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

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The food industry appears to have minimal concerns with this topic. After all, the raw materials are natural, the processing mild and the byproducts are biodegradable and non-toxic. However, the delivery of beneficial and attractive products to consumers requires more than the simple conversion of agricultural materials and, the industry will need to consider all of its operations more critically. For example: (1) large scale processing can produce byproducts which threaten the local environment simply by the oxygen demand for biodegradation; (2) physical processes are forced to compromise between energy efficiency and unacceptable damage to product quality; and (3) packaging is an integral part of the product. These materials are less degradable than the foodstuff itself and represent a significantly unacceptable source of environmental pollution.

Examples of past and current successes will be given, together with the emerging challenges of redesign of processes and products.

1. Introduction

The food industry is the largest industrial sector in the UK, the annual expenditure by householders being £47.3 billion in 1994 (National Food Survey 1994). The industry's supply chain, see figure 1, stretches from the production of raw materials, through food processing in factories, to the distribution of products to the retail trade and hence to the consumer. In terms of added value through the supply chain, agriculture contributes £9 billion, manufacture £14 billion, retailing and distribution £9.5 billion and catering £10 billion (Food and Drink Foresight 1995). Employment in the production sector is 0.5 million with around 1 million in distribution and retail.

The complete supply chain of the food industry, from the production of raw materials, via food processing to the consumption and disposal by the consumer is complex, see figure 1. Some of the environmental issues facing the industry can be identified in this diagram and are discussed below.

Raw materials for the food processing industry include fruits, cereals, vegetables, meats and poultry, fish and food ingredients such as fats and oils, sugar, flavourings, thickeners, emulsifiers. The production methods for these raw materials often involve the use of fertilizers, pesticides/fungicides in addition to the consumption of plants, animal products, energy, water, etc. Obviously, there are several environmental issues in the production of the raw materials which should not be considered separately from the operations of the food processing industry.

One of the major materials supplied to the food processing industry is the packag-

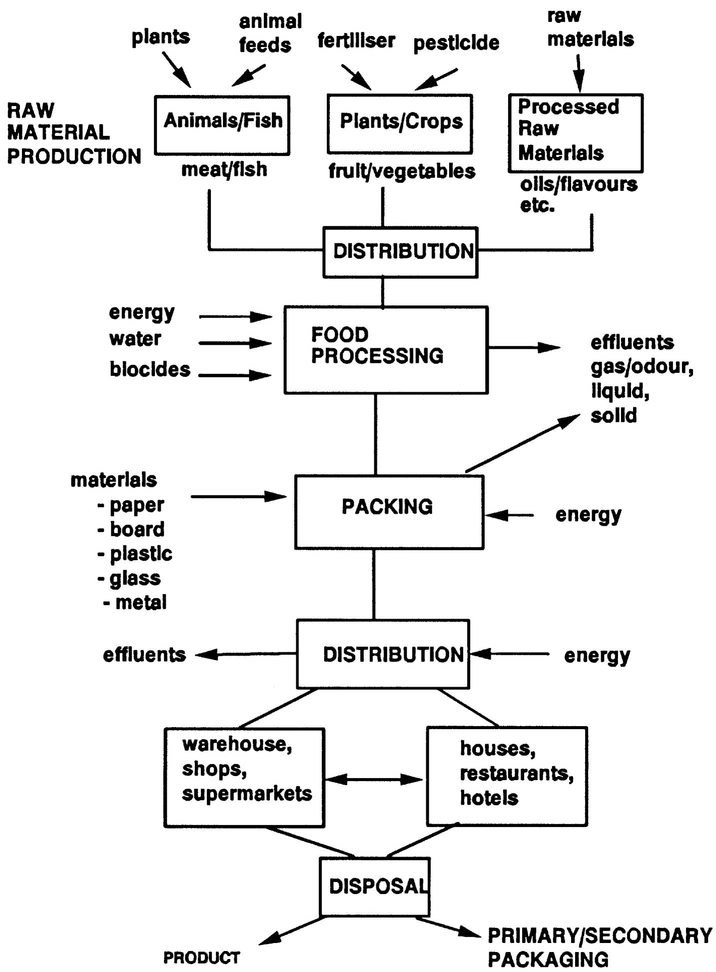

Figure 1. The food supply chain.

ing which is used to protect the processed food from deterioration and/or contamination (primary packaging) and to provide physical protection through the distribution and retailing operations (secondary packaging). It is worthy of note that the food industry, of all the manufacturing industries, makes the largest demand on packaging, whether it be paper/board (including laminates), plastics, glass or metal. Indeed, the food industry is responsible for around two thirds of the total industrial usage. Finding ways to reduce this packaging quantity and its subsequent waste is a demanding task. The issues surrounding the optimum strategies for the selection, recycling, reuse and disposal of this packaging are extremely complex, and cannot be resolved in isolation from other factors such as the product itself and its complete distribution chain.

The food processing industry in the UK is large and diverse with a few major multinational companies at one extreme and a very large number of small and medium size enterprises at the other. This, together with the convenience of location close to sources of perishable raw materials means that the factories in the industry are geographically scattered with many small operations. In the limit, the 'factory' becomes mobile, following the available raw material. Examples of this are factory ships and, to a degree, the combine harvester. This geographical spread coupled with the biodegradability of waste foodstuffs indicate a benign situation. However, the very large number of factories mean that the overall consumption of water and energy are significant and it is not feasible to concentrate production into a few highly efficient processing units and gain the advantage of scale. Additionally, wastage from sectors of the food industry ranges from around 1.0% loss by weight for dairy and oil and fat processing, through 15% for certain confectionery operations and in excess of 50% for some meat products (Gorsuch 1986; Niranjan & Shilton 1994).

The food industry also includes many energy intensive operations such as sterilization/pasteurization and drying through to refrigeration of products during distribution, warehousing and retailing. All this dictates the need for energy minimization to be a key element in the industry's efforts to be environmentally friendly.

Finally, in the disposal from the consumer, some of the food is eaten and digested and goes to the sewage system. Some goes into garbage bins, together with much of the packaging material, for landfill or combustion.

It is clear from this brief introduction that the total supply chain of the food processing industry is complex with several areas of environmental concern, e.g. fertilizers, pesticides, packaging, energy utilization, water usage, see figure 1. As a result it is not feasible to consider just the 'food processing' operation in isolation from the full supply chain. For example, it is not reasonable to minimize the environmental impact in processing operations if this solution presents an even larger problem elsewhere in the chain. As another example, the energy requirements for processing and the amount of waste materials could be minimized by improvements to the raw materials during farming/agriculture.

Life-cycle assessment (LCA) provides one way of taking an integrated approach to gaining environmental benefits across the total supply chain. The stages in LCA include drawing the system boundary, inventory (of raw materials, energy usage, effluents, etc.), assessment of environmental impact, followed by improvements to the system. However, the methodology for impact assessment is not fully agreed and the database for the inventory is not complete especially for many of the natural materials found in the food and agricultural industries. Nevertheless, LCA does provide a way forward to develop a framework for taking an integrated view of the environmental issues in food processing.

Referring to figure 1, the LCA approach of defining the boundary, calculating the demands on raw materials and energy, evaluating the losses, etc., becomes apparent. However, since LCA is not yet a complete methodology, the following sections of this paper focus only upon some environmental case studies in 'food processing' and the food supply chain. The role that 'clean technology' can play is then highlighted and finally some of the research barriers that stand in the way are identified. However, any proposed solutions which use clean technology in the food industry to minimize environmental impact must ultimately be viewed in a full supply chain and LCA context.

2. Case studies

(*a*) *Case study 1—white fish products*

(i) *Fish fillets*

When we eat the typically British 'fish and chips', we need to remember that the succulent white fillet of fish represents less than half the weight of the whole fish when it was swimming in the sea. The head, bones, skin and digestive system (guts) are not normally eaten and have to be disposed of in some way. Traditionally large white fish such as cod or haddock, would be gutted at sea. The guts would be thrown overboard and thus not be a waste problem to the fisherman. The gutted fish could then be processed at sea—beheaded, filleted and skinned—and the resultant waste also discarded overboard.

Nowadays most fish are landed whole and the process steps of filleting, etc., will be done on land. As a consequence, a significant amount of fish waste—skin and bones—have to be disposed of in an acceptable way.

The yield of boneless fillet from the fish frame will depend on the size of fish and the species. Typical filleting yields will be about 40% for cod, but as high as 60% for salmon because of the small size of both the head and digestive system of the salmon. Filleting can be carried out by hand or by machine. It is interesting to note that the yield from hand filleted fish is still greater than from machine filleting.

It is important that abundant fresh water is available during fish filleting and skinning steps in order to keep the fish flesh wet and clean. All of this water will end up as effluent from the factory which will be expensive to dispose of due to its high biological oxygen demand (BOD).

The most cost effective way of disposing of fish waste is to convert it into fish meal which can be used for animal feed or fertilizer. However, this waste is unstable and decomposes rapidly rendering it not only unfit for use, but generating a highly unpleasant odour! The waste is of low value which means that the fish meal factory must be close to the filleting factory in order to avoid excessive transport costs/times. Further, fish meal production is not a very profitable process, therefore the factories need to be large—taking in waste from more than one filleting factory—in order to be economically viable.

Thus it can be seen that the production of 1 kg of fish fillet requires over 2 kg of starting fish, the disposal of more than 1 kg of non-fillet fish material, and the processing of at least 1 kg of high BOD wash liquor.

(ii) *Surimi (Lanier & Lee 1992)*

Of the approximate 100 million tonnes of fish caught every year, the single most caught species is Alaska Pollack at 4–6 million tonnes. Half of this total is converted into a fish paste called surimi, most of which is used to make traditional Japanese products such as Kamaboko (you may well have tasted the fish analogue 'crab sticks'). In essence, surimi is minced fish fillet which is washed to give a white, tasteless rubbery product after cooking. This surimi is then mixed with other ingredients like starches and egg proteins, then shaped and cooked to give the surimi based products like crab sticks. The basic surimi process starts with headed and gutted fish. The flesh is then removed from the bones and skin by mincing, washed several times to remove the water soluble proteins, pigments, fats and flavours leaving the contractile (myofibrillar) proteins. The proteins are then passed through a fine screen to remove particles of bone and connective tissue before being de-watered. Traditionally, because surimi was unstable, it was used as soon as it had been prepared. However, in the late 1950s it was discovered that if cryoprotectants such as sorbitol and sugars were added prior to freezing then the properties of surimi would be preserved. This transformed surimi processing from a 'close to sea, cottage industry', using locally caught fresh fish, into the worldwide operation that it is today, with surimi being processed in any ocean where the appropriate fish can be caught.

Table 1. *Liquid milk composition*

fat	3.75%
lactose	4.85%
protein	3.30%
minerals	0.72%
water	87.5%

Table 2. *Cheese composition*

	protein (%)	fat (%)
cheddar	25.4	34.5
edam	24.4	22.9
parmesan	35.1	29.7

The process of washing means that the recovery of surimi from the whole fish is even lower (at about 20%) than the yield of boneless fillet. To make matters worse, the washing step is usually carried out twice with a ratio of one part fish mince to three parts water; this means that for every kg of fish mince processes, at least 6 kg water. The water used for washing must be potable, i.e. low in salt to avoid solubilizing the contractile proteins. The washings contain proteins and pigments, making the BOD of the effluent stream much higher than that produced from simple fish filleting. The amount of water needed depends on the freshness of the fish used, for very fresh fish the ratio is about six times and for staler fish the ratio can be as high as 10–20 water to fish mince. The freshness of fish is also very important in determining the quality of the final surimi. Therefore, it is highly desirable to ensure that the fish used for making surimi is extremely fresh, ideally less than 12 hours old.

Thus it can be seen that the manufacture of surimi-based shell fish analogue products is dependent on a very wasteful fish muscle purification process which uses large quantities of water and must have very fresh fish as a starting material. Not surprisingly, therefore, factories have been moved on board to maximize freshness of raw materials and 'free' waste disposal.

(*b*) *Case study 2—cheese production (Robinson 1994)*

Milk is a fluid consumed directly by almost all societies. See table 1 for the composition of milk in its liquid form.

When consumed as a liquid, the 'solids' are largely digested and the liquids disposed of by the individual. (The effluent is not an issue for food manufacturers but only for the sewage industry.) However, fermentation of milk by benign organisms has been practised for at least 8000 years, producing the interesting textures and flavours of cheeses and yoghurts. Currently, about 11 million tonnes of cheese are produced annually, and for obvious reasons of economy of scale, process is centralized in increasingly large sites. The composition of cheeses varies but in every case is much higher in solids than the original milk, for example see table 2.

Irrespective of the local tradition, the processes initial stages produce a curd and liquid whey whose composition is given in table 3.

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

Table 3. *Liquid whey composition*

protein	0.7%
lactose	4.5%
salts	0.6%
acid	0.6%
water	93.6%

This represents an annual byproduct of about 4.5 million tonnes of a liquid stream with very high biological oxygen demand (BOD).

In the past, this was disposed of into local water ways or added directly to animal feed. Indiscriminate dumping has now been stopped in most countries and a key factor in the economics of cheese manufacture is now the disposal or resale costs of whey. However, this has now become a success story, thanks largely to the introduction of ultrafiltration (UF) and reverse osmosis (RO).

Because whey is biologically unstable, its treatment has also been localized near or at cheese manufacturing plants. A combination of sterilization, RO evaporation and drying, produces a dried powder for use in animal feeds and calf milk food, and potable water. This accounts for almost 90% of the use of whey in the EU, and a cost analysis of a cheese plant producing 100 000 tonnes of whey per annum shows that the capital cost of RO equipment can be recovered within one year (Pepper 1987).

There are even more advantages to be gained if hygiene is improved and processing is milder. The use of UF produces a protein concentrate, which, if not excessively heat treated, is of considerable functional value. Here, a compromise between energy efficiency and product value has to be reached. It is inefficient to transport and store whey in a liquid state and the suspension is an almost perfect medium for microorganisms. As a result, whey is usually dried, by fluidized bed, roller or spray drying. Engineers can calculate the most energy efficient process, but these frequently require that the liquid whey reach temperatures of greater than 70 °C. Unfortunately, this exceeds the thermal denaturation temperature of the constituent proteins. Protein denaturation is a highly cooperative, first-order process comparable with melting, and in concentrated solutions is irreversible (Ruegg *et al.* 1975). Thus the most energy efficient process is not optimal for the recovery of native protein. The whey protein, α-lactalbumin and β-lactoglobulin have similar solubility and heat setting properties as egg white (ovalbumin). Since much of culinary practice in bakery, confectionery, etc., uses the properties of egg white, functional whey protein powders can command a comparable ingredient price which is at least £2000 tonne^{-1}. This whey product therefore is as valuable as the primary cheese.

(*c*) *Case study 3—instant coffee (Beck 1996)*

For those of you who make coffee directly from ground beans, the volume of wet spent grounds represents an inconvenience. However, a factory producing instant coffee is faced with a massive disposal problem. The grounds have considerable calorific value but not at the solids contents recovered from the primary extraction. At the Nestle factory in Staffordshire, instant coffee, equivalent to five billion cups per annum is manufactured. Spent grounds are pressed, producing a dense cake and a viscous coffee oil. The cake provided a fuel source capable of providing up to 50%

of the sites steam demand, but the pressed liquid was sprayed onto fields since the BOD exceeded the capability of the municipal system.

Such procedures are scarcely environmentally friendly and the liquid also has considerable calorific value. Two stage recovery, of fines by centrifugation and coffee oil concentration, produced further fuel and saves one third of a million pounds per annum. The next step will be to recycle potable water.

3. Classification of clean technologies

Having outlined some particular case studies in the food industry, let us now take a generalized approach to clean technologies for the industry.

If one considers only the food processing part of the entire food supply chain (figure 1), we can generalize the 'unit operations' of the industry to include conveying, washing, heating, cooling, extraction, emulsification, drying, etc. The equipment used in these processes has to be cleaned (and often sterilized) and, in addition to the main products, the entire operation results in a further series of waste streams containing carbohydrates, fats, proteins, etc.—sometimes accompanied by residual pesticides, fungicides, cleaning agents and biocides. The 'waste' takes the form of solids (e.g. fine particulates, bones, fats), liquids (e.g. oils, flavours) or gases (e.g. odours). Thus the 'waste streams' are often these materials suspended in large volumes of water or air. These wastes are usually readily biodegradable by natural micro-organisms and enzymes. However, there is a major role for clean technology to minimize the overall environmental impact by improving the raw materials, improving the unit operations, using re-use and recycling strategies and improving waste treatment.

The relevant 'clean technologies' can be classified into the following categories.

(1) *Reduction at source*. This covers improvement of raw materials. In the case of the food chain, these are agricultural products, which have already been subject to breeding for increased yield. The next step will be to 'design' raw materials, particularly plants which require less treatment with fertilizer or pesticides. Genetic engineering is being introduced to achieve these aims, as well as targetting traits which will reduce waste biomass. Short stalk cereals, 'leafless' peas and ripening controlled tomatoes are examples already introduced.

(2) *Recycling*. This includes procedures which permit the recycling of energy, water and potential waste streams back into earlier stages of the process. Formal techniques exist for energy minimization and water minimization (Linhoff 1993; Wang & Smith 1994). However, attention must be paid to possible microbial contamination in any water minimization solutions which involve water recycling/re-use.

(3) *Recovery*. These are technologies that allow material previously regarded as waste to be recovered/treated and thus used as a marketable product in its own right. The example of whey recovery has been given above.

(4) *Conversion*. These include the conversion of waste material streams into energy for improvement of the energy efficiency of the process or other processes on the site. For example anaerobic digestion of some fat laden aqueous streams can provide not only intensified treatment (taking up less space) and low levels of biomass production, but also generate methane which can be burned to provide heat for use elsewhere in the processing operations. Coffee solids recycling is a further example.

(5) *Treatment*. This covers the on-site treatment of waste streams to minimize the environmental impact, e.g. odour removal from gaseous streams.

(6) *Disposal*. This covers the routes available off-site to dispose of waste streams via third parties, for example fish meal processing.

In order to achieve improvements in environmental performance in food processing, all the above approaches should be considered in an integrated way. Thus the best response to increasing pressures from regulation and legislation is via an integrated environmental management system (Zaror 1992) with regular environmental audits providing a database from which improvements in performance can be measured.

Whichever of the above routes, or combination of routes, are taken to yield potential environmental benefits, it is important to remember that most of the products from the 'food processing' industry have a relatively low 'added value'. Thus the capital and running costs that the industry can tolerate for any new clean technology are severely constrained. To illustrate this pressure on costs, it is interesting to note that in the UK in 1950 consumers spent about 25% of their income on food. In the period to 1994 this figure had dropped steadily to about 11% (National Food Survey, MAFF, 1994) as food production became more efficient in response to continuous consumer pressure. There is no evidence that there will be less pressure in future.

4. Research challenges

As the above discussion illustrates, the food industry is not free from environmental problems. Thus there is a constant search for improvements that can lead to fundamental changes in the industry's operations, leading to new processes and procedures. In parallel, incremental improvements to existing processes are also sought.

In this section we highlight some of the technical barriers to progress where research and development effort could be advantageous.

(a) The development of a life-cycle assessment (LCA) methodology and database for the food processing supply chain. In particular, an agreed approach to the assessment of 'environmental impact' is needed. Only when such a procedure is available can a rational approach be taken to the evaluation of the significance of individual 'clean technologies'.

(b) Biotechnology and breeding techniques to modify animal and plant raw materials. These could facilitate waste and energy reductions in processing as well as minimization of pesticides, etc., in agriculture.

(c) The further development and application of energy and water minimization techniques in food processing.

(d) Improved separation technology, e.g. membrane processes for product recovery that have significantly lower fouling and longer membrane life.

(e) Techniques for improved waste treatment, e.g. biological treatment with reduced sludge generation, super-critical oxidation, improved odour removal from gaseous streams.

(f) Improved techniques for 'cleaning in place' of process equipment to reduce the amount of water, steam, surfactants, biocides required.

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Discussion

A. Wagner (*Kilburn, London, UK*). Many foods are seasonal and the vulnerability of many life forms also varies on a seasonal basis. So, if one could alter the timing of waste disposal or harvesting, then it might be possible to reduce the environmental damage.

P. Lillford. Yes indeed. Since the majority of our waste is biodegradable, what is now viewed as pollution could be redistributed to become a positive input to the food cycle.

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