Maximizing Efficiencies in the Food System: A Review of Alternatives for Waste Abatement

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ABSTRACT

The biological and technological inefficiencies in the total food system are examined. Energy from sunlight is converted into human food with rather poor efficiency, as only a small portion of the energy available is recovered as food. Maximum efficiency in energy flow is obtained if humans consume plants for food rather than feeding animals for production of human food. The waste generated at each stage in food production and processing is examined and waste abatement alternatives are presented. These alternatives include: changing consumer demand to accept food that generates less waste during production, changing production and processing cycles to be more efficient or accommodate waste products in the environment through conversion to useful products or classical treatment as sewage. Recent advances in reducing the environmental impact of food processing wastes using these technological alternatives are examined. Emphasis is placed on alternatives which maximize overall efficiencies in the food system.

Food producers and processors have tried to maximize the value of food output in relation to the costs incurred. In the past this was done with little regard to the environmental and social costs or consequences (64). This philosophy and man’s inventiveness have resulted in appearance of thousands of new food products which consumers have eagerly purchased. Since environmental and social restraints could be largely ignored, cost inputs from these two sources were negligible, and production at relatively low costs could be maintained. This has led to several practices with both beneficial and detrimental results. For example, increased production efficiency could be obtained by use of fertilizers and pesticides (15) with little apparent regard for environmental discharges. Food processors, usually producing wastes with less recalcitrant properties, also contributed to the total ‘waste load’ of food from production to consumption.

While consumers were anxious to receive the maximum number of goods and services at minimum costs, certain members of society became concerned at social and environmental costs not previously considered. The popular awakening of the public, both in the U.S. and internationally, to the price of cheaper (64) goods and services without regard to environmental pollution has led to laws passed by the U.S. Congress which severely curtail past practices and will ultimately increase the cost of goods and services to the consumer. New attitudes must be developed by every sector of agriculture to learn to live with these new constraints (79). Society must also become obliged to live in harmony with its essential food producing and processing systems. It should be the national goal to accomplish this harmony at modest cost to consumers and producers as well.

The role of scientific research in this area is to discover alternative processing techniques which result in the maximum benefit to all with minimum serious tradeoffs. The waste production and utilization problem has recently been reviewed by several authors. These reports emphasize the waste load produced (39, 88), the alternatives available (4.5,20,26,28,30,43,59,70) or the relative costs of waste treatment (42, 81). This review will concentrate on maximizing the efficiencies of the food system as a whole by minimizing waste at each step. Emphasis will be placed on those processes which reduce the impact of food wastes on the environment through product or by-product recovery and recycling.

EFFICIENCY OF FOOD PRODUCTION

Production, processing, and consumption of food result in some degree of waste at each stage (Fig. 1). We are faced with certain constraints, at least at present, on the maximum efficiency of food production. If we were to maximize biological production and food processing efficiencies and consume all we produce, we would have minimum waste. Deviations from maximum efficiency during production, processing and consumption result in waste production and require more energy inputs to alleviate environmental damage, thus further reducing efficiencies and increasing costs. To understand the relative magnitude of production and utilization efficiencies, it may be useful to examine the production of one food, corn, from planting to consumption. The Committee on Agricultural Production Efficiency from the National Academy of Sciences had developed this illustrative example (2).

Sunlight is a free and plentiful source of energy, but only about 45% of the energy spectrum is of the proper wavelength for photosynthesis. Only the reds and blues are useful to plants. Green, ultraviolet and infrared light are not of the proper wavelength (67). While 45% of the energy in sunlight is available, only about 0.1 to 3% is actively converted into biomass by the plant (2). The rest is used in catabolic respiration processes with release of CO₂, and inherent metabolic inefficiencies. Furthermore, only about one-half of the biomass is available for food or
feed. Using corn as an example, only about 0.4% of the energy in sunlight that impinges on the plant’s leaves is harvested as food or feed.

About 40% of the food energy in our diet comes from meat and animal products which are produced relatively inefficiently from plants. For example, when feed is expressed in kg of corn per kg of live weight gained, broilers consume 2.4, hogs 5.6, and cattle 11.1 (2). Thus, it appears that 40% of our diet is derived from animals that consume 80% of the energy available in harvested crops. While there is serious research to increase yields and the photosynthetic efficiency of plants and the feed conversion efficiency of animals (21,85), we may reach certain biological limits which result in wasted calories or energy. Comparing efficiencies throughout the food chain, it is evident that the energy utilization by the plant is by far the most inefficient or wasteful. However the energy wasted, sunlight, does the least damage to the environment. On the other hand, inefficiencies in every other step in the food chain result in biological waste. While some biological wastes are apparently unavoidable due to inherent biological inefficiencies (i.e. not all of the corn plant is edible) some wastes can be avoided by application of appropriate processing technologies.

REGULATIONS AND FOOD PROCESSING

The inefficiencies of each step in the food production-consumption process result in waste which may or may not have an environmental impact. For example, if the processing wastes from vegetables are left in the field, the least impact on the environment may be experienced. However, if an inferior product (bruised or diseased) reaches the processing plant, some of the product will contribute to the organic waste load of the waste water (39). It is these biological wastes which cause the most serious environmental impact. Accumulation of both liquid and solid wastes in waterways causes severe changes in the microhabitat of the normal communities of plants and animals. Increased organic loads in streams may surpass the streams’ normal oxidative capacity and dramatically change population balances (49). These imbalances result in undesirable changes in the waterways and are the subject of much concern and the basis for environmental regulation through public laws.

Reduction of the impact of wastes on the environment has been the goal of the Environmental Protection Agency and has been the underlying philosophy of many state and federal laws passed (72). The goal of Public Law 92-500 passed in 1972 (23) was to restore and maintain the chemical, physical and biological integrity of the native waters. It was to provide for fishable and swimmable waters by 1983 and for zero discharge of pollutants into waterways by 1985 (22). To reach these goals a plan was implemented to have industries meet these standards by the best practical technology. Further legislation in 1977 (Clean Water Act of 1977) changed the pathway to achieve the 1985 goals to include an economic factor. Also, the laws now include a provision for waste classification into three control groups: toxic compounds, conventional pollutants and non-conventional pollutants. Emphasis is now placed on the toxic substances discharged (heavy metals, etc.) and is of less concern to food processors (72). Most food processors fit the second category by producing conventional pollutants. For these pollutants, biochemical oxygen demand (BOD), suspended solids (TSS), pH, and fecal coliforms are regulated. These pollutants must be controlled using readily available reasonable technology that meet the cost test. The cost test is based on two interrelated factors (a) the reasonableness of the relation between cost and

\[
\text{TOTAL ENERGY BALANCE}^a
\]

10^12 calories light/3 mo. → Human food, 4 x 10^12 calories as corn + 6 x 10^12 calories wasted

Animal feed, 2 x 10^12 calories as corn + 8 x 10^12 calories wasted

\[
^a\text{Calories calculated on the bases of production of corn for human consumption directly or as beef when corn is used a ration.}
\]

Figure 1. Energy flow in the food system. Adapted from Agricultural Production Efficiency (2).
the effluent reduction benefits, and (b) comparison of the industry category or subcategory cost and associated pollutant reduction for publicly owned treatment plants (72).

**ALTERNATIVE APPROACHES FOR INCREASED EFFICIENCIES**

**Change demand**

Reduction of waste and subsequent environmental protection through increased efficiencies have been the goals of the food industries, not only because of legislative mandates, but also because of increased economic incentives to do so. Alternatives for waste abatement should be examined for the entire food system, as well as from the food processing viewpoint (Fig. 2). First, it may be possible to change consumer demand so that people consume products that generate less waste in their production. For example, the low efficiency of producing animals for human food from corn has been discussed (21). Others have emphasized the desirability of single cell protein as an alternative protein source (77). However, most consumers will not change their eating habits to eat less meat as long as they can afford to purchase it.

**Change production processes**

A second alternative approach for waste abatement is to change the production process (Fig. 2). For example, many changes in the food production system have resulted in increased yields of foods from plants and animals. These include high yielding plant varieties (15) which have a higher proportion of edible than of inedible plant parts, thus producing less waste. Higher animal feed conversion ratios also generate less waste (as manure, etc.) and thereby increase the overall efficiencies of food production and economic value for consumers.

Food scientists are normally concerned with what happens after the food is grown and have contributed greatly to increased efficiencies in food processing. Post-harvest technology, the first step in maintenance of food value, has resulted in higher quality farm produce reaching the consumer. Advances have included controlled atmosphere storage for fruits and vegetables (54), and locating meat processing plants close to animal production facilities. These practices result in less waste because the product of highest quality reaches the consumer and the maximum yield reaches the processing plants. This is the first place in the total processing scheme for waste reduction, and has received considerable research emphasis. Also, most field waste from fruits and vegetables is now routinely left in the field, resulting in less waste at the processing plants. These practices all combine to give the highest quality product delivered to consumers or to processing plants (39) at a reasonable cost.

**Change processing**

Once the food reaches the processing plant, waste production and treatment becomes a critical issue because large amounts of waste are generated in one place and have locally high impact (39). Each industry generates different concentrations and types of waste materials (Table 1). Identification of the amount and composition of the waste generated in different kinds of food processing industries is the first step in a waste utilization or reduction approach and has been the subject of numerous reports (3,6,9,10,32,37,62,68). While complete input-output data are not always available, it is possible to generalize waste load characteristics from these data (Table 1). Meat processing results in tremendous quantities of both liquid and solid waste. For example, poultry processing results in solid wastes of 270 g/kg live weight and water usage of 14,000 mg/kg (BOD$_5$), as well as a very large volume of water used for bird washing and giblet fluming. By contrast, the milk industry produces little solid waste, but very concentrated liquid wastes. Vegetable processing liquid wastes are in general less concentrated, except for starchy wastes such as from potatoes. However, considerable solid waste is generated during normal processing of vegetables.

The most significant approach for waste reduction at the processing plant is to adopt practices and technologies which result in significant improvements.

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**Figure 2. Waste abatement alternative actions. Adapted from a systems approach to problem-oriented research planning: a case study of food production wastes (I).**
in recovery of the final salable product (Fig. 2). While all processors attempt this (to stay in business!), some new applications of technologies have resulted in increased product yield and quality while reducing waste. An example of this approach is the use of ultrafiltered milk to make cheese (Table 2). This process has been demonstrated for several cheese varieties including Mozzarella and Cheddar (17), Petit Suisse and Camembert (50). The increased yield is due to retention of proteins in the cheese normally excluded in the whey. Since whey is a major pollutant in the dairy industry, this process is an important new application of ultrafiltration technology. The vegetable industry has been successful in adapting new peeling techniques using lye (80) and various surfactants (46) to peel fruits (14) and vegetables (51). This results in substantial increases in product yield and quality while reducing waste. An example of this approach is the use of lye peeling to generate a caustic waste which requires substantial treatment before discharge. The meat industry has increased yields of better quality (more tender) meat to the consumer by enzymatic treatment of animals before slaughter. The ProTen process developed by Swift results in more tender meat cuts and less waste due to inferior meat quality (54).

**Accommodate wastes**

While efforts to increase production and processing yields have been made, the most attention has been paid to developing new methods to accommodate waste products (Fig. 2). These have been mostly in two areas: application of processing or recovery technologies to food waste streams, and anaerobic or aerobic waste digestion methods.

For by-product recovery to be successful, the waste water must not vary in composition and must contain a by-product that has some value or special use. Often a nondestructive harvesting technique must be employed for maximum by-product value. Technologies developed for pure chemical separations have been applied to treatment of liquid food processing wastes for by-product recovery. The techniques found useful have included ultrafiltration, reverse osmosis, electrodialysis and ion exchange. For example, processes have been developed for treating potato waste to recover many potentially valuable components from waste water process streams. Researchers at the Eastern Regional Research Center were instrumental in developing ion exchange procedures for recovering amino acids, potassium, organic acids, phosphates and proteins from potato wastewaters. In this process (35), the dilute wastes were first concentrated to 2.5% solids by inplant water use modifications, then the concentrate was subjected to ion exchange (73) which recovered inorganic cations and precipitated proteins. A second ion exchange recovered proteins and a third recovered organic acids (35). The protein recovered (19) would be used as an animal feed, and the cations as a fertilizer. A 1971 economic analysis of these processes (61), indicated that this scheme was not economically practical at that time. The best alternative was effluent drying of potato process wastes and utilization as animal feed. Protein recovery from

### TABLE 2. Technologies which result in increased yield and decreased waste production.

<table>
<thead>
<tr>
<th>Industry</th>
<th>Subcategory</th>
<th>Process</th>
<th>Increased yield</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meat</td>
<td>Beef</td>
<td></td>
<td>39%&lt;sup&gt;A&lt;/sup&gt;</td>
<td>(54)</td>
</tr>
<tr>
<td>Dairy</td>
<td>Cheese</td>
<td>Ultrafiltration</td>
<td>16-20%</td>
<td>(56)</td>
</tr>
<tr>
<td>Fruit and vegetables</td>
<td>Peaches</td>
<td>Lye peeling</td>
<td>Marginal</td>
<td>(83)</td>
</tr>
<tr>
<td></td>
<td>Pears</td>
<td></td>
<td>Marginal</td>
<td>(83)</td>
</tr>
<tr>
<td></td>
<td>Potatoes</td>
<td></td>
<td>12-40%</td>
<td>(51)</td>
</tr>
<tr>
<td></td>
<td>Pimiento</td>
<td></td>
<td>30%</td>
<td>(9)</td>
</tr>
<tr>
<td></td>
<td>Peppers</td>
<td></td>
<td>6%</td>
<td>(47)</td>
</tr>
<tr>
<td></td>
<td>Apples</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>A</sup>The increase in yield quoted here is an increase in meat acceptable for dry heat cooking from 29% in a conventional carcass to 68% in a Pro Ten carcass.

### TABLE 1. Solid and liquid wastes<sup>4</sup> generated during processing of food.

<table>
<thead>
<tr>
<th>Processed Food</th>
<th>Total solid waste (g/kg)</th>
<th>Liquid volume (mL/kg)</th>
<th>BOD&lt;sub&gt;5&lt;/sub&gt; (mg/kg)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetable</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kale</td>
<td>16</td>
<td>0.004</td>
<td>11,000</td>
<td>(8)</td>
</tr>
<tr>
<td>Spinach</td>
<td>20</td>
<td></td>
<td>11,000</td>
<td>(8)</td>
</tr>
<tr>
<td>Mustard greens</td>
<td>16</td>
<td></td>
<td>10,000</td>
<td>(8)</td>
</tr>
<tr>
<td>Turnip greens</td>
<td>15</td>
<td></td>
<td>9,000</td>
<td>(8)</td>
</tr>
<tr>
<td>Collards</td>
<td>13</td>
<td></td>
<td>8,000</td>
<td>(8)</td>
</tr>
<tr>
<td>Potatoes</td>
<td>66</td>
<td>0.012</td>
<td>44,000</td>
<td>(10,70)</td>
</tr>
<tr>
<td>Peppers (lye peel)</td>
<td>65</td>
<td>0.020</td>
<td>33,000</td>
<td>(9)</td>
</tr>
<tr>
<td>Tomatoes (lye peel)</td>
<td>14</td>
<td>0.010</td>
<td></td>
<td>(88)</td>
</tr>
<tr>
<td>Dairy</td>
<td>Cheese whey</td>
<td>9.000</td>
<td>270,000</td>
<td>(7)</td>
</tr>
<tr>
<td>Skim milk</td>
<td>0.070</td>
<td></td>
<td>1,500</td>
<td>(3)</td>
</tr>
<tr>
<td>Ice cream</td>
<td>0.080</td>
<td></td>
<td>3,000</td>
<td>(2)</td>
</tr>
<tr>
<td>Meat</td>
<td>Red</td>
<td>0.440</td>
<td>25,000</td>
<td>(2)</td>
</tr>
<tr>
<td></td>
<td>Poultry</td>
<td>0.270</td>
<td>50,000</td>
<td>(3)</td>
</tr>
<tr>
<td></td>
<td>Eggs</td>
<td>0.111</td>
<td>15,000</td>
<td>(32,37)</td>
</tr>
</tbody>
</table>

<sup>4</sup>Waste loads calculated per unit weight of product.
other processing wastes (e.g. dairy) by ion exchange has also been demonstrated (63) but its use is restricted by economic consideration.

Pressure filtration of waste solutions to remove water only (reverse osmosis) or to harvest large molecular weight components such as proteins (ultrafiltration) has also been a technique applied to wastes for by-product recovery. Whey proteins have been successfully harvested by ultrafiltration. In this process, a whey concentrate was produced containing 16% solids, of which 42% was protein (38). This protein concentrate could be used as is, or dried for food formulations. Reverse osmosis is usually more difficult to employ because of membrane fouling, but has been developed for recovery of protein from oilseed flour to reduce waste production (47) and produce protein isolates. Reverse osmosis has also been used to concentrate citrus centrifuge effluents (6). Electro dialysis has been suggested as a useful method for waste treatment. In this process, ionic species can be removed from solution with anion and cation selective membranes and an imposed voltage (38). The process has been described for reducing the ionic content of cheese whey proteins.

While these examples of nondestructive harvesting techniques are advantageous because they produce products that have undergone limited destruction, they can be expensive to operate and maintain. Therefore, other less costly harvesting techniques have been often employed. For example, flocculating or precipitating agents can be used to harvest specific large molecular weight products such as proteins from meat packing effluent. The Alwatech process is used commercially to precipitate meat proteins from meat packing effluents using lignosulfonic acid (an approved feed additive) to produce a protein-rich animal feed (31). A polymeric flocculating agent, chitosan, has also been suggested as a general flocculant for food processing wastes (11). Flocculating agents and precipitants are effective but may have limited uses in food by-product recovery until properly approved as food additives.

Heat or acid and base precipitation of proteins or other components from waste streams can be legally used in human foods, but these treatments can denature or alter the food value of the harvested components. Processes to precipitate proteins from food processing wastes have been demonstrated for meat (31,36) and vegetable processing industries (43,45,52). In most instances these precipitants are used as animal feeds (82).

In some instances the by-product recovered can be used directly in the human food system, e.g. whey proteins (38), or be further processed to yield important components such as flavors (43). However, in many instances the harvested by-product has little value in human foods and has been used for animal feeds (41). This is an excellent use for some human food wastes because food is recycled and maintained in the food system and may act as a substitute for human foodstuffs normally fed to animals. Feeding waste to animals is also desirable because they can often assimilate materials which humans can not. Feeding of both solid and liquid wastes to animals has been widely demonstrated. A silage-like product can be prepared from fruit and vegetable processing wastes (56) or solid wastes can be fed directly to ruminants (34) or swine (16). The liquid wastes from food processing may be harvested, dried and used as poultry or cattle feed. Many reports emphasize the feasibility of this approach to waste abatement (11,13,31,39,41,45,52,82). However, as energy costs continue to increase, drying may not be economically feasible.

Growing microorganisms in dilute wastes fortified with suitable nutrients has been suggested as a possible approach to pollution abatement (7,44). Often cells are grown until a suitable reduction in dissolved organic matter (BOD) is reached. The cells may be harvested by filtration or centrifugation and used as single cell protein (SCP) for animal feed. This process has been suggested by some (44,78), and demonstrated for many wastes including whey (57,58,87), citric acid waste (12,40), lye peeling effluents (7), cellulose wastes (18,25,29,61,89), potato waste water (48,60), coconut water (76), and rice straw (84), to name a few. Many of these processes are aerobic and require high energy inputs for aeration. For such costly inputs to be feasible, the conversion to cell mass must be rapid and very efficient and produce a high quality or easily extractible protein. A second valuable by-product of microbial metabolism, such as microbial oil, might also be produced to increase the financial attractiveness of the process (57,58). Anaerobic fermentations to produce ethanol are attractive because of the limited aeration necessary to produce a potentially valuable fuel as well as SCP. This process has also been demonstrated for many wastes (18,25,29,42,63), but is limited by the cost of distilling the ethanol. An alcoholic fermentation of whey to produce wine has been successfully demonstrated (66,69) and would avoid distillation costs.

Conversion of solid wastes to valuable by-products may be preferable to the common practice of landfill treatment (27). Silage production is feasible in some cases, as mentioned previously (56). Composting of some solid wastes has been suggested for ultimate use as soil conditioners (27,53). The potential fuel value of some wastes has been recognized by some (66,83), but the practice is limited by the energy expenditure necessary to dry the wastes.

The most common practice in food waste abatement practices has been to try and neutralize the effect of wastes on the environment (Fig. 2). Anaerobic and aerobic digestion and land application facilities have been modeled after traditional sewage treatment practices (24,71,75,91). Plants are designed on the basis of waste concentration and volume of flow. Minimization of dissolved organics in waste is important in waste treatment and can result from good plant management practices (74). The volume of waste-water produced in
food processing can be substantial. Reductions in volume are obvious for good process control and have been the subject of several national symposia sponsored by the Environmental Protection Agency, and other published reports (30,33,37,55,68,74,90).

Treatment of liquid wastes by classical anaerobic and aerobic digestion methods is popular because readily available engineering technologies can be easily applied to waste treatments. However, it is probably the least efficient from a systems point of view, as the waste products are not recycled in the food system as would be the case for use as animal feed or by-product recovery. The relative cost of digestion treatments has nonetheless made this the method of choice. As costs change thru governmental cost incentives (4) and increases in value of recoverable by-products, anaerobic and aerobic digestion may become less attractive.

SUMMARY

Waste production in the food system is defined by certain inherent biological limitations such as light conversion efficiencies. The limitations in subsequent processing steps are primarily technological. Many approaches to increase the efficiency of the overall waste utilization process have been developed. The most promising are those that regard waste as a resource and change technologies to harvest the most product (ultrafiltration, etc.). Increased research effort in this area should be emphasized, as it is likely to generate the most economically attractive benefits. When increased product recovery is not possible, the next best alternative is to harvest valuable by-products and recycle these in the food system. Alternatives such as composting, landfill and digestion as sewage may be employed most often but are least desirable from a food utilization and efficiency standpoint.

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