Productivity-Enhancing Technologies in Beef Production

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Submitted by: Isaac Aboagye

Definition

Use of productivity-enhancing technologies (PET: growth hormones, ionophores, and beta-adrenergic agonists) to improve productivity has recently garnered public attention regarding environmentally sustainability, animal welfare, and human health.

1. Introduction

It is estimated that the human world population will exceed nine billion by 2050 [1], raising a global concern over food security, especially in developing countries. Increasing consumption of animal protein has been suggested as one of the sustainable strategies to address food security, especially for the nearly 800 million people in the world who subsist on less than US$ 2.0 a day [2]. Globally, of the 60 g of daily protein intake recommended for an adult (>18 years and 75 kg [3]), approximately one third is acquired from animal protein [4]. Animal protein is a rich source of the most commonly limiting essential amino acids, including leucine, methionine, and lysine [5][6][7], as well as vitamin B12 [8], calcium [9], and heme-iron [10]. Furthermore, animal protein is generally more digestible and the amino acids more bioavailable due to the absence of the anti-nutritional factors associated with plant-based proteins [11][12][13].

Despite these benefits, the potential of animal agriculture to feed a growing population has been questioned over environmental concerns, including the use of 30% of the global arable land for feed production, 32% of the world's freshwater [14], and production of 14.5% of global greenhouse gas emissions (GHG [15]). Beef cattle production has been deemed to be the most environmentally unsustainable among the major livestock production systems [16] as its land, water, and carbon footprints are 28-, 11-, and five-fold higher, respectively, than pork or chicken production[17]. However, studies in Brazil [18], Australia [19], United States (US [20]), and Canada [21][22] have demonstrated that modern intensive cattle production has lowered the environmental footprint of beef production on an intensity basis, as result of reductions in land and water use, as well as GHG emissions.

The beef production systems in these countries usually involve transitioning animals from a cow–calf system (cow herd produces calves) to a backgrounding system (weaned calves fed forage-based diets) and then to finishing diets (steers/heifers, fed high-energy grain-based diets), prior to being sent to a processor or packer. Use of productivity-enhancing technologies (PET) in these "conventional" production systems has been adopted to improve productivity [23] and may reduce the environmental footprint. Cattle operations not using PETs are often referred to as "natural" production systems. Growth-enhancing technologies include implants, estrous suppressants, beta-adrenergic agonists (βAA), and ionophores [23].

Despite demonstrated benefits in productivity, consumers perceive that PETs may have negative impacts on the environment, food safety, and animal welfare [24][25][26]. As a result, more than half of consumers participating in a global internet survey declared that they preferred meat and other animal food products from beef cattle that did not receive growth implants or antibiotics [27]. These online responses may contain inherent biases, as they were based on claimed behavior rather than direct measurement of product preferences within the food service and the retail sectors.

2. Productivity-Enhancing Technologies in Beef Production

Globally, many PETs such as hormones and ionophores have been used in beef for more than 60 years, while other approved products such as βAA have only been approved within the last few decades (Table 1 [28][29]).

Table 1. Productivity-enhancing technologies commonly used in beef production.

Class [a]	Mode of Action	Substance [b]	Mode of Administration
Growth hormones			
Endogenous/Synthetic	Increase protein deposition at the expense of fat to increase growth rate and decrease amount of feed required for the animal to gain weight.	Estradiol-17β, Testosterone, Progesterone/Zearalenone, Trenbolone acetate	Implants
		Melengestrol acetate	In-Feed
Beta-adrenergic agonists	Redirect nutrients from digestive organs into muscle tissue, thus increasing muscle mass accretion at the expense of fat deposition.	Ractopamine chloride, Zilpaterol chloride	In-Feed
Antibiotics [c]			
Ionophores	Act against Gram-positive bacteria by altering membrane permeability to promote propionate formation in the rumen, which is more energetically favorable than acetate production.	Monensin, Lasalocid, Salinonmycin	In-Feed

Class	Mode of Action	Substance	Mode of Administration
Macrolides		Tylosin, Neomycin	
Aminoglycosides	Has bacteriostatic effect on both Gram-positive and Gram-negative bacteria, thus reducing microbial competition for nutrients.		In-Feed, water, or parenteral
Tetracyclines		Oxytetracycline, Chlortetracyclic	

[a] Used in growth promotion by beef producing countries, including countries in North America (US, Canada, Mexico), Australian–New Zealand region, South America (Brazil and Argentina), and Africa (South Africa). Approval of specific products depends on the regulatory framework within each country. [b] Synthetic derivatives of estrogen, testosterone, and progesterone are zearalenone, trenbolone acetate, and melengesterol acetate, respectively. [c] Globally not recommended for feed efficiency, except ionophores. However, implementation is subject to local and national legislation or regulation.

3. The Role of PETs in Global Beef Production

Differences in the regulatory framework among countries regarding the use of PETs not only impacts domestic production, but can also create non-tariff barriers to export. The use of PETs is permitted in North America (US, Canada, and Mexico) and Australia–New Zealand [30], which produced 20% (13.5 million tonnes: Mt) and 4% (2.9 Mt), respectively, of total global beef in 2018 (67.4 Mt [31]). Brazil and Argentina, which also supplied 15% (9.9 Mt) and 5% (3.1 Mt), respectively, of the global beef market in 2018 [31] also allow the use of PETs [32]. All of the above countries rely heavily on export markets and therefore, must meet requirements of those countries that do not allow use of PETs, including the European Union (EU), China, and Russia [33], which collectively produced 27% of global beef in 2018 (i.e., 10.6, 5.8, and 1.6 Mt, respectively [31]).

4. Impact of PET Use on Consumer Choice

Global per capita beef consumption ranges from 0.5 to 40 kg, with an average consumption of 6.4 kg in 2018 [34]. Consumption is influenced by many factors, including management practices (use of PETs), culture, palatability, appearance, and price [35]. The demand for beef and beef products raised without the routine use of PET and labeled as “raised without antibiotics”, “raised without added hormones”, “natural” (raised without antibiotics and additional hormones), “organic” (raised without antibiotics and additional hormones and feed that was not genetically engineered or produced using synthetic fertilizer), or “100% grass-fed” is growing, but still only constitutes a small portion of the total market as depicted in Figure 1 and Figure 2 [36][37][38]. The increase in consumer demand for beef raised without PET has increased the number of feedlot operators registered in “natural” programs in some regions of the US. From 2010 to 2018, the percentage of the 36,856 Texas beef producers enrolled in “natural” programs (i.e., raised without antibiotics and additional hormones) increased from 35% to 43%, while those enrolled in “raised without added hormone” programs increased from 5.2% to 23.8% (Figure 3 [39]). A study conducted by Nielsen Global Health and Ingredient–Sentiment Survey [27] with 30,000 online consumers from 69 countries indicated that the majority of the respondents from Europe (65%), Latin America (59%), Asia-Pacific (59%), Africa/Middle East (55%), and North America (54%) would avoid animal products containing hormones or antibiotics. Although online survey methodology allows for global outreach, it provides the sentiments of only existing internet users and not the total population. Again, because this survey was based on claimed behavior rather than verified measured data from abattoirs, wholesalers, hotels, restaurants, and grocery stores, biases may not truly represent the market trends in terms of types and volumes of animal products sold. Respondents may also not have a complete understanding as to how these additives are used in the industry and the regulatory oversight for their use. Furthermore, they also likely do not recognize the reduction in retail price associated with the use of PETs, which was estimated to lower the cost of US beef from US$ 15.50 to 13.80/kg [40].

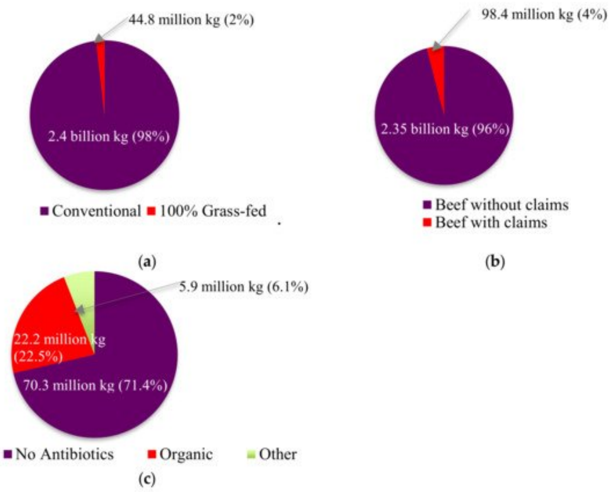

Figure 1. Volume of US retail beef sold in 2019 by (**a**) production (“conventional” vs. “100% grass-fed”); (**b**) total claims ("without claim" vs. "claim"); and (**c**) type of claim (“no antibiotic” vs. “organic” vs. other (e.g., Halal, Kosher or Kobe-Style)). Source: Modified from Beef [36].

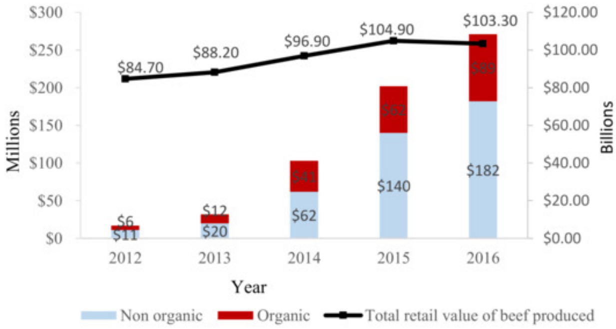

Figure 2. Total retail value (billions), "organic" and non-organic "grass-fed" beef retail sales (millions) from 2012 to 2016 in US. Source: Modified from Cheung et al. [37]; USDA [38].

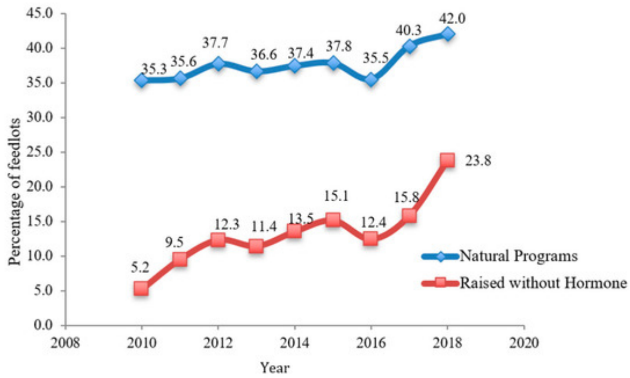

Figure 3. Percentage of feedlots that enrolled in "raised without hormone" or in one or more "natural" programs in Texas, US. Source: Modified from Odde et al. [39].

In the US, labeling beef as "raised without antibiotics or hormones" can increase its price by as much as US$ 6.56/kg, a 47% premium over conventionally produced beef US$14.06/kg [41]. Similarly, in Canada, a recent study of consumers' willingness to pay premiums for beef products labeled as "use of antibiotics with no hormones", "responsible use of antibiotics with hormones", "responsible use of antibiotics with no hormones", and "no antibiotics and no hormones" reported that they had dollar premiums/kg of beef product at $12.13, $14.22, $21.08, and $30.07 CAD, respectively [42]. Lewis et al. [43] also examined willingness of European consumers to pay a premium when the average beef price was 18.27€/£ per kg and showed that German and British consumers would pay 29% and 20% more, respectively, for PET-free beef. Furthermore, in Argentina, Colella and Ortega, [44] showed that consumers that purchase from a supermarket were willing to pay a premium of (US$ 2.5/kg) for certified "organic" beef as compared to consumers that were purchasing unverified beef from a local butcher. Willingness to pay more for "natural" or "organic" beef is attributed to concerns over the environment, animal welfare, and food safety [24][26][35][43]. Even though some consumers may express concerns about PET use or preference for PET-free beef when interviewed, at the purchasing point, other attributes such as price largely determine their purchasing behavior [35].

Recently, Hirvonen et al. [45] showed that meat products were more affordable for high-income nations such as Australia, New Zealand, Europe, and North America than low-income countries in South Asia and sub-Saharan Africa. Therefore, globally, the willingness to pay a premium for PET-free beef is likely heavily influenced by consumer income. Such a premium is unlikely to be a viable option for those who live on less than US$ 2.0/day in low-income countries, even though these populations are likely to realize the greatest nutritional benefit as a result of including meat in their diets.

5. PETs and the Environment

The use of PETs leads to improved production efficiencies [46][47][48]. However, assessments of the effects of PETs on the environmental footprint, including GHG emissions, land use and land use change, water and energy use, and impacts on biodiversity, water quality, and other ecosystem services are limited. Moreover, available studies have focused primarily on production systems in Canada and the US (Table 2).

Table 2. Summary of studies measuring the environmental impacts of productivity-enhancing technologies (PET) used in beef production.

Reference	Summary of Trial Design				Environmental Indices [e,f]					Country
	Methodology [a]	Production Stage [b]	Treatment [c]	Days on Feed	CO_2eq	Land	Water	Energy	NH_3 /Manure Excretion	
Basarab et al. [49]	LCA	Backgrounding and finishing phases	IMP or control	Backgrounding: 312 days. Finishing: 146 to 207 days.	5.8% ↓	7.8% ↓	NR	NR	NR	Canada

Reference	Summary of Trial Design				Environmental Indices					Country
	Methodology	Production Stage	Treatment	Days on Feed	CO eq	Land	Water	Energy	NH /Manure Excretion	
Capper [50]	LCA	Backgrounding and finishing phases	βAA + IMP + MGA + ION ("conventional"); and no additives ("grass-fed" or "natural" animals).	Backgrounding: 123 to 159 days. Finishing: 110 to 313 days.	14.8–40.3% ↓	18.3–44.7% ↓	17.9–75.2% ↓	14.9–28.6% ↓	17.9–50.5% ↓ N and 20.7–51.4% ↓ P excretions	US
Capper and Hayes [51]	LCA	Backgrounding and finishing phases	βAA + IMP + ION + MGA; or control.	Backgrounding: 148 to 159 days. Finishing: 116 to 209 days.	8.9% ↓	9.1% ↓	4.0%↓	7.1% ↓	8.9% and 9.6%, ↓ N and P excretions, respectively.	US
Cooprider et al. [52]	Animal trial	Finishing phase	βAA + IMP + ION; or control.	146 to 188 days.	31.4% ↓ non-CO_2 emissions	NR	NR	NR	NR	US
Stackhouse et al. [53]	LCA	Backgrounding and finishing phases	IMP + ION only; βAA + IMP + ION; or control.	Backgrounding: 182 days. Finishing: 121 to 212 days.	6.6–8.0% ↓	NR	NR	NR	7.7–13.5% ↓ NH_3 emissions.	US
Stackhouse-Lawson et al. [54]	Animal trial	Finishing phase	ION only; IMP + ION only; βAA + IMP + ION; or control	107 days.	9.6–16.4% ↓CH_4 emissions	NR	NR	NR	30% ↓ NH_3 emissions	US
Webb [55]	Animal trial and LCA	Cow–calf, backgrounding, and finishing phases	ION only; IMP + ION only; βAA + IMP + ION; or control.	Backgrounding: 91 days, Finishing: 152 to 183 days	1.1–7.7% ↓	NR	1.0–5.8% ↓	1.1–5.5% ↓	0.7–5.1% ↓ reactive N	US

[a] Type of study conducted: LCA = Life cycle assessment, with PETs administered during backgrounding and finishing phases only, except Webb [55], who included implanted pre-weaned calves during the cow–calf phase; Animal trial = a study that used steers at the finishing phase. [b] Assumes a production system comprised of three distinct phases: cow–calf, backgrounding, and finishing. Grain-based diet during finishing phase except where indicated. [c] IMP = Implants (trenbolone acetate, estradiol, zearalenone); MGA= melengestrol acetate; ION = Ionophores (Monensin); βAA = Beta-adrenergic agonist (zilpaterol chloride and ractopamine chloride). [d] ADG = average daily gain; G:F = gain:feed. In Stackhouse et al. [53] and Webb [55], linear growth was assumed during the backgrounding phase; and during the finishing phase, ADG was adjusted when days on feed were extended as a consequence of lower feed quality and availability, which were assumed to limit growth. [e] Where ↓= decrease, ↑ = increase, and NR= not recorded; In all studies, the production indices and environmental parameters for all PET treatments were compared with control (no additives); however, in Capper [50], "conventional" animals (administered PETs) were compared with "natural" or "grass-fed" animals (no PETs administered for either). [f] Environmental indices were expressed on an intensity basis (per kg of beef); CO_2eq = carbon dioxide equivalent; CH_4 = methane; NH_3 = ammonia; N = Nitrogen; and P = Phosphorus. [g] The total number of cattle considered under "grass-fed" was 12,510,000 and for "natural" was 8,257,000 animals. [h] The total number of cattle in the production system without PETs was 3,651,000 animals.

6. PET, Food Safety, and Animal Welfare

Concerns regarding the development and spread of antimicrobial resistance due to the use of antibiotics for growth promotion in animals has recently led to the ban of in-feed antibiotics such as tetracycline and tylosin for growth promotion in many countries including Canada (Table 1 [56]). These antibiotics are used in treating infectious disease in animals as well as humans, and therefore there are concerns that this practice may compromise the therapeutic effectiveness of antimicrobial drugs in human medicine [57]. The Global Roundtable for Sustainable Beef (GRSB), which represents beef producers, veterinarians, scientists, retailers, and other value chain partners in over 20 countries, recommended that with the exception of ionophores, antimicrobials should not be used for feed efficiency [58]. Ionophores are not currently used for therapeutic purposes in humans [57]. Wong [59] argued that ionophores such as MON are technically antibiotics and should also be banned. However, implementation of this recommendation is at the discretion of local and national legislative and regulatory authorities.

Furthermore, approval of PETs for use requires toxicology testing to determine maximum residue limits (MRLs) in beef for human consumption.

While others have adopted the guidelines of the Joint FAO/WHO Expert Committee on Food Additives (JECFA), some countries have developed their own guidelines [60][61][62]. Due to differences among guidelines, the MRLs established for PETs in beef and beef products may be low or non-existent in some countries. Independent institutions including JECFA and government institutions from several countries including Canada, Australia, and the US do not analyze the offal (i.e., abomasum, omasum, small intestine, and reticulum) for βAA. Consequently, there are no established MRLs for this PET in these tissues. In a recent US study by Davis et al. [63], RC concentrations were higher in offal (13 to 105 ppb) and in small intestinal digesta (20 ppb) from beef cattle than the limits recommend in the muscle tissue by most countries (i.e., 10 to 30 ppb). The lack of established MRLs means that beef products such as edible offal may exceed recommended allowable limits, as was the finding of Davis et al. [63]. There are limited studies on the effects of RC and ZC on human health, but preliminary data reviewed by authorities at the European Food Safety Authority (EFSA) suggested that a single dose (≥ 0.76 µg/kg body weight) of these βAA may cause transient cardiovascular disease and bronchodilation, posing a risk to asthmatic patients [64]. However, residue levels in muscle, liver, and kidney were well below the MRLs established by regulatory agencies in Canada [65], Australia [66], and the US [67].

There are also animal welfare concerns due to the use of diethylstilbestrol (a hormone) and clenbuterol (a βAA) as a consequence of their endocrine disrupting properties [68][69], dilation of the trachea [70], and disruption of metabolism [71]. As result of concerns over these responses, the use of these additives in beef production has been discontinued. Nevertheless, worldwide, there are animal welfare concerns regarding currently used βAA products such as ZC. More recently in the US, Neary et al. [72], hypothesized that ZC (8.3 mg/kg on feed DM basis for 21 days) increased the risk of cattle developing heart disease. In that same year of their experiment, the use of this product also was proposed to contribute to the development of lameness and increase the mortality of cattle during the finishing phase [73]. In 2013 and 2014, some of the largest meat processing plants such as Tyson Foods and Cargill in both the US and Canada suspended the purchase of cattle fed this product. Subsequently, Merck Animal Health also removed this product from the market until such a time that additional data can be generated to evaluate product safety [74][75].

To address concerns relating to ZC use, scientists from EFSA reviewed 12 studies between 2012 and 2016 (excluding [72]) to examine the animal health and welfare of more than 200 cattle and concluded that ZC was not responsible for death and lameness in beef cattle [64]. Although a study by Neary et al. [72] (n = 11) suggested that ZC may compromise cardiac function, it is possible that other respiratory diseases were responsible, possibly making the link between cardiac injury and ZC coincidental [76][77][78]. A follow-up US study using 30 Angus steers showed no evidence of myocardial injuries or an increase in heart rate associated with ZC (8.3 mg/kg on feed DM basis) and RC (300 mg/d) after 23 days of treatment [79]. Similarly, after feeding RC to finishing cattle at 400 mg/d, Hagenmaier et al. [80] did not report an increase in heart rate. In addition to concerns regarding physiological responses to PETs, public perception suggests that their use leads to increased stocking density and compromised animal welfare. Decisions regarding stocking density are based on adequate bunk space in conventional systems and forage availability in pasture-based systems, and in either case are not dictated by PET use. Thus, with the current recommended dosages and administration guidelines, these PETs have not been reported to have adverse effects on consumer health or animal welfare.

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Keywords

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