GLOBAL FOOD
WASTE NOT, WANT NOT.

Institution of
MECHANICAL
ENGINEERS

Improving the world through engineering

IT IS ESTIMATED THAT 30–50% (OR 1.2–2 BILLION TONNES) OF ALL FOOD PRODUCED ON THE PLANET IS LOST BEFORE REACHING A HUMAN STOMACH.

DR. TIM FOX
CENG FIMECHE
HEAD OF ENERGY
& ENVIRONMENT, IMECHE

With the global population estimated to reach 9.5 billion by 2075, mankind needs to ensure it has the food resources available to feed all these people. With current practices wasting up to 50% of all food produced, engineers need to act now and promote sustainable ways to reduce waste from the farm to the supermarket and to the consumer.

This report has been produced in the context of the Institution's strategic themes of Energy, Environment, Education, Manufacturing and Transport, and its vision of 'Improving the world through engineering'.

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EXECUTIVE SUMMARY

FEEDING THE 9 BILLION: THE TRAGEDY OF WASTE

By 2075, the United Nations' mid-range projection for global population growth predicts that human numbers will peak at about 9.5 billion people. This means that there could be an extra three billion mouths to feed by the end of the century, a period in which substantial changes are anticipated in the wealth, calorific intake and dietary preferences of people in developing countries across the world.

Such a projection presents mankind with wide-ranging social, economic, environmental and political issues that need to be addressed today to ensure a sustainable future for all. One key issue is how to produce more food in a world of finite resources.

Today, we produce about four billion metric tonnes of food per annum. Yet due to poor practices in harvesting, storage and transportation, as well as market and consumer wastage, it is estimated that 30–50% (or 1.2–2 billion tonnes) of all food produced never reaches a human stomach. Furthermore, this figure does not reflect the fact that large amounts of land, energy, fertilisers and water have also been lost in the production of foodstuffs which simply end up as waste. This level of wastage is a tragedy that cannot continue if we are to succeed in the challenge of sustainably meeting our future food demands.

WHERE WASTE HAPPENS

In 2010, the Institution of Mechanical Engineers identified three principal emerging population groups across the world, based on characteristics associated with their current and projected stage of economic development.

- Fully developed, mature, post-industrial societies, such as those in Europe, characterised by stable or declining populations which are increasing in age.
- Late-stage developing nations that are currently industrialising rapidly, for example China, which will experience decelerating rates of population growth, coupled with increasing affluence and age profile.
- Newly developing countries that are beginning to industrialise, primarily in Africa, with high to very high population growth rates (typically doubling or tripling their populations by 2050), and characterised by a predominantly young age profile.

Each group over the coming decades will need to address different issues surrounding food production, storage and transportation, as well as consumer expectations, if we are to continue to feed all our people.

Third World and Developing Nations
In less-developed countries, such as those of sub-Saharan Africa and South-East Asia, wastage tends to occur primarily at the farmer-producer end of the supply chain. Inefficient harvesting, inadequate local transportation and poor infrastructure mean that produce is frequently handled inappropriately and stored under unsuitable farm site conditions.

As the development level of a country increases, so the food loss problem generally moves further up the supply chain with deficiencies in regional and national infrastructure having the largest impact. In South-East Asian countries for example, losses of rice can range from 37% to 80% of total production depending on development stage, which amounts to total wastage in the region of about 180 million tonnes annually. In China, a country experiencing rapid development, the rice loss figure is about 45%, whereas in less-developed Vietnam, rice losses between the field and the table can amount to 80% of production.

BETTER USE OF OUR FINITE RESOURCES

Developed Nations
In mature, fully developed countries such as the UK, more-efficient farming practices and better transport, storage and processing facilities ensure that a larger proportion of the food produced reaches markets and consumers. However, characteristics associated with modern consumer culture mean produce is often wasted through retail and customer behaviour.

Major supermarkets, in meeting consumer expectations, will often reject entire crops of perfectly edible fruit and vegetables at the farm because they do not meet exacting marketing standards for their physical characteristics, such as size and appearance. For example, up to 30% of the UK's vegetable crop is never harvested as a result of such practices. Globally, retailers generate 1.6 million tonnes of food waste annually in this way.

Of the produce that does appear in the supermarket, commonly used sales promotions frequently encourage customers to purchase excessive quantities which, in the case of perishable foodstuffs, inevitably generates wastage in the home. Overall between 30% and 50% of what has been bought in developed countries is thrown away by the purchaser.

Controlling and reducing the level of wastage is frequently beyond the capability of the individual farmer, distributor or consumer, since it depends on market philosophies, security of energy supply, quality of roads and the presence of transport hubs. These are all related more to societal, political and economic norms, as well as better-engineered infrastructure, rather than to agriculture. In most cases the sustainable solutions needed to reduce waste are well known. The challenge is transferring this know-how to where it is needed, and creating the political and social environment which encourages both transfer and adoption of these ideas to take place.

Wasting food means losing not only life-supporting nutrition but also precious resources, including land, water and energy. These losses will be exacerbated by future population growth and dietary trends that are seeing a shift away from grain-based foods and towards consumption of animal products. As nations become more affluent in the coming decades through development, per capita calorific intake from meat consumption is set to rise 40% by mid-century. These products require significantly more resource to produce. As a global society therefore, tackling food waste will help contribute towards addressing a number of key resource issues:

Effective Land Usage
Over the last five decades, improved farming techniques and technologies have helped to significantly increase crop yields along with a 12% expansion of farmed land use. However, with global food production already utilising about 4.9Gha of the 10Gha usable land surface available, a further increase in farming area without impacting unfavourably on what remains of the world's natural ecosystems appears unlikely. The challenge is that an increase in animal-based production will require greater land and resource requirement, as livestock farming demands extensive land use. One hectare of land can, for example, produce rice or potatoes for 19–22 people per annum. The same area will produce enough lamb or beef for only one or two people. Considerable tensions are likely to emerge, as the need for food competes with demands for ecosystem preservation and biomass production as a renewable energy source.

Water Usage
Over the past century, fresh water abstraction for human use has increased at more than double the rate of population growth. Currently about 3.8 trillion m^3 of water is used by humans per annum. About 70% of this is consumed by the global agriculture sector, and the level of use will continue to rise over the coming decades. Indeed, depending on how food is produced and the validity of forecasts for demographic trends, the demand for water in food production could reach 10–13 trillion m^3 annually by mid-century. This is 2.5 to 3.5 times greater than the total human use of fresh water today.

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IN SOUTH EAST ASIAN COUNTRIES, LOSSES OF RICE CAN RANGE FROM 37–80% OF THE ENTIRE PRODUCTION.

Better irrigation can dramatically improve crop yield and about 40% of the world's food supply is currently derived from irrigated land. However, water used in irrigation is often sourced unsustainably, through boreholes sunk into poorly managed aquifers. In some cases government development programmes and international aid interventions exacerbate this problem. In addition, we continue to use wasteful systems, such as flood or overhead spray, which are difficult to control and lose much of the water to evaporation. Although the drip or trickle irrigation methods are more expensive to install, they can be as much as 33% more efficient in water use as well as being able to carry fertilisers directly to the root.

In processing of foods after the agricultural stage, there are large additional uses of water that need to be tackled in a world of growing demand. This is particularly crucial in the case of meat production, where beef uses about 50 times more water than vegetables. In the future, more-effective washing techniques, management procedures, and recycling and purification of water will be needed to reduce wastage.

Energy Usage

Energy is an essential resource across the entire food production cycle, with estimates showing an average of 7–10 calories of input being required in the production of one calorie of food. This varies dramatically depending on crop, from three calories for plant crops to 35 calories in the production of beef. Since much of this energy comes from the utilisation of fossil fuels, wastage of food potentially contributes to unnecessary global warming as well as inefficient resource utilisation.

In the modern industrialised agricultural process – which developing nations are moving towards in order to increase future yields – energy usage in the making and application of agrochemicals such as fertilisers and pesticides represents the single biggest component. Wheat production takes 50% of its energy input for these two items alone. Indeed, on a global scale, fertiliser manufacturing consumes about 3–5% of the world's annual natural gas supply. With production anticipated to increase by 25% between now and 2030, sustainable energy sourcing will become an increasingly major issue. Energy to power machinery, both on the farm and in the storage and processing facilities, together with the direct use of fuel in field mechanisation and produce transportation, adds to the energy total, which currently represents about 3.1% of annual global energy consumption.

RECOMMENDATIONS

Rising population combined with improved nutrition standards and shifting dietary preferences will exert pressure for increases in global food supply.

Engineers, scientists and agriculturalists have the knowledge, tools and systems that will assist in achieving productivity increases. However, pressure will grow on finite resources of land, energy and water. Although increasing yields in hungry countries is an appropriate response to an emerging food crisis, to ensure we can sustainably meet the food needs of over three billion extra people on the planet by 2075, the Institution of Mechanical Engineers calls for initiatives to be taken to reduce the substantial quantity of food wasted annually around the world. The potential to provide 60–100% more food by simply eliminating losses, while simultaneously freeing up land, energy and water resources for other uses, is an opportunity that should not be ignored. Factors affecting waste relate to engineered infrastructure, economic activity, vocational training, knowledge transfer, culture and politics. In order to begin tackling the challenge, the Institution recommends that:

1. The UN Food and Agriculture Organisation (FAO) works with the international engineering community to ensure governments of developed nations put in place programmes that transfer engineering knowledge, design know-how, and suitable technology to newly developing countries. This will help improve produce handling in the harvest, and immediate post-harvest stages of food production.
2. Governments of rapidly developing countries incorporate waste minimisation thinking into the transport infrastructure and storage facilities currently being planned, engineered and built.
3. Governments in developed nations devise and implement policy that changes consumer expectations. These should discourage retailers from wasteful practices that lead to the rejection of food on the basis of cosmetic characteristics, and losses in the home due to excessive purchasing by consumers.

FEEDING A GROWING GLOBAL POPULATION

The world's human population is currently estimated to be in excess of seven billion people[1] and median variant projections of growth over the 21st century from the UN suggest that the number might peak at about 9.5 billion towards 2075.[2] If the less conservative projections from the UN are realised, this peak could be as high as 14.2 billion.[3] However, such overall numbers do not reveal the spatial variation and demographic trends that might be expected to emerge as changes take place across the globe. Indeed, there are considerable differences in the growth rates, age composition and socio-economic outcomes projected for different regions of the world during the next few decades. In this regard, the Institution of Mechanical Engineers has previously identified three principal emerging groups based on characteristics associated with their current and projected stage of economic development.[2] These are:

- Fully developed, mature, post-industrial societies, such as those in Europe, characterised by stable or declining populations increasing in age profile.
- Late-stage developing nations that are currently industrialising rapidly, for example China, which will experience decelerating rates of population growth, coupled with increasing affluence and increasing age profile.
- Newly developing countries that are beginning to or about to industrialise, primarily in Africa, with high to very high population growth rates (typically doubling or tripling their populations by 2050), characterised by a predominantly young age profile.

It is from the last grouping that the principal contribution to 21st century population growth is projected to arise.

Meeting the food requirements of an increasing number of people, as we move towards 9.5 billion, will present many significant physical, political and socio-economic challenges. Finding acceptable solutions to these will require engineers to share engineering practice knowledge widely in society, and exercise ingenuity in providing innovative sustainable approaches, alongside the contributions from scientists and agriculturalists. The overall scale of the challenge is indicated by other long-term projections, based upon population growth, which suggest a 70% increase in the demand for agricultural production will have emerged by mid-century.[4] This will be compounded by a significant shift away from a predominance of grain-based diets towards substantial consumption of animal products, as nations become more affluent[5]. Indeed, forecasts have indicated a potential increase during the next four decades of about 40% in global average per capita calorific intake through meat consumption from 440kcal to 620kcal per day,[6] with large regional variations linked to the stage of development of individual countries. For example, in East Asia and Sub-Saharan Africa, annual per capita meat consumption by weight is projected to increase by 55% and 42% respectively through to 2030, whereas in the fully industrialised countries, including Europe and North America, the projected increase is only 14%.[7]

To date, history has shown that in response to population growth and dietary changes, engineering and science consistently deliver advancements that enable increased yields and production to meet demand.[2] For example between 1960 and 2000, production of rice, maize and wheat grew by 66–88% in Asia and Latin America[8]. This three-fold increase in yields of cereal crops was achieved by the introduction of high-yield varieties, the application of chemically engineered fertilisers and advancements in crop management techniques. Over the same period, average global meat consumption in terms of weight per capita per year increased 50%, with a doubling and tripling in East and North Africa and East Asia respectively[7]. Indeed, it is over 200 years since, with the global population at about one seventh of what it is today, the Reverend Thomas Malthus made his now famous prediction, that sooner or later further population growth would be checked by famine, disease and widespread mortality.[9] This prediction was echoed in the work of Paul Ehrlich in the 1960s[10] and is yet to be shown to be relevant in the context of human ingenuity, adaptability and inventiveness.

There are identifiable and known opportunities today to increase yields into the future.[11] In sub-Saharan Africa for example, where the largest population increases are anticipated, work on the Millennium Villages[12] initiative by New York's Columbia University has shown that through addressing the issues of depletion of soil nutrients, it is possible to more than triple cereal grain yields from one tonne per hectare (where it has been since the 1960s) to beyond three tonnes per hectare.[8] This has been largely achieved through closer control of fertiliser application, improved cultivars (high-yield seeds) and the application of up-to-date engineering and agronomic knowledge. For those villages involved, this has meant that their annual food production has increased in excess of their calorific needs.[13] Similarly, the implementation by the Malawi government of incentives for improved cultivars combined with fertiliser application, has led to a tripling of maize yields, transforming the nation from a food aid recipient to a food exporter and food aid donor.[13] These and many other examples suggest that in sub-Saharan Africa, food security can be substantially improved into the future through an ecologically sound Green Revolution based on science and engineering.[13]

However, although there is a consensus among agriculturalists and policymakers that increasing agricultural productivity in hungry countries is an appropriate response to an emerging world food crisis,[13] several factors have the potential to obstruct progress. These include:

- The area of land available for agriculture will reduce due to factors including environmental degradation, stresses related to climate change, restrictions aimed at preservation of ecosystems, and competition with other land-use demands such as biomass-derived energy initiatives, urbanisation, transport, industrial and leisure needs.
- Increased competition for available water from urban developments and industry will reduce the quantities available for crop and livestock production in a world of uncertain rainfall patterns due to the effects of global warming.
- Energy costs, particularly for fossil fuels, are likely to rise substantially with increasing demand and reducing availability of easily exploitable secure supplies. This applies to fuels used directly to power field machines, processing equipment, transportation and storage facilities as well as to the significant amount of natural gas that is used in the production of fertiliser and pesticides.
- Problems in recruiting labour to work in agriculture as nations develop and many alternative occupations arise, which are considered to be more attractive by younger generations.

Although solutions to these issues may emerge over time, in addition to a focus on increased food production, it would be prudent to develop and implement a range of approaches in parallel that can help mitigate their potential impact. One such approach is to recognise the amount of food that is wasted annually across the world and work to make substantial reductions in this quantity.

The total quantity of food produced globally on an annual basis is currently about four billion metric tonnes,[14] of which it is estimated by the Institution that 30–50%, or 1.2–2 billion metric tonnes, is lost or wasted every year before consumption (for further reading on estimates see, for example, FAO and SIWI reports[14,15]). This enormous waste of food is due to the combined effects of regional deficiencies in agricultural knowledge, inadequacies in engineered infrastructure and management practices, as well as wasteful political, economic and societal behaviours. If the world population is projected to increase by about 35% to a peak of 9.5 billion in 2075, and eliminating this waste has the potential to provide 60–100% more food for consumption, then in simple terms there is a clear opportunity to provide a major contribution towards meeting the growing demand for food in the 21st century merely through waste reduction and elimination. Furthermore, due to the large demand that food production puts on other natural resources including land, water and energy, such an approach offers significant benefits in terms of sustainability and reduced environmental risk.

The Institution of Mechanical Engineers recognises that the only sustainable strategy for providing sufficient food for future generations is not only to seek the most efficient and effective methods of food production, but also to concentrate effort on ensuring that as much of that food as possible is fully utilised by the human population. This report therefore considers from an engineering perspective, key factors contributing to the current unacceptable level of food waste across the world, as well as the wider implications of these for sustainably supporting the projected population growth in the 21st century, and presents practical solutions to the key issues along with recommendations for change.

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OVER 2.5 TRILLION M³ OF WATER IS CONSUMED BY THE GLOBAL AGRICULTURAL SECTOR EACH YEAR.

RESOURCES USED IN FOOD PRODUCTION

The global food supply system is an extensive worldwide network engaging a broad range of individuals and businesses including farmers, processors, logistics specialists and traders, ranging in scale from multinational chains to the corner shop and market stall. Supported by engineers, technologists and scientists, all play their roles in producing a perishable product and delivering it in good condition to the consumer. The wide range of foodstuffs handled by the system include those derived from plants such as cereal grains, pulses, oilseeds, vegetables and fruit, and those derived from animals including meat, eggs and dairy products.

Farmers and horticulturalists operating in every region of the world produce a vast quantity of food, totalling about four billion tonnes of edible product per year. In doing so they utilise large quantities of a variety of resources and raw materials (often referred to as 'inputs'). Many of these inputs are from finite sources, and in many cases food production is in competition with other human endeavours for their use. Wasting food therefore results in an unneccessary and unsustainable use of these resources. This section considers the resources used in food production and the scale of their use. In addition to the obvious items of land, people and water, energy is used to drive agricultural field machinery, greenhouses, irrigation systems, storage facilities, transportation and the production of fertilisers and pesticides.

LAND

Global food production currently utilises approximately 4.9Gha of the 14.8Gha of land surface area on the planet, though only about 10Gha of the latter is capable of supporting productive biomass (ie not desert, tundra, mountains etc) for agriculture.[16,17] Thus some 50% of the available suitable land is already appropriated. The amount of land used for human habitation, in the form of towns and cities, is realtively small at 0.03Gha and, despite large-scale urbanisation in the future, it is unlikely to become significant in proportional terms. Although this might suggest that there is plenty of room for the expansion of food production, it needs to be recognised that the balance of unused land currently supports the world's remaining natural ecosystems. Considerable tensions are likely to emerge as competition develops for use of available land between the need for food production, demands for preservation of ecosystems and the desire to produce biomass as a source of renewable energy.[17]

During the past few decades, the increasing demand for food associated with a period of unprecedented global population growth has been largely met by increasing yields and, to a lesser extent, expansion of farmed land (historically the route to increased production). In this regard, as yields have improved substantially, through the implementation of improved cultivars, engineering and field practices, increased production between 1960 and 2000 was achieved with a relatively modest land-use expansion of only 12%.[17] However, emerging evidence suggests a substantial global trend in developing nations, of dietary preferences shifting away from cereals and grains to consumption of animal products[5] (for example, in China between 1981 and 2004, the annual per capita grain consumption declined from 145kg to 78kg in the cities, while over the same period intake of meat products rose from 20kg to 29kg per year).[18] This indicates that the challenge of increased production will become much harder in the coming decades, particularly if substantial damage to the world's ecosystems through expansion of agricultural land area is to be avoided.

The core of the challenge is found in the fact that in terms of land-use, agricultural food production based on livestock is far less efficient than that based on crops, largely because only about 3% of the feed energy consumed by livestock remains in edible animal tissue.[17] Thus, animal-based agriculture needs considerably greater areas of land to output product of equivalent energy value; for example while one hectare of land is needed to produce sufficient rice or potatoes to feed 19 to 22 people per year, the same area would produce enough lamb or beef to supply only one or two people. For this reason, 78% of current agricultural land is already used for livestock production, either for direct grazing or feed crops.

Forecasts for the amount of land that will be needed to deliver sufficient food to feed the increasing population through the 21st century are highly dependent on assumptions made regarding trends in these dietary preferences. Indeed recent work in this area[17] has attempted to comprehensively and realistically analyse a range of possible scenarios through to 2050, ranging from a high-meat consumption: low production efficiency 'worse case', to one characterised by a 'best case' of low-meat consumption: high production efficiency. In the former the total land use area under cultivation would require expansion to 8.83Gha by 2050 to meet the food demand, which at about 88% of available productive land is a considerable threat to the world's ecosystems, whereas in the latter a contraction to 4.13Gha would occur, representing about a 15% reduction on today's figure.

In these scenarios, high production efficiency considers a sustained annual yield growth of 1% and increased recycling of wastes and residues, together with adoption of a diet composed of a substantial amount of pork and poultry product which characteristically has a less-demanding land-use requirement. Given current trends in both dietary preferences and production efficiency, it is concievable that something closer to a high meat consumption/high production efficiency outcome may emerge and in that case the land-use figure for food production would, following a 2025 peak of 5.26Gha, fall back to around present levels at 4.82Gha in 2050. In the context of a productive land resource of about 10Gha, such an outcome might appear reasonable. However, adding the land-use demands that will emerge from current aspirations around the world to increase biomass production for energy sourcing, potentially up to 30% of global primary energy by 2030 compared with about 10% today,[19] competing needs for food and energy are likely to define the key land-use tensions in the coming decades.

WATER

All branches of agriculture and horticulture depend on a reliable supply of water delivered by natural rainfall, watercourses such as springs, ponds, rivers and streams, or by engineered means including irrigation, hydroponics and others. Over the past century, human appropriation of fresh water has historically expanded at more than twice the rate of population increase. An estimated 3.8 trillion m^3 of water are now withdrawn for human use each year,[20] equivalent to the contents of 1.5 billion Olympic-sized swimming pools. The bulk of this abstracted water, about 70%, is taken by the agricultural sector.[2]

It takes substantial quantities of water to grow and harvest food, and even more water is required if the food is processed before consumption. Assuming that the food supply for an average person is 3,000kcal per day by 2050 and is derived 80% from plants and 20% from animals, the water needed to produce that quantity of food will be around 1,300 m^3 per capita per year[21] (eg half the contents of an Olympic-sized swimming pool per person each year). It has been estimated that water requirements to meet food demand in 2050 might, depending on how food is produced and the validity of current assumptions on future trends in population and diet, be between 10 and 13.5 trillion m^3 per year, or about triple what is currently abstracted in total for human use.[22]

While detailed estimates of the water requirements for specific crops and livestock products vary considerably, most studies agree on the main points. Essentially foodstuffs derived from crops consume a small fraction of water compared to those derived from animals. Within the crop category, potatoes, groundnuts and onions are quite efficient in terms of their use of water. For every cubic metre of water applied in cultivation, the potato produces 5.60kcal of dietary energy, compared to 3.86kcal calories in maize, 2.3kcal in wheat and just 2kcal in rice.[23] For the same cubic metre of water, the potato yields 150g of protein, double that of wheat and maize, and 540mg of calcium, double that of wheat and four times that of rice. For example, depending on climate, variety, agricultural practices, length of the growing season and degree of onward processing, between 500 and 4,000 litres of water are required to produce 1kg of wheat.[24] But to produce 1kg of meat requires between 5,000 and 20,000 litres of water.[25] In general overall terms the energy content of food materials varies from approximately 2kcal per cubic metre of water in the case of plant-based food and 0.25kcal per cubic metre for food derived from animals.[26]

Irrigation
Irrigation is delivered through engineering and has the potential to dramatically increase food production. Currently it is estimated that about 40% of the world's food supply is produced on irrigated land that extends to approximately 17% of available agricultural land.[27] Expansion and more effective use of existing irrigation schemes will be necessary in future if the current per capita food supply is to be maintained.[28] However, the systems used for irrigation in many countries are in poor condition or use water inefficiently. Where they rely on pumping, wasting water also wastes energy.

Despite the fact that flood or overhead spray irrigation systems are difficult to control and waste water (for example the continued use of overhead sprays results in large quantities of water being lost through evaporation, while poorly managed irrigation increases the risk of loss of large areas of productive land to salinity), many countries still persist in their use. Designs based on drip or trickle irrigation require more capital investment than flood or spray techniques, but studies[29] have shown that it can be 33% more effective than those two cheaper methods in terms of crop produced for each unit of water applied. Drip or trickle irrigation also offers the further benefit that it can be engineered to enable fertilisers to be applied directly to the roots of the plants where they provide greatest benefit, without the necessity for specialist fertiliser application machines. Improved methods of land preparation for irrigation, including the use of GPS-controlled precision levelling systems, can further enhance the performance of drip irrigation systems.

In some countries, for example Saudi Arabia, India and Pakistan, self-sufficiency programmes have subsidised the cost of energy for irrigation, or in extreme cases provided free energy.[30] This frequently encourages waste of both water and energy while denying water to villages and other farms that need this precious resource.

For a number of years, Saudi Arabia pursued a policy of self-sufficiency in wheat and dairy products,[31] heavily subsidising the entire process of bread production and the keeping of dairy cattle. Ever deeper boreholes were required to access water for large-scale irrigation schemes in order to grow wheat and alfalfa in an arid desert. Even though this was successful from a technical perspective, it was not sustainable due to the high cost of pumping water from great depths and the lack of an aquifer replenishment programme. The latter is an essential requirement for the sustainable engineering and management of underground water supplies.[2] Farmers in many countries have traditionally relied on various forms of well to supply irrigation water; however for success this is highly dependent on the rate of natural or artificial replenishment.

India and Pakistan have suffered from similar challenges. The Indian state subsidised the cost of electrical power for irrigation, which resulted in over-application and wasted water; since the water essentially had no cost, it had no value. In Pakistan, some Central African states and parts of the Middle East, the proliferation of boreholes often funded by international agencies, drained aquifers to the extent that only saline water could be produced.

Demands for irrigation water frequently compete directly with those of urban populations and industry. The Eastern States of the USA have experienced bitter disputes between farmers and urban populations over water rights, and this situation is being repeated in Southern Australia [32] In the Middle East, there have been long-running disputes over access to water between Turkey and Syria,[33] Palestine and Jordan.[34] It is very likely that such disputes will become more common and bitterly contested in the future, particularly as climate change induced stresses increase[35].

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BY 2050, BETWEEN 10–13.5 TRILLION M³ OF WATER MAY BE NEEDED IN FOOD PRODUCTION EACH YEAR.

PROCESSING

Beyond the agricultural stage of food production, subsequent processing of basic foodstuffs can consume considerable additional quantities of water. For example, a recent study in the USA discovered that companies processing a range of vegetables consumed between 13 and 64 tonnes of water for each tonne of vegetables.[36] In the case of fruits, consumption ranged from 3.5 to 32 tonnes of water for each tonne of fruit. **Table 1** shows a detailed listing, from a recent Europe-based study,[37] of the water consumption figures for the processing of a wide range of food products. The large quantities typically involved for each product suggest that there is scope for mechanical engineering to reduce the volume of water required, for example through the introduction of more-efficient washing systems, improved water recycling and other advanced measures,[38] as well as the introduction of more-effective management procedures.

Table 1: Typical values for the volume of water required to produce common foodstuffs[37]

Foodstuff	Quantity	Water consumption
Apple	1 kg	822 litres
Banana	1 kg	790 litres
Beef	1 kg	15,415 litres
Beer	1 × 250ml glass	74 litres
Bio-diesel	1 litre	11,397 litres
Bread	1 kg	1,608 litres
Butter	1 kg	5,553 litres
Cabbage	1 kg	237 litres
Cheese	1 kg	3,178 litres
Chicken meat	1 kg	4,325 litres
Chocolate	1 kg	17,196 litres
Egg	1	196 litres
Milk	1 × 250ml glass	255 litres
Olives	1 kg	3,025 litres
Pasta (dry)	1 kg	1,849 litres
Pizza	1 unit	1,239 litres
Pork	1 kg	5,988 litres
Potatoes	1 kg	287 litres
Rice	1 kg	2,497 litres
Sheep Meat	1 kg	10,412 litres
Tea	1 × 250 ml cup	27 litres
Tomato	1 kg	214 litres
Wine	1 x 250ml glass	109 litres
Cotton	1 @ 250g	2,495 litres

ENERGY

Energy is a key engineered resource across all food production stages and it has been estimated that, if the contribution consumed in processing and transporting food is included, it takes an average input of 7–10 calories of energy to produce one calorie of edible food.[39] Much of this energy currently comes from fossil fuel sources, which makes it problematic with regard to its potential contribution to global warming and subsequent climate change. The overall 7–10 calorie average figure does not however reveal the differences between plant-based and meat-based foods. For example about 3 calories of energy are needed to create 1 calorie of edible plant material, whereas grain-fed beef requires some 35 calories for every calorie of beef produced.[39] This clearly has implications for sustainability if global dietary trends continue to move towards high meat content.

Table 2 illustrates the breakdown of energy consumption for each component for the case of a typical wheat production process.[40] This clearly shows that the single biggest energy input in modern industrialised arable farming is in the use of agrochemicals (fertilisers, pesticides, growth agents etc). As much as 50% of energy used in this example of a modern engineered food system goes towards the production of artificial fertilisers and pesticides. These chemicals are absolutely critical to the supply side of the equation. Increased fertiliser application has in the past been responsible for at least 50% of yield increases.[41]

Table 2: Typical values for energy consumed in wheat production[40]

Source/application	MJ/ha	
Human	6	(0.03%)
Seed	1,266	(5.60%)
Fertiliser	10,651	(47.20%)
Pesticides	911	(4.00%)
Electricity	4,870	(21.60%)
Machinery	1,741	(7.70%)
Fuel	3,121	(13.83%)
Total	22,566	

Fertiliser

Large quantities of chemical or mineral fertilisers are used in commercial agriculture. Generally these contain nitrogen compounds – primarily anhydrous ammonia, ammonium nitrate or urea, which are powerful stimulants to the growth of green plants – together with varying proportions of compounds containing phosphorous and potassium, frequently referred to as phosphate and potash. In the period 1961 to 1999, the use of nitrogenous and phosphate fertilisers increased by 638% and 203%,[42] respectively, while the production of pesticides increased by 854%.[43]

Although phosphate and potash compounds are typically obtained by mining minerals, nitrogen compounds are manufactured from ammonia using the Haber process. In the latter, atmospheric nitrogen is combined with hydrogen obtained largely from natural gas though other hydrocarbons sources such as coal (particularly in China) and oil are also used. Since 950m^3 of natural gas is required to produce each tonne of ammonia (global production of fertiliser is currently some 178 million tonnes per year),[44] the fertiliser manufacturing industry consumes roughly 3–5% of the entire world natural gas production, equivalent to 1–2% of the world's annual energy supply.[45] Producing and distributing nitrogen fertilisers currently requires an average of 62 litres of fossil fuels per hectare. Given that the amount of land under modern farming methods is anticipated to increase by 12.5% in the coming three decades,[46] as a result of the transfer of engineering and agricultural practice knowledge to developing countries, it is projected that demand for this resource will increase substantially by mid-century. The total annual demand for fertiliser has been estimated to increase 25% by 2030 to 223 million tonnes, of which some 62% would be nitrogenous.[47]

Storage
Frequently, crops as they are harvested from the field are not in a suitable condition to be stored for long periods. In many countries, grains including wheat, maize and rice are too damp for direct transfer to storage, so need to be dried. Drying large quantities of material requires substantial amounts of energy to be delivered through engineered infrastructure, particularly in the form of electricity or fossil fuels such as oil or gas. Once dried and placed in storage, the condition of the stored commodity must be maintained, which is a further demand on energy supplies. Moulds and fungi will quickly affect most foodstuffs if their moisture content is too high, but since they cannot reproduce at low temperatures, the food can be stored quite safely if the temperature is below a critical level; maintaining that level needs additional energy to provide heating or cooling, depending on the local conditions.

Processing
Food processing also uses large amounts of electricity and/or fossil fuels, and can be remarkably inefficient in terms of the energy consumed relative to the energy delivered to the consumer. Unfortunately the detailed analysis of actual energy usage in processing is highly individual to a specific food type, difficult to ascertain and not amenable to broad generalisation. As a convenient illustration, **Table 3** is presented for a typical fast-food burger sandwich.[48]

The total engineered energy consumption of the burger sandwich is high in comparison to many fresh foods, since several of its components undergo processing and are prepared remotely, then chilled or frozen, before transportation for distribution and thawed subsequent to reheating. Since the end product contributes 540kcal or 2.3MJ to the consumer's diet,[49] it typically uses between three and eight times more energy in its production and distribution than it delivers to the consumer as food.

Table 3: Typical energy consumption from human engineered energy (ie not derived directly by the product from nature) for components of a typical fast-food burger.[48]

	Low MJ	**High MJ**
Bread 74g	0.96	3.20
Burger 90g	5.60	10.00
Lettuce	0.09	4.36
Onions	0.06	0.12
Pickled Cucumber	0.05	0.06
Cheese	0.54	0.90
Total	7.30	18.64

It is important to note that even with this standardised food item there can be considerable variations in energy consumption, depending on how or where each of the ingredients is produced. For example, lettuces grown in a greenhouse generally require a much greater input of engineered energy than do those grown in a field, but variations to this norm will result if the vegetable is being transported a significant distance from soil bed to outlet. As one example of this, some 90% of the entire US lettuce crop is produced in the Salinas valley in California, and transported countrywide by refrigerated truck or even aircraft.

Machines

Modern agricultural production is heavily reliant on machinery, and this represents another big consumer of energy in the food production chain. As engineers have improved the design and performance of machines, many large-scale farms in the most-developed countries have been able to function with smaller teams of people operating increasingly powerful and sophisticated equipment. In this regard, precision GPS systems have been in use since the late 1980s and facilitate precise control of many field operations through intelligent machines communicating with system-equipped tractors that incorporate multiple electronics. This high-powered equipment enables field operations to be carried out effectively, and with the minimum use of labour, at the most appropriate time for the crop.

In developing countries, manual labour and draught animals are increasingly being replaced by smaller machines engineered for low-cost manufacture. Two-wheel-drive 'walking tractors', often equipped with a range of implements for cultivation, seeding, harvesting and transport, have been in common use in Asia for many years, but are now being adopted in large numbers throughout Africa. Diesel engines are also being used in increasing numbers to provide power for small-scale processing plants such as mills, where they replace traditional manual methods. Agriculture currently consumes approximately 3.1% of total global energy consumption, this is divided 2.5% in developed countries and 0.6% in developing countries.[50] As the rate of adoption of agricultural machines increases in developing countries, both the total proportion of agricultural energy use and the component used in developing countries are likely to rise.

Almost all field equipment is powered by diesel engines. These include farm tractors, harvesting machines and a wide range of mechanical handling and transport equipment. In addition, diesel-powered irrigation pumps are vitally important but consume large quantities of energy. All of this contributes to a global consumption by agriculture of approximately 120 million tonnes of diesel fuel annually.[51]

As populations become more concentrated in urban areas, fewer people are available and willing to work as labourers in primary agriculture, which is a major driving force in farm mechanisation and the use of engineered infrastructure. The use of machinery can be expected to expand significantly in future years but its adoption may be constrained by the availability of knowledge, political will and the cost of fuels.

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AGRICULTURE CURRENTLY CONSUMES APPROXIMATELY 3.1% OF TOTAL GLOBAL ENERGY CONSUMPTION.

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IN INDIA, 21 MILLION TONNES OF WHEAT IS WASTED EACH YEAR DUE TO INADEQUATE STORAGE AND DISTRIBUTION SYSTEMS.

WASTING WHAT WE ALREADY HAVE

Reducing the current level of food waste, which on a global scale represents up to 50% of the 4 billion tonnes of food production every year,[14,15] offers a significant opportunity for helping to meet the challenge of feeding the world's increasing population, as well as conserving diminishing resources that could be utilised for other human activities. Finding those opportunities, however, requires an understanding of the pattern and scale of wastage. This varies as a function of economic development stage[52], since many factors affecting wastage relate to engineered infrastructure, economic activity, knowledge transfer and level of vocational training, rather than purely agricultural policies.

In less-developed countries, such as those of sub-Saharan Africa and South-East Asia, wastage tends primarily to occur at the farmer-producer end of the supply chain.[52,53] In this regard, inefficient harvesting, inadequately engineered local transport systems and deficiencies in infrastructure mean that crops are frequently handled poorly and stored under unsuitable farm site conditions or in inadequate local facilities. As a result, bruising, moulds and rodents destroy or at least degrade large quantities of food material, and substantial amounts of foodstuffs simply spill from badly maintained vehicles or are bruised as vehicles negotiate poorly maintained roads. In South-East Asian countries, for example, losses of rice range from 37%(54a) to 80%(54b) of the entire production, depending on development stage, and total about 180 million tonnes annually. In China, a country experiencing rapid development, the figure is about 45% whereas in less-developed Vietnam, rice losses between the field and the table can amount to 80% of production.[54b] Cumulatively this loss represents not only the removal of food that could otherwise feed the growing population, but also a waste of valuable land, energy and water resources. In the case of water for example, about 550 billion m^3 of water is wasted globally in growing crops that never reach the consumer;[55] this water could be used for other human activity or to support natural ecosystems.

Wastage tends to move up the distribution chain as the standard of development improves and regional and national transport, storage and distribution facilities fail to match the improvements made at the farm level. This is a particular issue in transition countries, including India and the former Soviet Republics, which require massive investments in the food logistics chain. Many of the grain stores in the former Soviet Republics were engineered and constructed in the 1930s, and cold-storage warehouses and food processing facilities date back to the 1950s. As a result they are inefficient by modern engineering standards, and frequently both insanitary and unsafe. The current practices in the developed world of preserving food by chilling and freezing instead of canning and drying, place significant demands on the integrity of infrastructure, which exacerbates this problem. Maintaining a cold chain for fresh or chilled food is significantly more demanding of engineering than merely transporting and storing a relatively robust product such as a can. It demands the engineering of reliable electricity supplies, transport and interchanges, plus measurement, monitoring and continual management, which is often beyond the technical capacity of transitioning countries.

Moving from canning to freezing demands energy infrastructure

The process of canning or preserving food products in hermetically sealed jars requires significant energy input at the processing plant, but once the package is sealed, no further energy is required to preserve the food. Unfortunately, although chilling or freezing produces a food product that retains more of its original nutrients, this type of processed food needs a secure cold chain throughout its distribution and storage, right down to household level, necessitating the provision of a reliable energy infrastructure to every store, vehicle and home.

FIELD WASTAGE

In mature, fully developed countries, more-efficient farming practices and better-engineered transport, storage and processing facilities ensure that a much greater proportion of the food product reaches the locality where it will be consumed. However, at this level behavioural characteristics associated with consumerism, excess wealth and mass marketing lead to wastage[52,53]. Key points at which these losses occur include in the field prior to harvesting, at the supermarket and in the consumer's home. For example, substantial quantities of perfectly edible fruit and vegetables are rejected by the major buyers at the farm in the pre-harvest stage because they do not meet marketing standards for their physical characteristics, such as size and appearance. For that produce that does appear in the supermarket, strategies for sales promotion frequently encourage customers to purchase excessive quantities which, in the case of perishable foodstuffs, inevitably generates wastage in the home[52].

Overall, wastage rates in vegetables and fruit are considerably higher than for grains. In the UK, a recently published study[56] has shown that 46% of potatoes grown is not delivered to the retail market. The details revealed that 6% was lost in the field, 12% was discarded on initial sorting, 5% was lost in store, 1% was lost in post-storage inspection and 22% was lost due to rejection after washing. A similar survey[57] in India showed that at least 40% of all its fruit and vegetables is lost between grower and consumer due to lack of refrigerated transport, poor roads, inclement weather and corruption. Controlling and reducing the level of wastage is frequently beyond the capability of the individual farmer, distributor or consumer, since it depends on market philosophies, security of power supply, quality of roads and the presence or absence of transport hubs. These are all related more to societal, political and economic norms, as well as engineered infrastructure, rather than to agriculture.

In mature, developed economies such as the UK and USA, the purchasing policies for fresh produce operated by the major supermarkets actively encourage waste in the field. In this regard, rather than entering into supply contracts with farmers, these large-scale purchasers procure produce through 'supply agreements' where the benefits are weighted in the favour of the buyer. Penalties are imposed for failure to deliver agreed quantities of fresh fruit and vegetables during the year, which encourages farmers to grow much more crop than they need as a form of insurance against poor weather and other factors that may reduce the yield. Furthermore, entire crops, or portions of crops, can be rejected prior to harvest on the grounds of physical appearance. As a result of these factors, up to 30% of the UK vegetable crop is never harvested.

In less-developed countries, most agricultural operations, including harvesting, are carried out by hand. This means that the farmer must have sufficient labour available to harvest and carry his crop off the field. Inevitably it is a slow process and frequently poor weather conditions or attacks by pests of all types reduce the quality or quantity of crop harvested, or may destroy it altogether.

Frequently, manual harvesting methods involve the repeated handling of crops as they pass along poorly engineered transport infrastructure from field to farmyard, farmyard or onsite storage to transport hub, and from there to the consumer. Picking produce into boxes or baskets is a relatively simple method of producing a unit load that can be engineered to suit the carrying vehicle, be it bicycle or cargo plane, and also protects the crop. In ideal cases, this container can also match the processing plant, enabling field handling, drying, storage and transport to be carried out without directly handling the crop at all.

Mechanised harvesting systems, such as those engineered in developed countries, have the potential to increase the rate and efficiency of the process in developing nations, but they must be supported by logistics and storage systems that match the capacity of the harvester. Many attempts to introduce mechanised harvesting have foundered in this regard, due to inadequate local capacity to transport and store the crop at the rate it was harvested and lack of skills for equipment maintenance.

WASTE AT STORAGE

In the majority of cases, food crops are harvested only once per annum and so need to be placed in a secure storage facility in order to provide a regular supply of food throughout the year. Additionally, since pricing of most agricultural commodities are greatly dependent on the local market conditions, a lack of effective storage facilities frequently forces farmers to sell their produce as soon as it is harvested. Unfortunately, as everyone else in the district is also trying to sell their crop at the same time, this gives buyers and traders a huge commercial advantage. Local stores enable farmers to regain some control over the market, as they provide a buffer between supply and demand, and regional and national storage infrastructure ensure efficiency in market functioning while maintaining food supply security. But in order to operate such stores, it is essential that they are engineered to suitable standards, and connected to both the energy and transport infrastructure.

In general terms, the vast majority of foodstuffs can be regarded as perishables. Although when managed under ideal conditions cereals, including wheat and maize can be stored for as long as five years, if the conditions are not satisfactory, they can deteriorate rapidly. Others, including root vegetables, can be stored for several months, again under good conditions, but losses can be high if conditions are not ideal. Soft fruit, leaf vegetables, meat and dairy products are true perishables and can be stored only under closely controlled conditions. Researchers around the world have determined the best conditions for storing the majority of food crops and typically these are defined by temperature, humidity and oxygen level.

Grains and oilseeds are relatively less perishable than other crops, but still require care and skill in storage as they are not inert material, but living seeds. The water content of the seeds must be reduced to a level that is safe for storage as soon as possible after harvest. Alternatively, the temperature of the stored crop must be reduced. Often both of these can be achieved by good engineering of ventilation systems.

Grain is often dried using air streams that are heated by furnaces using gas or oil. These must be carefully engineered and managed to conserve energy and also to avoid damage to the grain. Rice in particular is very susceptible to cracking if the speed of drying is too high. Accurate temperature control is particularly important when drying malting barley, seed crops and oil seeds. Most modern grain drying machines utilise electronic temperature control systems, and many use heat recovery systems to take the best advantage of the energy used to drive off excess moisture.

Buildings and structures used for long-term storage must be hygienic and engineered to prevent the entry of birds or vermin, while providing adequate ventilation. Oilseeds need particular attention, as they are susceptible to heating if they are allowed to become wet. The development of oilseed varieties with ever higher oil contents has introduced a need for more-effective control of storage conditions, as vegetable oil reacts adversely to moisture. Moderate quantities of moisture degrade the oil, producing high levels of free fatty acids, while excessive levels can lead to self-heating and even fire.

Grain wastage in store varies widely with the type of crop and the region. In a developed country such as Australia, wastage of 0.75% in stored grain is at the upper end of acceptability, whereas Ghana, one of the more developed of the emerging West African economies, recently experienced a 50% loss rate of stored maize from a total 2008 production of one million tonnes[58] Considerably greater levels of tonnage loss exist in other larger developing nations, such as India for example, where about 21 million tonnes of wheat annually perishes due to inadequate storage and distribution,[57] equivalent to the entire production of Australia. In neighbouring Pakistan, losses amount to about 16% of production, or 3.2 million tonnes annually, where inadequate storage infrastructure leads to widespread rodent infestation problems.[59]

In the former Soviet Republics of Eastern Europe wastage rates remain high, with Ukraine typical of the region at 25–50% losses.[60] Given typical grain production levels of about 24 million tonnes in Ukraine,[61] this amounts to losses of some 6–12 million tonnes annually for that country alone. The majority of grain, and vegetable, stores in Eastern Europe date back to the 1930s in both design and engineering, making them inadequate for today's needs. Substantial numbers are based on low sheds that lack simple engineered infrastructure, such as adequate rainwater drainage, which leads to grain spoilage from moisture. The larger stores are built from concrete slabs with inadequate joints, the result of which is that both weather and insects find routes for penetration.

Storage facilities for fruit and vegetables require a much higher standard of engineering and management than grain crops. For example, in the case of fruit, systems that incorporate controlled atmosphere conditions as well as temperature and humidity management are required, as many types respond to gaseous ethylene, carbon dioxide and oxygen, and so the presence or absence of quantities of these gases can have a great effect on their storage life[62] (unfortunately, every type of fruit has its own particular requirement of best storage temperature and atmosphere, so it is often not possible to store several types of fruit in a single store). Harvesting operations in many instances involve fruit and vegetables being transported directly off the field into pack houses, where they are graded before packing for storage or shipped directly to market. Often freshly harvested crops are hot from the sun and so must be cooled before they can be stored. Removing 'field heat' as quickly as possible is one engineering solution that allows the storage life of even the most fragile of fruit crops to be extended.[63] For example, chilling strawberries in the field can extend their shelf life to as long as eight days, compared with one or two days with ambient storage. However, many less-developed nations are located in the warmer, hotter regions of the world, such as India and Africa where post harvest losses of fruit and vegetables can range between 35–50% annually,[2,52] and these countries lack the engineered infrastructure required to facilitate such post-harvest cooling.

Ideally, stores need to be equipped with condition sensing and monitoring systems working in conjunction with ventilation or refrigeration plant in order to produce a suitable storage regime. Of course, in addition to requiring trained and competent engineers and operations staff, such advanced stores are wholly dependent on the engineering of a reliable electrical supply that has the capacity to power such equipment. Very few developing countries have a reliable rural electrical supply and lack of this resource is a major factor in the quantity of crops spoiled in storage. Even in the UK, the USA and Canada, many farms in remote areas lack an electricity supply that has the capacity to power modern equipment, and the high capital cost and complexity of such facilities generally means that they are provided at large scale on a commercial basis and managed by specialist companies. In the latter case, ideally stores are located in close proximity to food producing areas and linked to distribution warehouses near to consumer centres through good transport infrastructure.

WASTE IN TRANSPORTATION

Efficient and effective transportation of foodstuffs requires engineered facilities to be available on the farm to load vehicles rapidly with little or no damage. However, in many less-developed areas where manual harvesting is the only approach available, picked produce such as fruit and vegetables is simply loaded into inadequate vehicles by hand, from piles previously made in the field, and often bruised or damaged in the process. During transport to the farmyard or onsite store, further damage occurs, as transit takes place on poorly maintained roads and continuous bumping adds further bruising. At the store they are unloaded and often piled in further heaps, sustaining additional bruising and damage, all of which results in produce being thrown away due to severe spoiling, trimmed back to a fraction of its original size or suffering a substantial reduction in its shelf life. If picked directly into recyclable crates, damage and loss in such produce can be reduced substantially and handling efficiency increased, even when mechanical handling equipment is not available. This relatively simple solution can dramatically reduce the level of wastage, but it is often not used.

However, introducing handling crates for vegetables or fruit in isolation is not sufficient by itself and should ideally be part of a planned and integrated system. The size, design and engineering of the crate need to be selected to suit the fruit or vegetable being transported, the equipment that is used to handle it and also the transport vehicle. In the USA, it is common for specially adapted forklifts to handle 12 pallets as a unit load, while in other regions of the world, the unit load carrier is a bicycle. Forklift or pallet trucks require a level, smooth floor for operation and frequently need a loading bay in order to access a vehicle; in many cases such engineered infrastructure is not available and unlikely to be provided in the near future. It is therefore important that the entire route from field to market is planned as an integrated system, taking into account the local conditions and engineering capability.

Innovation in integrated handling and transport

A leading East Anglian farm provides a good example of what can be achieved through planning and engineering of an integrated handling and transport system.[64] The farm has invested in a high-capacity system for the handling, drying and storage of onions. Instead of using plastic crates, its handling unit is the 20ft shipping container. Onions are loaded directly into specially constructed containers holding about 18 tonnes, in the field. These containers are carried to the drying unit and then to the pack house. This system enables two men to handle over 100,000 tonnes of onions annually with minimum loss or waste. However, in order to achieve this high level of efficiency, the entire operation was carefully planned and engineered around the modular container.

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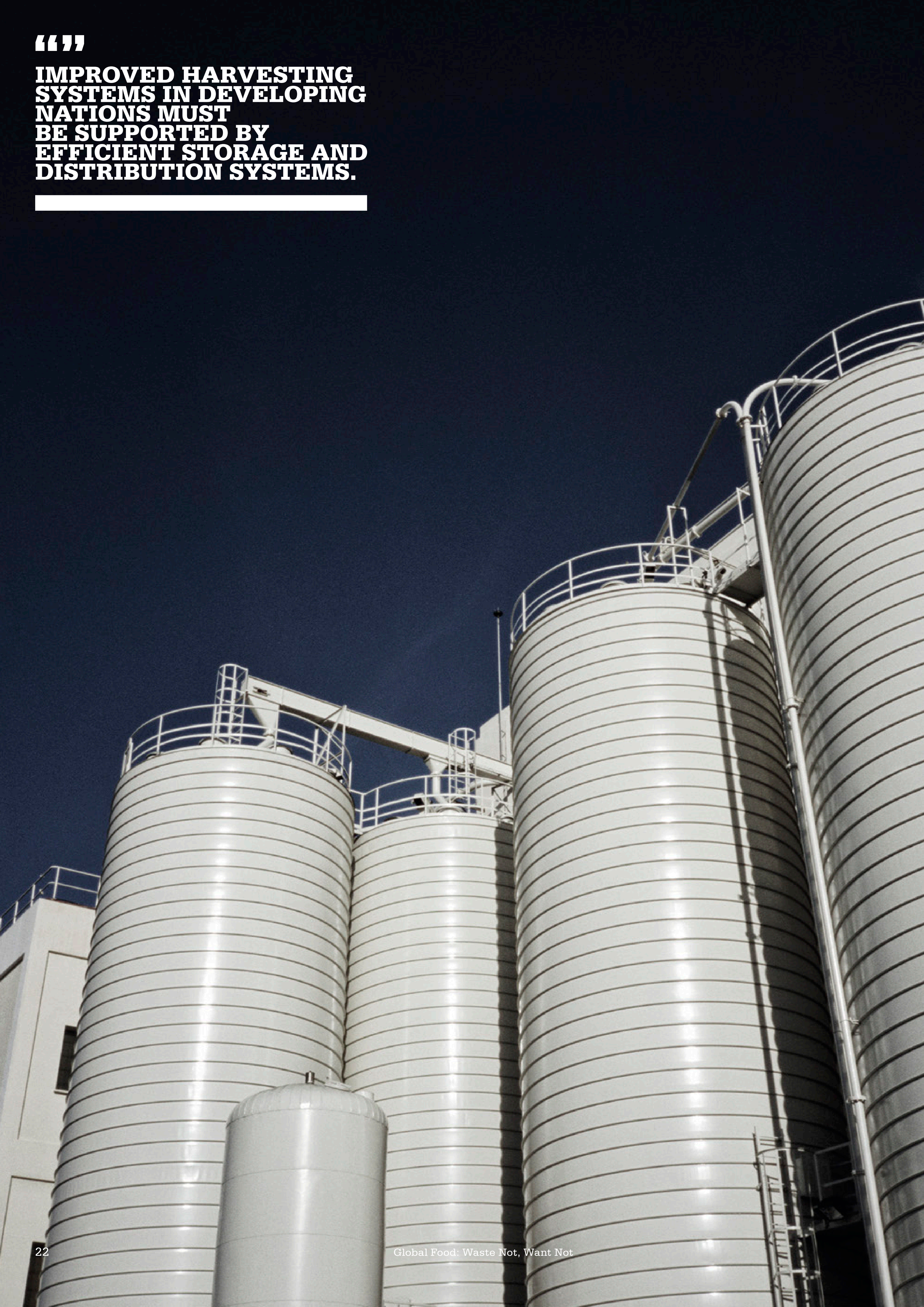
IMPROVED HARVESTING SYSTEMS IN DEVELOPING NATIONS MUST BE SUPPORTED BY EFFICIENT STORAGE AND DISTRIBUTION SYSTEMS.



WASTE AT THE MARKETPLACE AND IN THE HOME

The logistics systems and marketing practices of modern supermarkets in mature developed countries, ensure that perishable produce spends the minimum amount of time on display, reducing in-store wastage. But in less-developed economies, where open stalls are the primary marketplace for foodstuffs, wastage rates are considerably higher. Stallholders use a variety of methods to preserve their goods through the day, from spraying vegetables and salads with water to using ice shavings to preserve fish. However, these methods are not particularly effective, they are frequently insanitary and risk contaminating the food.

In the least-developed societies, patterns of domestic wastage vary dramatically between rural and urban households. Rural families are obliged to store staple crops from their annual harvest right through the year, so it is vitally important that losses are kept to a minimum. But storage facilities are often primitive, often remaining unchanged for generations, and attacks by rodents, insects and moulds are common. In urban areas, wastage is reduced to an absolute minimum by the simple process of purchasing only enough food for the day, or even the meal. Small shops and market stalls purchase foods from a farmer or processor and dispense tiny quantities from bulk bags or cans. It is not unusual for families to buy food twice or even three times daily.

Incongruously, it is in the most ‘advanced’ and affluent societies where the largest quantities of food are wasted at the consumer end of the chain.[52,65] Although mature, developed societies have substantially more efficient, effective and well-engineered market logistics, 30% of what is harvested from the field never actually reaches the marketplace (primarily the supermarket) due to trimming, quality selection and failure to conform to purely cosmetic criteria.[66] This can include such reasons as the packaging is slightly dented, one piece of fruit is bad in an otherwise perfectly good bag of fruit, or it is thrown out in the warehouse because it had ripened too soon. In this way the global food industry produces large amounts of food waste, with retailers generating 1.6 million tonnes of food waste per year.[66]

Of the quantity that does reach the supermarket shelves, 30–50% is thrown away by the final purchaser in the home,[52,66] often at the direction of conservative ‘use by’ labelling. Labelling of many foods can actually encourage waste. Many consumers have a poor understanding of ’best before’ and ‘use by’ dates, and these dates are generally quite conservative, as they are driven by the retailer’s desire to avoid legal action. Promotional offers and high-pressure advertising campaigns, including bulk discounts and ‘buy one get one free’ offers, encourage shoppers to buy large quantities in excess of their actual needs[52], which leads to substantial food wastage in the home. In the UK, for example, about seven million tonnes (worth about £10.2 billion) of food is thrown away from homes every year.[52,66] It is estimated that this costs the average household £480 a year[67] which accumulates to £15,000–24,000 over a lifetime. £1 billion-worth of the food wasted annually in the UK is food still ‘in date’ and so is perfectly edible.[68] If this quantity of food was not wasted, the saving in energy consumed in its production, packaging and transport, would be the equivalent of taking 20% of cars off the road in the UK.[68]

However, despite current complaints of rising prices, food in the UK represents quite a small part of the average family’s spending. A recent report shows that the average family in the UK spends 11% of its budget on food,[69] which helps to explain why it is not valued more highly. The excessive waste is a complex issue, but partially due to a long-term national policy of ‘cheap food’[67] which results in it being grossly undervalued. For example, as a general policy, the catering industry often throws away a third of its food,[70] as restaurants deliberately order too much in order to avoid running out. Because the food is generally regarded as the least costly resource in a catering operation, it is viewed as disposable.

IN THE UK, SEVEN MILLION TONNES OF FOOD VALUED AT ABOUT £10 BILLION IS THROWN AWAY FROM HOMES EVERY YEAR.

WHAT NEEDS TO CHANGE?

Rising world population, combined with improved nutrition standards and shifting dietary preferences, will in the coming decades continue to exert pressure for increases in the global food supply. Engineers, scientists and agriculturalist have knowledge, tools and systems that will assist in achieving increases, but their scale and success is dependent on the availability and affordability of a number of resources, many of which are diminishing. Currently, vast quantities of foodstuffs, estimated at 30–50% of total global production, are lost or wasted between the field and consumer. The primary cause of this wastage is inadequate engineering and agricultural practice knowledge, deficiencies in management skills, poorly engineered infrastructure in the form of electricity and potable water systems, and storage and transport facilities which are often not fit for purpose. Further wastage results from the commercial practices of modern supermarkets that demand cosmetically perfect foodstuffs and encourage the more-affluent consumers to purchase excessive quantities.

Regardless of a nation's stage in economic development, or where in the food chain the food is wasted, its loss is not a loss merely of the nutritious material itself but also of the land, water and energy resources that were expended in its production, processing and distribution to the point of loss. This makes the level of loss encountered in developed countries even more unsustainable, since much of the food that is casually thrown away by consumers has been transported right around the globe to reach that household.

In order to reduce the current levels of foodstuffs wastage, improvements must be made at all stages in the chain of production, distribution and storage, from the producer/farmer right into the consumer's home. The changes that are needed vary on a case-by-case basis, with the development stage of the individual nation under consideration, however there are a number of key issues that can be identified that have implications for action by governments, the engineering profession and wider general public.

In nations of the world that are considered developed in economic terms, such as those of Europe and North America, existing infrastructure often needs to be updated and its connections to transport improved as engineering and technology advances. One quite recent development for example, is the increasing quantity of grains that are transported by shipping container, making better use of available road, rail and marine transportation systems. Alongside such changes, education, training and management systems need to be installed and applied in order to take best advantage of the new facilities and methods and, wherever possible, opportunities taken to work towards reductions in current levels of waste.

The prime area to address in this group of countries, however, is the fact that under current market conditions, many staple foodstuffs are regarded as low-cost commodities and, as such, rarely receive the focus on waste that they deserve. A case in point is that until the supply and demand for cereals converged from 2008 to 2010, the world prices of cereals had remained relatively static for many years,[71] and when inflation is taken into account, had decreased. As a result, there was little interest or financial benefit in reducing the levels of waste. Under current and projected market conditions though, it is likely that waste control programmes will be much more beneficial in economic and political terms, and so practitioners should be encouraged to pursue these with greater vigour.

As the value of food crops increases over time, it might be expected that the current practice of discarding large quantities of edible and nutritious fruit and vegetables on purely cosmetic grounds will become less economically viable. However, governments should not wait for food pricing to trigger action on this wasteful practice, but instead proactively pursue food policy initiatives that change consumer preferences, dissuade retailers from operating in this way, and lead to increases in the quantity of these 'defective' items in the retail markets. In this regard it will be necessary to shift a deeply embedded marketing and consumer culture and make changes to thinking on the management and care of foodstuffs, which will need to be implemented throughout the wholesale and retail distribution chains, as well as in individual households. Ultimately, as prices of foodstuffs increase, these improvements are likely to become increasingly self-driven and build incrementally on the government-catalysed action.

Turning to those nations of the world that are currently experiencing rapid development, these are heavily engaged in programmes of infrastructure improvement that, while they are aimed primarily at facilitating market access, have the added potential of reducing waste. For example, Brazil has engineered long-distance roads, enabling inland farms to transport grain crops to the ports.[72] Improved transport and port facilities in Chile have dramatically increased that country's access to export markets for its fruit and wine[73], and there are several programmes under way in the former Soviet states to improve the quality of storage facilities for many different crops.[74] In China, dramatic improvements in engineered infrastructure have made it possible for that country to access world markets in a number of commodities, including as two examples, apples and garlic.[75] All these improvements to physical infrastructure need to be supported by education, training and management systems, in order to improve engineering practice knowledge, avoid the mistakes made already by the developed nations, and ensure that they are operated and maintained to the highest levels of effectiveness.

In the less-developed countries, particularly those of sub-Saharan Africa and South East Asia, crop harvesting, handling, storage and transport infrastructure needs the most attention, and facilities must be engineered that are appropriate for the level of technology that is available locally. The latter is essential in order to ensure resilience and sustainability are established in the early stages of development, particularly in a world of increasing environmental risks, such as climate change. Engineered infrastructure includes the provision of roads, and reliable supplies of electricity and potable water, but also more easily provided basic components such as grain storage bags that are less accessible to insects, and appropriately sized bulk storage facilities such as silos and tanks. Advances in the engineering of solar and wind energy may facilitate the installation of refrigeration for storage in more-remote areas, though the affordability of smaller-scale cooling systems for the storage of primary agricultural products is always likely to present challenges. Above all, systems and components should be such that their capital and operating costs are appropriate to the value of the material being handled and stored.

More fundamentally, in newly emerging and developing countries, knowledge transfer is needed to inform producers of the characteristics of their crops and to disseminate advice on how best to store foodstuffs. Governments need to recognise the scale and urgency of the situation, and establish training and educational programmes to improve the level of best practice understanding, particularly in the post-harvest sector. Inevitably, in the case of very perishable crops, this advice is likely to be how to gain best and most-rapid access to the market. The transfer of management expertise is also required to apply this technical education, with the aim of bringing as much of the farmer's crop to market in a saleable condition as possible. Politicians and regulators have an important role to play in this regard, as they should be capable of balancing the need for sanitary/phytosanitary controls with removing obstacles to free trade that currently cause the loss of significant quantities of fragile horticultural crops at certain contested border crossings.

There is also a large role for the financing institutions, as the funding schemes needed to enable these improved systems to be developed are likely to require significant investment to be put in place and considerable financial innovation. As an example of the scale of investment required, a feasibility study is about to be launched in Ethiopia to develop a national network of grain storage facilities, and the anticipated cost of this network is expected to be at least $1 billion.[76] This scale of investment will be required for multiple commodities and in numerous countries, and co-ordinated efforts are going to be essential. However, currently there is a marked lack of co-operation between the various development agencies, as evident for example in the case of the EU, the UN and World Bank/IFC, which are all working independently on grain warehouse systems in Uganda, with no apparent intercommunication. This needs to change.

The changes described above cover a broad range of improvements needed across a variety of development stages, and require the deployment of an equally wide range of skills. Researchers, engineers and technicians from multiple disciplines will be called upon to devise, install and maintain facilities and equipment that improve current methods of food production and product handling, from initial planting through to human consumption. These will involve the expansion and improvement of infrastructure ranging from field machines, roads and railways to electricity generation and distribution systems, potable water supplies, heating, ventilation, waste disposal systems and storage buildings. Electronics, systems and IT engineers will be needed to develop improved and lower-cost environmental controls, while mechanical and civil engineers will be required to improve the built environment including structures, transportation and mechanical handling systems. In this regard the scale of the challenges and the need to think in a more systems-orientated approach, to build in resilience and embed sustainability, will require increased levels of interdisciplinary, multidisciplinary and collaborative working across the various disciplines and institutions of the engineering profession.

In years past, each individual family unit maintained its own stock of foodstuffs, fresh and preserved, but in developed countries this responsibility has transferred to the industrialised food chain. This trend is now being followed by developing and newly developing nations alike, as they implement approaches and practices largely adopted by the nations that industrialised before them. The outcome is that an increasing proportion of the world's population is removed from involvement in and knowledge of the food supply system, merely becoming food consumers at the end of a supply chain. This creates a culture with little understanding of the source and value of food. If waste is to be reduced to the point of elimination, in order to help ensure the growing numbers of people can be fed with minimum resources and environmental risk, this lack of association needs to be rectified. Indeed, there is little benefit in increasing production alone when, under current practices and behavioural norms, a third to a half of the food produced is simply thrown away. It is time to redress the balance, recognise the value of food, and work towards helping feed future generations through vigorous efforts to reduce waste.

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TO DEVELOP A NATIONAL NETWORK OF GRAIN STORAGE FACILITIES IN ETHIOPIA ALONE WILL COST AT LEAST $1 BILLION.

RECOMMENDATIONS

In order to help prevent a future global food crisis, the Institutiton of Mechanical Engineers recommends:

1. The UN Food and Agriculture Organisation (FAO) works with the international engineering community to ensure governments of developed nations put in place programmes that transfer engineering knowledge, design know-how, and suitable technology to newly developing countries. This will help improve produce handling in the harvest, and immediate post-harvest stages of food production.
2. Governments of rapidly developing countries incorporate waste minimisation thinking into the transport infrastructure and storage facilities currently being planned, engineered and built.
3. Governments in developed nations devise and implement policy that changes consumer expectations. These should discourage retailers from wasteful practices that lead to the rejection of food on the basis of cosmetic characteristics, and losses in the home due to excessive purchasing by consumers.

CONTRIBUTORS

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- George Aggidis FIMechE
- Prof Ian Arbon FIMechE
- Colin Brown FIMechE
- Charles Clarke AMIMechE
- John Earp FIMechE
- Tim Fox FIMechE
- David Greenway FIMechE
- Alistair Smith FIMechE
- Bob Stannard MIMechE
- David Warriner MIMechE
- Simon Whatley FIMechE
- David Williams FIMechE

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CLAAS
770
LEXION

Institution of Mechanical Engineers

1 Birdcage Walk
Westminster
London SW1H 9JJ

T +44 (0)20 7304 6862
F +44 (0)20 7222 8553

environment@imeche.org
www.imeche.org