Food Irradiation as a Method of Limiting Crop Loss in Developing Nations

by

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1. Introduction

The world today contains an estimated 6.7 billion humans, and our population is growing at an unprecedented rate, consuming an ever-increasing amount of global resources. According to United Nations projections, the majority of this growth will occur in the third-world nations of Africa, and, to a lesser extent, Asia, among those peoples least able to afford the increasing burden on their resources. Clearly, what is needed in these African nations in the near future are more efficient, low-cost methods of using those resources they already have.

Foremost among the problems faced by African developing nations is a lack of a reliable, sufficient, and nutritious food supply. Much of the African population survives on malnourished diets irregularly supplied by subsistence agriculture. In addition, crop loss due to both pests and post-harvest spoilage is much higher than in first world nations, with cold-storage technologies and modern pesticides. Equally important are the lives lost each year to food-borne disease. In the United States alone, food-borne infections cause an estimated 76 million cases of illness and 323,000 hospitalizations annually, for an estimated annual treatment cost of $6.7 billion and a death toll of thousands. [1] In developing nations, of course, these casualty figures are much higher. It is precisely this crop loss and food-borne disease which this thesis proposes to address, by both proposing and evaluating a method, namely, food irradiation, to diminish crop loss in African villages and small-towns.

As stated by Fritz Kaferstein in the Journal of Public Health Policy, "In developing countries with warm climates, with non-grain staples, vegetables and fruits, the postharvest loss is believed to exceed 50%. With commodities such as dried fish, insect infestation is reported to result in a loss of 25% of the product with an additional 10% lost due to spoilage. While not all of these losses can be prevented by food irradiation, the technology does offer unique potential to destroy insect infestation and reduce spoilage." [2]

2. History and Use of Food Irradiation

Although patents for using irradiation to kill food-borne bacteria were filed in the United States and Great Britain as early as 1905, due to politics and popular hysteria, it was not until the 1980s that the FDA legalized low-dose irradiation of pork, herbs, spices, vegetables, and fruit. [3] By the end of the 1990s, despite FDA legalization of irradiated beef after a fatal *E. Coli* outbreak, less than 0.002% of the food consumed in the United States was irradiated, due to public concerns and fear campaigns regarding the safety of irradiated products. [3] Although food irradiation is slowly gaining wider acceptance among the general population of the United States today, sterilization of medical devices through irradiation using similar techniques has long been accepted practice in the health care industry, with over 100 such facilities currently licensed. [4]

Nevertheless, according to the Center for Disease Control (CDC), the "safety of irradiated food has been studied for four decades, making it the most intensively assessed of any food safety process. Extensive nutritional assessments, toxicity studies, and feeding trials have not indicated a risk, and the process has been approved by many regulatory agencies around the world." Overall, irradiation changes nutritional value far less than the already accepted processes of canning and pasteurization of milk adopted by most industrialized nations [1], and does so at minimal cost. In the United States, with a well-developed nuclear industry and stable power grid, the process of irradiating food adds considerably less than 10% to its base cost. Moreover, the United States government estimates that for every $1 spent on food irradiation, consumers will save $2 on health-related costs. [5]

Although irradiation is certainly not a panacea that will eliminate the necessity for a sanitary food preparation environment, when used as approved on foods, disease-causing germs are reduced or eliminated, the food does not become radioactive and remains safe for human consumption, dangerous substances do not appear in foods, and the nutritional value of the food is essentially unchanged. [4]

The CDC estimates " that if all the pork in the United States were to be irradiated, Americans would lose only 2.3 percent of the vitamin B_1 in their diets...Irradiation converts small amounts of vitamin C in fruit to another equally usable form, so nothing is lost. In fact, multigenerational studies of animals fed irradiated foods show that not only is it safe, but the nutritive value remains virtually unchanged." [4]

Irradiation may be used to kill a wide variety of disease-causing agents present in food. Parasites (such as tapeworms [6]), insects (such as those responsible for grain infestations resulting in crop loss), and other complex organisms are easily killed at the low doses of 0.1 kGy (kilogray) or less, while values of 1-4 kGy can kill many bacteria, replacing various chemicals and pesticides used for this purpose. Bacterial spores and some viruses are killed by 10-45 kGy dosage. Viruses and prion particles, on the other hand, are generally not ideal targets this technology, as viruses may survive doses of 10 kGy or higher, and prion particles are not inactivated by irradiation, except at extremely high doses not approved for foods. [7] The World Health Organization has declared food irradiation in doses up to 10 kGy to be safe for human consumption, and has declared that doses as high as 75 kGy will likely cause no problems. [8] Low doses of irradiation may also be used to prolong the shelf life of fruits and vegetables by delaying ripening, inhibiting mold growth, and preventing sprouting. [4]

3. Methods of Food Irradiation

Three primary methods of sterilizing food with radiation are used today. X-ray sterilization, electron beam sterilization, and fixed-source irradiation.

3.1 Fixed-source Irradiation

The primary method of food irradiation in the United States is through fixed-source irradiation. A commercial facility of this type costs several million dollars to build, and its essential elements are contained within a room with 2 ft. thick concrete shielding. Food is moved though this room, containing a cobalt-60 or cesium-137 gamma radiation source, on a conveyor belt, exposing it to sterilizing radiation. These high energy rays can penetrate deeply, making it possible to treat bulk foods on shipping pallets. The source is stored a pool of water when not in use, shielding it further.

Overall, such a facility may process 50-200 million lb of meat per year. [7] This type of facility requires heavy shielding and the active participation of a nuclear industry, although the food irradiation facilities themselves do not become radioactive, and do not create radioactive waste. [4]

Fixed-source facilities of this type in the United States are regulated by the Nuclear Regulatory Commission (NRC), with cobalt-60 sources being produced in commercial nuclear reactors. [1] Cesium 137, however, is a by-product of the manufacture of weapons-grade radioactive substances. [4] Cobalt-60 sources have a half-life of 5 years, requiring periodic replacement or 'recharging' in a reactor, while cesium-137 sources have a half-life of 31 years, are not often replaced, and must be sent to a storage site after use. Alternatively, nuclear waste or spent fuel rods could be used as a radiation source, although this raises many security and political issues. [9]

3.2 Electron Beam Irradiation

The second type of radiation facility, more often used for irradiation of medical instruments than food, is the electron-beam facility. Medical e-beam sterilizers have been in use for over 15 years. [4] In this type of facility, a stream of high-energy electrons are emitted from an electron gun, a device similar to that found in a television tube, although more powerful. Although some shielding is required to prevent escape of stray electrons, the amount of shielding needed is considerably less than that present in a fixed-source facility. The electron gun can be easily turned on and off by simply supplying power to it, and no radioactivity is involved. [1] No nuclear industry support is needed, and the entire apparatus may fit in a fairly small area.

Unfortunately, the range of the electron beam is very limited, and can only penetrate about 3 cm. (slightly over 1 in.) into most materials. With an electron gun on either side, this limits the maximum thickness of food to be processed to 2 inches. [7]

3.3 X-ray Irradiation

The final type of facility used in food irradiation is the x-ray facility. Four commercial x-ray food irradiation units have been built in the world since 1996. [4] The x-ray units used in these facilities are essential more powerful versions of those found in medical and dental offices [7]. In such units, a high-energy electron beam is directed at a thin metal foil. Upon hitting this target, high-energy x-rays are produced, which can penetrate food to a much greater distance than electron beams. As with a fixed-source facility, heavy shielding is required to protect workers from these x-rays. However, an x-ray facility, like the electron beam facilities, may be switched on and off at will, does not use a radioactive source, and does not require the presence of a nuclear industry. [1] The downside to using such facilities is the high energy costs associated in producing x-rays of sufficient energy to rapidly and efficiently sterilize large quantities of food.

4. Common Irradiation Doses

Many of the most damaging food-borne bacteria may be easily killed off by exposure to radiation. To achieve a 90% reduction in the number of bacteria present, the following doses are required [1] (Table 1):

Table 1: Dose needed for a 90% reduction in number of bacteria

Bacteria	Dose in kGy
Campylobacter	0.20
Toxoplasma cysts	0.25
E. coli O157	0.30
Listeria	0.45
Salmonella	0.70
Cl. botulinum spores	3.60

To achieve a 99.999% reduction in bacterial counts, 5 times this dosage is required. [1]

Note that these levels of radiation are not necessarily sufficient to kill bacterial spores, so cold packaging is necessary for irradiated meats until they are ready to eat. [10] In dosages high enough to destroy such spores, although the food remains nutritious and edible, it may exhibit a slightly changed texture, flavor, or odor. Although many American consumers may not favor purchasing food with such changes, the health benefits of such irradiation remain especially valuable in third-world nations without widespread accessibility to refrigeration technology and sanitary meat packaging conditions.

E. coli O157 causes an untreatable infection which can lead to severe complications, including hemolytic uremic syndrome, chronic renal failure, and death, and causes cause more than 100,000 cases of illness per year. *Campylobacter jejuni* is the most common of all food-borne bacterial infections, causing 2 million yearly cases, and can lead to a neurological disorder known as Guillain-Barre′ syndrome. *Salmonella* causes an estimated 1,400,000 cases of illness and 16,400 hospitalizations per year. *Listeria monocytogenes* an estimated 2600 cases per year of severe invasive illness, of which about 25% lead to the death of the patient (or fetal loss in pregnant women). *Toxoplasma gondii* is the most common of all parasitic foodborne infections, causing an estimated 400-4,000 cases of congenital disease each year, including hydrocephalus, mental retardation, blindness, and sometimes even death, as well as more than 200,000 noncongenital illnesses, leading to approximately 750 deaths per year, 375 of which may be the consequence of foodborne infections. (All of the numbers reflect cases within the United States alone).

Although many foods may be irradiated safely, not all foods respond well to the treatment. Shellfish, for example, may not be easily irradiated, as the radiation will damage the live oyster inside the shell before harming any bacteria within. Egg whites subject to irradiation become milky and more liquid, and the use of radiation on any seeds which are meant to sprout (alfalfa sprouts, for example), may interfere with the viability of the seeds before harming any bacteria (inhibiting the sprouting of potatoes with 0.5 kGy, on the other hand, would considerably increase their shelf life). [4, 9] Radiation may cause flavor changes in dairy products, and tissue softening in certain fruits, such as nectarines and peaches. [7]

While 1.8 kGy is a suitable radiation level for meat products such as ham and frankfurters (to kill live bacteria), 3 kGy of radiation is needed to kill 90% of hepatits A on lettuce and strawberries. [11, 12] Sliced ginger irradiated at 5 kGy remains just as pungent as non-irradiated ginger, and has storage life of 70 days at 10 °C, compared to 40 days for non-irradiated ginger. [13] In a study done concerning the National School Lunch Program, it was found that irradiation up to 3 kGy had no effect on the sensory qualities of ground beef patties after either 0 or 6 months of storage. [14] Approved radiation doses for food products sold in the United States may be seen in the table below, along with the year approval was granted [1]. Actual safe doses are well above these limits.

Table 2: Approved Food Irradiation Doses in the US

Year	Food	Dosage (kGy)	Purpose
1963	Wheat flour	0.20-0.50	Control mold
1964	White potatoes	0.05-0.15	Inhibit sprouting
1986	Pork	0.30-1.00	Reduce cases of Trichinosis
1986	Fruits & vegetables	1.00	Increase shelf life and control insects
1986	Herbs and spices	30.00	Sterilize
1990 (FDA)	Poultry	3.00	Reduce bacterial pathogens
1992 (USDA)	Poultry	1.50-4.50	Reduce bacterial pathogens
1997 (FDA)	Fresh meat	4.50	Reduce bacterial pathogens
2000 (USDA)	Fresh meat	4.50	Reduce bacterial pathogens

5. Proposed System

5.1 Necessary Characteristics

As mentioned earlier, grain (corn, wheat, etc.) may be irradiated with doses of 0.1 kGy to kill any insects infesting them. However, such a procedure would not provide any protection against reinfestation, and multiple treatments may be needed. A grain elevator has been proposed which would contain a conveyor belt system feeding into an continuously-operating electron beam irradiation system, enabling constant irradiation of the contents of the grain silos, and keeping the grain insect-free without needing pesticides. [15] However, while such a system may be reasonable for large-scale agricultural centers in the United States and possibly in the agricultural export markets of South Africa, it does not represent a viable solution for the rest of the continent. In addition, any portable electron beam source would not be able to irradiate food deeply enough for such a system to be useful.

Likewise, except for the case of South Africa, which already has a nuclear program and large-scale industrial agriculture, a fixed-source radiation system would pose too many security and safety hazards for it to be feasible, nor would a source of nuclear material be easily found.

Thus, any food irradiation device usable in developing countries should by necessity be an x-ray emitter, with no radioactive sources to provide security concerns, and able to provide deeply-penetrating, high energy beams to sterilize food. Portability (i.e. the ability to be carried on a truck) would be another useful feature, as the irradiation system could be carried between towns and villages, which may not be able to regularly transport their crops to and from a major population center (or other non-portable irradiation facility) before consumption.

Next, the issue of what types of products to irradiate must be addressed. Food grain is an obvious choice, as it requires both low dosages and packs easily into whatever shape desired, with the obvious disadvantage of possibly requiring frequent re-irradiation to protect from reinfestation. Seed grain, unfortunately, is not a candidate for radiation treatment, as even the small amount of radiation needed to destroy insects will inhibit sprouting.

Despite the wide range of health benefits to be gained by irradiating meat products, given the lack of readily available refrigeration technology, such treatment would be pointless unless done in a dosage high enough to destroy bacterial spores as well as the bacteria themselves (i.e. 50 kGy instead of 1-5 kGy). Although such low dose irradiation may be an option in major population centers with a stable power grid and refrigeration in meat markets, the vast majority of African markets, even in urban areas, do not refrigerate their meats. Thus, for irradiation of meats to be useful in this region, doses of 50 kGy and up must be used. Finally, fruits and vegetables are an ideal candidate for irradiation, as treatment of 1-3 kGy will delay ripening and mold growth, often greatly extending storage life.

5.2 Ideal System

Thus, we see that the ideal food irradiation unit for use in developing nations in Africa would be a self-contained, shielded, x-ray emitter, which could be run on an external diesel generator, and carried along with fuel wherever it would be needed. Such a unit would have to be able to provide doses of either 100, 4500, or 40000 Gy (depending on usage) quickly and efficiently, while using a small amount of fuel and be reliable enough to pay for itself within a reasonable period of time. The machine itself would consist of a simple lead-shielded 1 m. cubic box, inside of which would be a downward-facing x-ray emitter.

5.3 Calculations for Power Requirements

Three different metals are commonly used as targets in x-ray systems: tungsten, tantalum, and gold. When used to produce high-energy X-rays, these materials will also produce unacceptable photo-neutrons, raising the possibility of inducing radioactivity in the food treated. The threshold for these photo-neutrons to begin to be produced is 8.1 MeV in gold, 6.6 MeV in tantalum, and 6.2 MeV in tungsten, thus setting a limit of approximately 7.5 MeV as the highest safe operational energy for a commercial X-ray food irradiation system. [16]

In a commercial x-ray unit, computer models show a conversion efficiency of electrons to photons absorbed of 4% at 5 MeV, and 8% at 7.5 MeV. In other words, in a 7.5 MeV electron unit, 8% of all electrons emitted from the electron gun used will contribute to the X-rays actually incident upon the target surface area of the food. [16] These efficiency calculations, however, assume that the food to be irradiated will be placed on pallets and fed through the x-ray machine on a conveyor belt. Since the system proposed in this paper involves loading food by hand and irradiating it, efficiency should be slightly higher, as there will be no direct beam radiation wasted by 'gaps' between pallets on a conveyor belt system. Nevertheless, an efficiency of 8% is assumed in all calculations.

High-power x-ray machines are available with beam energies of 7.5 MeV operating at power levels of 100 kW, and possibly up to 200 kW. [16]

5.4 Shielding Requirements

In the downward-facing beam design proposed here, assuming no one crawls beneath the truck, the ground beneath the truck should provide adequate primary shielding for the x-ray beam. Secondary shielding, in the form of lead sheets however, would be needed on the other 5 sides of the machine, calculated to stop 99.99% of any 7.5 MeV x-rays which may have scattered sideways.

Monoenergetic photons are attenuated exponentially in a uniform target, according to the formula:

$$N(x) = N_0 e^{-\mu x}$$

where N(x) is the number of photons that reach a depth of x without being absorbed, and μ/ρ is the mass attenuation coefficient of the target material (μ represents the linear attenuation coefficient). For lead, the mass attenuation coefficient for 7.5 MeV x-rays is around 0.045 $cm^2\ g^{-1}$, and the density of lead is 11.34 g/cm^3. Thus, for 99.99% of 7.5 MeV x-rays to be stopped, the equation becomes:

$$0.01 = 100e^{-0.510x}$$

with a total of 18.06 cm. of lead needed per side. [17] Rather than shielding the exterior of the cube (which would be over 20000 lbs. of lead!), however, we can save a great deal of cost and weight by simply encasing the x-ray generating target itself in lead shielding in all non-downward directions (with a small opening for the electron beam, as needed). This shielding can be treated as a block of lead with (assuming a thin target, located in the center) a width and length of 36.12 cm., and a height of 18.06 cm. Although it may initially seem excessive to shield all sides from the direct beam, it is important to note that this device will be designed for civilian use, and it is necessary to incorporate as many safeguards as possible into its design. (In addition, this assumption greatly simplifies shielding calculations.) The total volume of lead needed, then will be 23,562 cm^3, weighing a total of 267 lb.)

5.5 Dose Calculations

Since this system will not have a conveyor belt feed, we can assume an active beam area of about 0.25 m^2 (0.5 m. by 0.5 m) in the center of the box, with food being loaded in 1-2 ft. thick (30.48-60.96 cm.) bags or boxes into the active area, and turned over once the center of the food package receives half the desired radiation.

Given a 200 kW power source producing 7.5 MeV x-rays with a 8% efficiency rate (8% of the total input power goes into photons which are incident directly upon the target area), the total number of 7.5 MeV x-rays incident upon the 0.25 m^2 target are:

$$200000\frac{joule}{\text{sec}}*0.08*6.24150974*10^{18}\frac{eV}{joule}*\frac{1}{1000000}\frac{MeV}{eV}*\frac{1}{7.5}=1.33152\times10^{16}\frac{xrays}{\text{sec}}$$

Three targets will be considered: meat (assumed to have a density of 1000 kg/m^{3}), fruit (assumed to have a density of 1000 kg/m^3, although actual density varies greatly between fruits, and packed with 15% free space between fruits, for a total density of 850 kg/m^3), and grain (exact density varies by grain, but is averaged here with a density of 750 kg/m^3). [18] Likewise, all three will be assumed as having a mass attenuation coefficient similar to that of water (0.03 cm^2 g^{-1}), giving linear attenuation coefficients of 0.03 for meat, 0.0255 for fruit, and 0.0225 for grain).

The absorbed dose rate of the food may be expressed by the equation:

$$D = \frac{CE}{A}\frac{\mu}{\rho}$$

where E is the average photon energy in joules, A is the target surface area, and C is the source activity in becquerels (Bq), with decays/sec (Bq) in this case being analogous to x-rays produced/sec. [W]

Adjusting for beam attenuation in the target, the activity C may be expressed as C(X):

$$C(x) = C_0 e^{-\mu x}$$

with C_0 defined as the initial source activity and x defined as the depth of the food at which activity is being measured (beam attenuation in the air due to the gap between the x-ray source and the food is negligible and is ignored, so x=0 at the surface of the food package). For 7.5 MeV x-rays, the x-ray energy E in joules is:

$$7.5MeV \frac{1000000eV}{1MeV} \frac{1.60217646 \times 10^{-19} Joules}{1eV} = 1.20163 \times 10^{-12} Joules$$

giving a final dose equation of

$$D = \frac{C_0 e^{-\mu x} E}{A} \frac{\mu}{\rho}$$

where $E = 1.20163\times10^{-12}$ Joules, $C_0 = 1.33152\times10^{16}$ x-rays/sec, $A = 0.25\ m^2$, μ is given in units of 1/m., ρ is given in kg/m^3, and the dose D is given in gray (Gy) per second. Values for μ and ρ are given below (Table 3):

Table 3: Density and linear attenuation coefficients for meat, grain, and fruit

Food	Linear attenuation coefficient (μ) in m.	Density (ρ) in kg/m^3
Grain	2.25	750
Fruit	2.55	850
Meat	3.0	1000

Since each package of food is to be irradiated for a given time and then turned over and irradiated for the same amount of time, the dose in gray per second at a depth x of a package of total thickness H may be given by:

$$D = \frac{1}{2}\left(\frac{C_0 e^{-\mu x} E}{A}\frac{\mu}{\rho} + \frac{C_0 e^{-\mu(H-x)} E}{A}\frac{\mu}{\rho}\right)$$

assuming the package is turned over halfway through irradiation. The equation above is minimized at x = 0.5H, meaning that the lowest dose is received halfway through the package. At this depth, the dose becomes:

$$D = \left(\frac{C_0 e^{-\mu(0.5H)} E}{A}\frac{\mu}{\rho}\right)$$

while the dose at either surface is given by:

$$D = \frac{1}{2}\left(\frac{C_0 E}{A}\frac{\mu}{\rho} + \frac{C_0 e^{-\mu(H)} E}{A}\frac{\mu}{\rho}\right)$$

5.6 Irradiation Time

Using the above equations, the amount of time needed to irradiate packages of meat, grain, and fruit of 50 cm. x 50 cm x H cm. (again assuming the package is turned over halfway through irradiation) is given below (Table 4):

Table 4: Irradiation time required

Food	Package width	Midpoint Dose (kGy)	Surface Dose (kGy)	Irradiation Time (sec)	Benefits
Grain/ flour	1 ft (30.48 cm.)	0.1	0.11	0.73	Kills pest infestations.
Grain/ flour	2 ft (60.96 cm.)	0.1	0.12	1.03	Kills pest infestations.
Grain/ flour	1 ft (30.48 cm.)	0.5	0.53	3.67	Mold control.
Grain/ flour	2 ft (60.96 cm.)	0.5	0.62	5.17	Mold control.
Fruit & vegetable	1 ft (30.48 cm.)	3	3.23	23.05	Increases shelf life.
Fruit & vegetable	2 ft (60.96 cm.)	3	3.95	33.99	Increases shelf life.
Meat	1 ft (30.48	4.5	4.98	37.02	Destroys bacterial

	cm.)				pathogens (does not destroy bacterial spores)
Meat	2 ft (60.96 cm.)	4.5	6.52	58.48	Destroys bacterial pathogens (does not destroy bacterial spores)
Meat	1 ft (30.48 cm.)	50	55.72	411.37	Destroys bacterial pathogens, bacterial spores, and some viruses
Meat	2 ft (60.96 cm.)	50	72.40	649.81	Destroys bacterial pathogens, bacterial spores, and some viruses

6. Generator Requirements

A typical fully enclosed John Deere 125 kW diesel generator (113 kW prime power, model MJ125 tier 3), costs $30,000 new, weighs 3,086 lb., and uses 8.4 gallons of diesel fuel an hour. [19, 20] An enclosed John Deere 250 kW diesel generator (227 kW prime power, model MJ250 tier 3), costs $50,000 new, weighs 6,483 lb., and uses 14.8 gallons of diesel fuel an hour. [21, 22]

7. Weight Considerations

In the United States, although each state determines its own maximum legal limit for truck weights allowed on U.S. roads, in general, most states limit traffic to a maximum weight of 80,000 lbs. Many European countries allow higher weights, and Australia in particular allows some vehicles of almost 140,000 lbs. on their roads. Although weight limits for African nations are harder to determine, for simplicity, a maximum weight of 60,000 lbs. will be assumed, due to the poor (or nonexistent) road networks of many African nations, necessitating the use of smaller trucks.

Out of this 60,000 pounds, the truck weight must be subtracted, then the x-ray machine weight, then the generator weight. What weight is left over will be assumed to be the fuel capacity for the truck. Thus, a fully loaded truck can hold

$$60000 - 300(x-ray) - 6483(generator) - 15000(truck) = 38217 lb.$$

pounds of fuel, assuming a truck cab weight of 15,000 lb. (likely an overly high estimate, as the largest trucks on US roads have cab weights of about 15,000 lbs.), and assuming the majority of the weight of the x-ray generator is that of the lead shielding. This 38,217 lb. of fuel can keep the generator running for over 350 hours (although, admittedly, much of this fuel will be used to move the truck between towns). This is more than enough fuel for a day's use of the generator and its transportation.

8. Economic Considerations

8.1 Fuel

Although the price of diesel per liter varies greatly per nation, depending upon fuel subsidies or taxation, diesel fuel in 2006 averaged $0.8581 per liter for African nations (averaged across 47 African nations). [23] Commercial diesel varies in weight from 6.85 to 7.2 lbs. a gallon, but will be estimated at 7 lbs. a gallon, for a total cost of $0.4640 per pound ($1.023 per kilogram), or $3.25 per gallon. [24]

Thus, a 125 kW diesel generator will use $27.30 of diesel fuel per hour of operation, and a 250 kW generator will use $48.10 of fuel per hour. (Oil costs for running the generators are negligible and have been ignored).

Using these values, fuel costs for food irradiation for packages of dimensions 0.5 m. x 0.5 m. x H m. using a 200 kW x-ray machine powered by a 250 kW diesel generator are calculated below (Table 5):

Table 5: Irradiation fuel costs

Food	Package width	Midpoint Dose (kGy)	Irradiation Time (sec)	Total cost (USD)	Cost per kilogram (USD)
Grain/ flour	1 ft (30.48 cm.)	0.1	0.73	0.0098	.00017
Grain/ flour	2 ft (60.96 cm.)	0.1	1.03	0.014	0.00013

Grain/ flour	1 ft (30.48 cm.)	0.5	3.67	0.049	0.00072
Grain/ flour	2 ft (60.96 cm.)	0.5	5.17	0.069	0.00060
Fruit & vegetable	1 ft (30.48 cm.)	3	23.0461	0.31	0.0048
Fruit & vegetable	2 ft (60.96 cm.)	3	33.99	0.45	0.0035
Meat	1 ft (30.48 cm.)	4.5	37.02	0.49	0.0065
Meat	2 ft (60.96 cm.)	4.5	58.48	0.78	0.0051
Meat	1 ft (30.48 cm.)	50	411.37	5.50	0.072
Meat	2 ft (60.96 cm.)	50	649.81	8.68	0.057

8.2 Market Value of Food

To determine the value of food irradiation, it is necessary to determine the market price of the food being irradiated, so as to calculate what percentage of the market value irradiation would cost. Using the data from Table 6, the price per kilogram of meat has been approximated as $1.50 (biased toward cheaper meats), the price per kilogram of fruit as $0.17 (biased toward cheaper fruits), the price per kilogram of flour as $0.30, and the price per kilogram of grain as $0.30 (biased toward cheaper and more commonly eaten grains) [25].

Table 6: Selected Market Prices in Kenya and Uganda

Commodity	Type	Nation	Price (per kg) (USD)
Maize (dry & green average, wholesale)	Grain	Kenya	$0.16
Rice (sindano & pishori average, wholesale)	Grain	Kenya	$0.65
Maize, grain (retail)	Grain	Uganda	$0.21
Maize, grain (wholesale)	Grain	Uganda	$0.15
Millet, grain (retail)	Grain	Uganda	$0.32
Millet, grain (wholesale)	Grain	Uganda	$0.27
Rice (retail)	Grain	Uganda	$0.62
Rice (wholesale)	Grain	Uganda	$0.53
Maize, flour (retail)	Flour	Uganda	$0.34
Maize, flour (wholesale)	Flour	Uganda	$0.28
Millet, flour (retail)	Flour	Uganda	$0.46
Millet, flour (wholesale)	Flour	Uganda	$0.38
Cassava Flour (wholesale)	Flour	Uganda	$0.22
Cassava Flour (retail)	Flour	Uganda	$0.27

Bananas, cooking (wholesale)	Fruit & vegetable	Kenya	$0.21
Mangoes (wholesale)	Fruit & vegetable	Kenya	$0.13
Passionfruit (grade 1 & 2 average, wholesale)	Fruit & vegetable	Kenya	$0.41
Oranges (wholesale)	Fruit & vegetable	Kenya	$0.18
Avacados (wholesale)	Fruit & vegetable	Kenya	$0.10
Red potatoes (wholesale)	Fruit & vegetable	Kenya	$0.11
White potatoes (wholesale)	Fruit & vegetable	Kenya	$0.10
Sweet potatoes (wholesale)	Fruit & vegetable	Kenya	$0.12
Sweet potatoes (wholesale)	Fruit & vegetable	Uganda	$0.12
Sweet potatoes (retail)	Fruit & vegetable	Uganda	$0.16
Irish potatoes (wholesale)	Fruit & vegetable	Uganda	$0.18
Irish potatoes (retail)	Fruit & vegetable	Uganda	$0.22
Beef (wholesale)	Meat	Kenya	$0.73
Goat (wholesale)	Meat	Kenya	$0.94
Chicken (wholesale)	Meat	Kenya	$1.85
Tilapia (wholesale)	Meat	Kenya	$1.11
Beef (wholesale)	Meat	Uganda	$1.24
Beef (retail)	Meat	Uganda	$1.33
Chicken (wholesale)	Meat	Uganda	$2.66
Chicken (retail)	Meat	Uganda	$3.44
Goat (wholesale)	Meat	Uganda	$1.53
Goat (retail)	Meat	Uganda	$1.59

Fish (wholesale)	Meat	Uganda	$1.52
Fish (retail)	Meat	Uganda	$1.73

8.3 Overall Cost

The cost of irradiation as a percentage of the market value of food is calculated below (Table 7):

Table 7: Cost of Irradiation Compared to Cost of Food

Food	Package width	Midpoint Dose (kGy)	Cost per kilogram (USD)	Cost as percentage of food value
Grain	2 ft (60.96 cm.)	0.1	0.00013	0.42%
Flour	2 ft (60.96 cm.)	0.5	0.00060	0.20%
Fruit & vegetable	2 ft (60.96 cm.)	3	0.0035	2.06%
Meat	2 ft (60.96 cm.)	4.5	0.0051	0.34%
Meat	2 ft (60.96 cm.)	50	0.057	3.8%

9. Conclusion

Surprisingly, the running costs of food irradiation by a diesel-powered x-ray machine are only a small fraction of the total value of the food being irradiated, even at the high doses required to kill bacterial spores in meat, making such a solution initially seem quite viable for local African markets. Such irradiation could save millions of lives each year, both through disease prevention and through increased crop yield and storage time. Especially useful would be irradiation of fruits and high-dose irradiation of meats, as they would not require multiple treatments as grain would (to prevent reinfestation).

Unfortunately, the initial expenditure needed to set up a mobile food irradiation unit is prohibitively high. Although a skilled truck driver trained in the use of the irradiation equipment commands a fairly low wage of approximately $100 a month, the truck and trailer itself may cost $100,000-$150,000 new, the diesel generator another $50,000, and the lead shielding alone on the x-ray system has a current market value of $22,000, for an initial setup fee possibly approaching $200,000 per unit; an exorbitant sum in most third-world economies!

In an urban marketplace, such as those found in Nairobi, Dar Es Salam, Kampala, and other major African cities, a stationary irradiation unit may offer an acceptable cost to benefit ratio. In such a case, no truck or trailer would be necessary, and a diesel generator would be optional (the x-ray generator could be connected to the local power grid, if stable). The cost of the x-ray unit itself could be easily offset by the large volumes of food passing through the marketplace daily, and the low cost of irradiation itself.

As a mobile unit serving village communities, however, the high initial cost puts the proposed system well out of the realm or possibility for most African nations, despite the low running costs. Perhaps if relief organizations and first-world governments were to subsidize the initial purchase of such systems, leaving local governments to fund the relatively low running costs, the proposed system could offer great health benefits at an acceptable cost.

As food irradiation slowly becomes more accepted in the public eye, perhaps first-world relief organizations will in the future be willing to fund food irradiation projects in African nations as a necessary health benefit, just as they are currently pushing for the introduction of genetically modified crops.

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