1}, excluding processing costs. Because most lignocellulosic materials contain approximately equal percentages of cellullose and hemicellulose, the raw-material cost of fermentable sugars for organisms able to use products of hemicellulose hydrolysis can be about half this, depending on the process yield. This is significantly less than the raw material costs at current EC prices for competing sources of fermentable materials, with wheat (60% starch) at £100–120 t^{-1} or beet (16% sucrose) at £25–30 t^{-1}. However, highly efficient hydrolysis processes will be needed if glucose produced by hydrolysis of lignocellulose is to compete with sugar at current world-market prices or with glucose syrup generated from grains purchased at world-market prices. The main need is thus for a high-yield low-cost cellulose hydrolysis technology to enable sugar streams suitable for use as fermentation substrates to be produced from lignocellulosic wastes at a competitive price.

13. Research and development

Within the EC, under the direction of DGXII (Directorate General XII, Research, Science and Education), a number of research and development (R & D) programmes touch on the question of the use of lignocellulose wastes. The main activities in the past have been associated with the 'Waste Utilization' programme and an increased interest has been stimulated by the present phase of the 'Biomass Energy' programme.

The R & D programme on Recycling of Urban and Industrial Waste started in 1979 and ran until the end of 1985 (Ferrero *et al.* 1984). Under this programme, detailed studies have been carried out on hydrolysis of cellulose and hemicellulose as well as on biodegradation of lignocellulose in general. Aspects of composting of such materials have been studied under the Secondary Raw Materials programme (Gasser 1985) and anaerobic digestion investigated under the Biomass Energy programme (Palz & Pirrwitz 1984).

The 'Biomass Energy' programme reached its third phase under a call for tenders in early 1985, contracts from which were being finalized in April 1986. Relevant work is being supported both in relation to alcohol production and in relation to bioconversion of biomass. The tender called for proposals as follows (*Official Journal* 1985).

Action B-1. Ethanol fuels: new or improved processes aiming at the production of ethanol fuels at low-cost and high-energy efficiency will be supported. Emphasis will be on innovative, small-scale systems. Pretreatment of the substrate such as hydrolysis may be included.

Action B-2. Basic studies on biological conversion: the fundamental aspects associated with the use of yeasts, bacteria, enzymes, etc., in biological biomass conversion that are investigated by means of microbiological and biochemical R & D will be supported.

For the ethanol project, it was further suggested that projects should be aimed specifically at improved processes for producing fuel ethanol (anhydrous) through fermentation from biological raw materials, including cellulosic materials. Systems that increase the potential for use of low-cost raw materials as substrates (e.g. wastes) and low-cost energy inputs (e.g. waste heat) and/or processes that result in co-production of valuable by-products are of particular interest. Novel organisms, new fermentations or alternative methods of separation, dehydration and denaturation may be considered. Such considerations were given in more detail in notes relating to the basic biology studies as follows.

Proposals should relate to the use of novel microorganisms and/or enzymes in the conversion of biological raw materials to fuels and/or chemicals. Work may be related to the development or isolation of specific strains with improved characteristics in terms of kinetics, heat sensitivity, resistance to substrate and end-product inhibition, or the ability to use a wider range of (or novel) substrates. The objectives should be to increase volumetric productivities (rates of reaction) and substrate-use efficiency and to decrease energy inputs in substrate preparation, fermentation and downstream processing. Pure cultures, mixed systems, isolated enzymes or immobilized systems are suitable. Studies may include isolation and biological characterization of new microorganisms, genetic manipulation of established species or strains, or investigations of control and mechanism of enzyme synthesis and/or action.

Following submission of proposals, some 21 contracts have been established, throughout the EC; of these, six involve British universities or institutions.

U.K.–U.S. collaboration

The interest in lignocellulose utilization in the U.K. has also been stimulated as a result of meetings held in conjunction with the U.K.–U.S. agreement on energy-related R & D (Anon 1984). One area chosen for discussion was biocatalysis (Anon 1985), because this was an area of interest to the U.S. Department of Energy as part of their ECUT (Energy Conversion and Utilization Technologies) programme. It has been suggested that in the U.S. the bulk-chemical industry could make substantial savings of oil equal to about 50% of present use within the chemical industry through the use of lignocellulosic raw materials.

At the present, the U.K. Department of Energy does not have a biocatalysis programme, although areas of possible collaboration were suggested at the joint U.K.–U.S. workshop held to discuss the subject. Further investigations have been carried out in the U.K. to determine whether there is a case for the Department of Energy to support additional R & D in biotechnology with a specific objective to encourage the development of industrial biocatalysts, and related technology, for application in the production of bulk chemical and liquid fuels. These have indicated that further investigations on the enzymic breakdown of lignocellulosic materials would be the most promising approach.

It is hoped that an increased funding from these collaborative ventures within both the EC and with the U.S. will enable further advances to be made, to bring such biological conversions nearer to commercial reality.

14. Conclusions

Very large amounts of lignocellulosic wastes are available within the EC. At present these are, in general, disposed of through processes of combustion, or allowed to decay in the field or following placement in landfill sites.

Collection is costly because such wastes are diffuse in nature. Hence, preference will be given to the use of those materials that are more easily collectable, or accumulate as processing by-products.

The main types of lignocellulosic wastes that are of widespread availability throughout the EC are cereal straw, forest and wood wastes, animal manures and waste paper.

Legislation exists to encourage recycling of waste paper and to discourage pollution of the environment, on the basis of the polluter paying.

A greater understanding of the biological processes associated with the breakdown of lignocellulose is of interest in respect of waste treatment through landfill deposition, anaerobic digestion, aerobic waste treatment and composting.

The availability of such wastes reflects the overall agricultural and trade policies of the EC as well as the demand for such materials by other competing technologies that are in use now and that might develop in the future.

Although it is the ambition of many research programmes to produce sugar syrups for use as fermentation substrates from such wastes, the use of such material is limited by market demand, unless it is used to produce fermentation alcohol.

It is possible to produce a number of chemicals from fermentation ethanol, or from lignocellulosic materials by other routes. However, the demand for such materials, other than ethanol used as a fuel, is insignificant compared with the amounts of such residues available.

References

Anon. 1984 *Renewable energy news*, no. 10. London: U.K. Department of Energy.
Anon. 1985 *US/UK Energy R & D, Anaerobic digestion and Biocatalysis*. London: UK Department of Energy.
Busch, H. P. 1985 In *Report on the 1st CEC Workshop on Agricultural Surpluses, part 1. Lignocellulosic biomass and processing* (ed. D. Schliephake & P. Kramer), pp. 235–273. Frankfurt am Main, Germany: DECHEMA.
CEFIC 1985 *Use of agricultural raw materials in the European Chemical Industry*. Brussels, Belgium: CEFIC.
Coombs, J., Hall, D. O. & Chartier, P. 1983 *Plants as solar collectors*. Dordrecht, Netherlands: D. Reidel.
CSO 1985 *Annual abstracts of statistics*, 1985 edition. Publication no. 121 of the Government Statistical Services. London: HMSO.
ETSU 1984 *Anaerobic digestion, a credible source of energy*. Harwell, Oxon: Energy Technology Support Unit.
FAO 1984 *Yearbook of agricultural production*, 1984 edition, Rome: Food and Agricultural Organisation of the United Nations.
Ferrero, G. L., Ferranti, M. P. & Naveau, H. (eds) 1984 *Anaerobic digestion and carbohydrate hydrolysis of waste*. London and New York: Elsevier Applied Science Publishers.

Gasser, J. K. R. (ed.) 1985 *Composting of agricultural and other wastes*. London and New York: Elsevier Applied Science Publishers.
MAFF 1984 *Straw disposal and utilisation*. London: Ministry of Agriculture, Fisheries and Food.
O. J. 1985 *Official Journal of the European Communities*, C69, 3–16. Luxembourg: CEC.
Morris, B., Crane, P. & Boehm, K. 1981 *The European Community*. London: Macmillan Reference Books.
Ollmann, H. 1985 In *Report on the 1st CEC Workshop on Agricultural Surpluses, part 1. Lignocellulosic biomass and processing*, (ed. D. Schliephake & P. Kramer), pp. 235–273. Frankfurt am Main, Germany: DECHEMA.
Palz, W. & Chartier, P. (eds.) 1985 *Energy from biomass in Europe*. London: Applied Science Publishers.
Palz, W. & Pirrwitz, D. (eds.) 1984 *Energy from Biomass, Proceedings of an EC Contractors Meeting, June 1983*. Dordrecht, Netherlands: D. Reidel.
Rexen, F. & Munck, L. 1984 *Cereal crops for industrial use in Europe*. Copenhagen, Denmark: Carlsberg Research Laboratory.

Discussion

J. M. Lynch (*Glasshouse Crops Research Institute, Littlehampton, West Sussex, U.K.*). Soil is the natural resource that governs crop productivity. Plant residues are decomposed by soil microorganisms to generate polysaccharide and humic materials, which are major factors governing soil structural stability. Utilization of crop residues in industrial processes or by burning in the field could have serious long-term consequences in soils that are prone to structural instability, such as many soils found in North America and Brazil, as the poor structures that could result would limit crop production. Caution should therefore be exercised in the utilization of lignocellulosic 'wastes' in these regions.

J. Coombs. I would agree with the general premise that it is necessary to continually add fresh organic material to soils to maintain their structure. This is well known. The amount of material required is higher in many tropical regions where rates of breakdown are increased by higher average temperatures. However, in most cultivation systems the amounts of organic wastes exceed by far that required for soil structure. Where the objective is to maintain nitrogen levels by addition of organic matter alone, the situation is different, but as far as humus is concerned, with an above-ground crop, the organic matter of the roots alone is often sufficient in quantity to provide sufficient organic carbon. In many cases, the wastes are already removed anyway, and accumulate at factory or processing sites, e.g. sugar cane bagasse, coffee pulp, citrus peel, palm-bunch stalk, etc. and are burnt or rot on the site. These materials would, or indeed are already, the first to be considered for use as a fuel or some chemicals.

J. F. Levy (*Department of Pure and Applied Biology, Imperial College of Science and Technology, London, U.K.*). I congratulate Dr Coombs on a most interesting paper, but I would like to change his perspective.

1. There is one very frightening statistic on a world-wide basis. Approximately half the World's forest crops are used for fuel in one form or another. This should make us think of the problem of the semi-arid regions of the Third World where wood is in very short supply or non-existent, with all the tragic consequences that this implies.

2. If we look on the situation from a U.K. point of view, do not let us forget that wood and wood products are our second biggest import, running into thousands of millions of pounds annually. While this is likely to remain a substantial commitment to U.K. as a nation, there is some alleviation occurring as far as *sawn softwood* is concerned. Twenty years ago only 2% of the sawn softwood used in the U.K. was British grown. Today it is 18–20%, and is likely to be 25% by the turn of the century. If we can produce the requisite technology to utilize what we can grow, this could rise to some 50% halfway through the next century.

3. Much excellent work is being done in North America on the better utilization of a tree. Conversion of a saw log to useful lumber is still usually well below 50% of the log volume. Apart from the saw logs, the lop and top can be used for other purposes. This gives us in the U.K. a rare opportunity to make use of our forest products (much of which was planted only to stockpile pit props) because we are, almost for the first time in our history, becoming a timber-producer country.

J. COOMBS. I agree; obviously, as agricultural surpluses increase in Europe it makes sense to divert land to tree production. This is realized by both the Biomass Energy Programme of the European Communities and the U.K. Biofuels programme. Both currently are supporting significant efforts in R & D for short rotation forestry and coppice production. The International Energy Agency has a similar programme, as does the Food and Agricultural Organization (FAO).

J. A. GASCOIGNE (*Cross & Bevan Laboratories, Arlesey, Bedfordshire, U.K.*).

1. With the large quantities of lignocellulosic wastes available, it is not worthwhile to look at the industrial production of minor components (e.g. waxes, sterols, terpenes)? This production may entail a new harvesting strategy to ensure optimum yield, but at present we are wasting an existing resource in favour of more exotic development.

2. For the last 100 years research into lignin utilization has yielded very few large-scale uses of this aromatic chemical. It seems a pity in the home of the coal-tar industry that more emphasis is not being placed on lignin as a readily available material for a whole range of organic intermediates.

J. COOMBS. As far as products like waxes are concerned, these were obtained as a by-product of cane-sugar processing for many years. However, the products were not able to compete on a cost basis with petrochemical-based products. The same problem, of relative cost, also applies to the use of lignin. The markets for speciality chemicals of this type are small, measured in thousands of tonnes; hence investment in new processes to meet a small-market demand are not justified so long as a better, lower-cost fossil feedstock is available.