

LEVERAGING LIVESTOCK TO PROMOTE A CIRCULAR FOOD SYSTEM

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ABSTRACT

Livestock provide multifaceted services to human societies worldwide. In developing countries, they are crucial assets and safety net for rural poor, and they provide nutrients-dense food to nourish people. In developed economies, growth in demand for animal-derived food is slowing while attention is growing over the role of livestock farming in an enhanced circular food system for sustainability. This analysis, focusing on the modern food systems in developed countries, aims to highlight the unique function of livestock that helps people re-harvest and upcycle crop and food residues generated along the food chain that are otherwise unfit for human consumption. First, human-unusable crop and food residue materials are described in three broad categories based on their characteristics and potential feeding attributes; the magnitude of biomass materials that are already used in routine animal feeding as well as residues that remain as underutilized resources are illustrated using the USA as an example. Then, the research and technology development critically needed for the future is discussed. As the world strives to produce more food with smaller environmental and climate footprints, upcycling the residual biomass via livestock for food production presents a viable pathway toward improved resource use, reduced pollution and enhanced food system efficiency.

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The primary function of agriculture is to produce food, fiber and fuel to serve human needs. Livestock farming is an important component of the modern agriculture and food systems with a double role to play. One is obvious—to produce nutrient-dense foods such as meat, milk, and eggs for people. Such foods are particularly critical to the world's poor as the main source of essential proteins and micronutrients for reducing stunting and wasting^[1]. The other role is not as obvious to the general public but equally, if not more, important—livestock animals can feed on crop and food residues that are unfit for humans to produce meat, milk, and eggs, thereby helping to maximize the beneficial use of biomass already produced and also to lower resource, environmental and climate burdens. The latter function is the essence of a circular food system that aims to extract maximal value from existing biomass to serve human needs. As the world strives to produce more food to feed the growing population, particularly the surging demand for animal-derived food in

developing countries, leveraging livestock to enhance food system efficiency and promote a circular food system is imperative.

The modern food and beverage systems generate large amounts of residual biomass from farm to fork. For example, 50%–70% of orange fruit is left in the pulp when making juice. In the USA, 4–7 Mt of oranges are used for juice-making each year^[2], leaving 2–4 Mt in the residual pulp^[3]. Another example is grain milling; the process leaves behind up to 25% residues. Annual mill residues amount to about 11 Mt in the USA^[4]. Further down the food supply chain, 13%–14% of fruit and vegetables delivered to supermarkets remain unsold^[5], which amounts to 6 Mt per year in the USA. Moreover, about 40 Mt edible food is estimated to be wasted by consumers (e.g., in restaurants and homes)^[6]. Additionally, certain non-food systems also generate large volumes of plant-based biomass materials. For example, the

USA ethanol industry generates DDGS (dried distillers grains with solubles) as byproduct, amounting to 44 Mt per year^[7]. The various food-beverage-fiber-biofuel residues are generally human-indigestible, unpalatable or undesirable biomass (IUUB), which are unfit for direct human consumption under normal circumstances. However, these materials are still rich in nutrients, e.g., calories, proteins and minerals (Table 1), therefore they have considerable biological value. Capturing the nutrients contained in this biomass in ways that enable the regeneration of food for people would be highly desirable.

Livestock are the ideal means for assisting societies to achieve this goal. As natural bio-processors, livestock have an innate ability to digest a wide range of biomass types and extract the contained nutrients for growth, maintenance and production. Around the world and historically, livestock have had a critical role in maximizing the beneficial use of biomass already produced, such as crop residues or food scraps, to serve human needs^[9]. Modern food systems are exceedingly complex and versatile, resulting from the intensification of primary production on farms, specialization of food processing/manufacturing postharvest, plus globalization of food sourcing and distribution via international trade. Decoupled livestock and crop farming has not only changed the long practice of on-site

recycling of nutrients in manure to cropland but also disrupted efficient reuse of various IUUB materials in animal feeding. Fortunately, this spatial divide does not mean a total severing of the services animals provide to society. In fact, large amounts of residues from crop and food processing industries (as byproducts) have been developed into commercial feeds, which are routinely used for livestock production. Additional to the industrial scale byproducts, there has been an upcycling of various crop residues or food scraps, such as unsold fruit and vegetables, in feeding dairy cows (Fig. 1). From the food system perspective, livestock-crop integration has maintained its functionality to a large extent. Nevertheless, massive amounts of IUUB materials, especially at the consumption stage of the food supply chain, remain underutilized or wasted. There is an opportunity for transformative changes to treat and manage these materials as feed resources instead of landfill wastes.

IUUB materials from the food system are diverse and versatile. To facilitate discussion, these are grouped here into three broad categories based on relevant characteristics and potential feeding attributes.

Type 1: Food-beverage-fiber-biofuel processing residues. Such residues are integral parts of the raw materials but are not meant

Table 1 Nutrient profile of select food-beverage-fiber-biofuel processing byproducts commonly used in livestock feeding

Byproducts	Dry matter (% as fed)	Crude protein (% DM)	Crude fiber (% DM)	Phosphorus (g·kg ⁻¹ DM)	Gross energy* (MJ·kg ⁻¹ DM)	Notes
Flour milling byproducts (wheat grain)	87.9 (87.0)	17.7 (12.6)	7.5 (2.6)	8.9 (3.6)	19.2 (18.2)	Wheat milling byproducts, including the parts of wheat kernel that are richest in proteins, vitamins, lipids and minerals. Useful in ruminant, swine, poultry or fish diets
Soybean meal (whole soybean)	87.7 (88.7)	49.5 (39.6)	7.2 (6.2)	7.1 (6.1)	19.5 (23.6)	Byproduct after oil extraction from soybeans; the most important protein source used to feed livestock animals
DDGS (maize grain)	89.0 (86.3)	29.5 (9.4)	7.9 (2.5)	7.9 (3.0)	21.4 (18.7)	Byproduct of maize-based ethanol facilities in most cases, containing primarily unfermented grain residues (protein, fiber, fat and minerals). As a commodity, DDGS is fed to all classes of livestock animals
Citrus pulp, dried (citrus fruit, fresh)	90.3 (15.8)	7 (6.5)	14 (2.9)	1.0 (2.0)	17.6 (18.1)	The solid residue after fresh fruits are squeezed for juice, consisting of peel (60%–65%), internal tissues (30%–35%) and seeds (up to 10%); used as a cereal substitute in ruminant feeds, due to its high energy content and good digestibility for ruminants
Cotton seeds, whole	92.3	21.8	28.1	5.9	23.8	The remains after cotton is ginned; can be crushed and the oil extracted, then the meal fed to adult ruminants

Data source: Feedipedia^[8]. In many cases, nutrients became concentrated in the byproducts, as compared to the raw unprocessed substrates (data in parenthesis)^[8]. *The amount of energy in the feed.



Fig. 1 Plant-based residual biomass fed to cows on a Chinese dairy farm (residues from tofu-making, tea-making, garlic packaging, cottonseeds and pelleted dried beets pulp), and two dairy farms in Pennsylvania, USA (apple cores, unsold fruit, vegetables, and baked goods). Photo credits: Zhengxia Dou, Joe Bender.

for human consumption because of food culture/tradition as well as current processing technology. Examples include orange pulp, wheat screenings, cottonseeds, and DDGS from maize-based ethanol industry. Large-scale processing facilities typically manage their IUUB materials as byproducts (also now called coproducts) for animal feeding. Such feedstuffs are easy to handle, conform to feeding standards and safety regulations, with extended shelf-life. As commercial feedstuffs, their nutritional attributes, e.g., protein, minerals and digestibility are well-established. Such high-quality feeds have been widely incorporated into animal feeding programs, contributing to the enhanced productivity of modern dairy, beef, swine and poultry operations.

Additionally, a wide range of IUUB materials are generated by numerous small-scale food and beverage processing facilities that are scattered across a country or region. Some of these facilities may operate steadily year-round, others periodically dependent on seasonal stocking supply and demand dynamics. Examples include residues from chocolate factories (steady year-round), apple pomace from cider or juice production (post-harvest only) in apple producing areas, or wet brewers grains from local or specialty breweries. Different from the mass-produced coproducts from large processing centers described above, these IUUB materials often leave the production sites as

raw residues without further treatment. They can be used for animal feeding on nearby farms through private arrangement with or without formal marketing-distribution channels. The nutritional attributes of these residues are generally steady and thus their incorporation into animal feeding programs is viable. A practical challenge is their relatively short shelf-life as untreated wet residues can be prone to spoilage.

Type 2: Food retail-distribution discards (also referred to as pre-consumer food discards or waste). This type of IUUB is generated at the forefront of the consumption stage in the food chain at the market-consumer interfaces, such as supermarkets, and various retail and wholesale centers. Different from Type 1 materials that are largely inedible (indigestible and/or unpalatable) for humans, Type 2 materials are meant for human consumption but became unsalable for various reasons. Type 2 food discards occur at numerous stores or locations, large and small, often as mixture of food items of various nature or form, e.g., plant or animal products, raw or processed, packaged or loose. Such food discards usually vary in composition as well as nutritional attributes. Variation in nutrient content as well as unpredictability constitutes a major challenge in terms of valorization for animal feeding. Source separation and further treatment to address this challenge is feasible. There is field evidence of unsold fresh fruit and vegetables being effectively

used on dairy farms (Fig. 1). However, this kind of practice is likely to occur on a case-by-case basis rather than widespread adoption in developed economies.

Type 3: Post-consumer food waste. Food wastage occurs at food service places and homes. Compared to Types 1 and 2 materials described above, food waste is generated in hundreds of millions of restaurants and households, resembling the concept of non-point source nutrients polluting waterways. Typically, food waste is a mixture of various materials, cooked or uncooked, whole or remnants, edible or inedible, animal or plant products or combined as in manufactured products. Source separation of plant- from animal-based food waste would be a logistical challenge. Potential use of food waste for feeding would be limited to certain animal species where permitted. For example, the USA has laws guiding the safe use of food waste for swine feeding, whereas under EU regulations this is currently prohibited^[10]. Innovative technologies to convert food waste into safe and nutritious animal feed, along with consistent and enabling policies, are urgently needed to support the upcycling and reuse of food waste through animal feeding for enhanced food security and sustainability.

Clearly, the livestock sector as a whole continues to serve society by extracting nutrients from IUUB materials while producing meat, milk, and eggs for humans. This is particularly true for Type 1 byproducts, with documented feed uses in the range of 90–100 Mt per year in the USA alone^[4,7]. By comparison, cereal grains (barley, maize, oats, rye, sorghum and wheat) used as animal feeds is about 126 Mt per year^[4]. The contribution from IUUB byproducts to national meat, milk and egg production is evidently substantial, and the role of livestock in promoting a circular food system toward sustainable food security is critical. Nevertheless, there remains the opportunity to further leverage the unique and unparalleled ability of livestock as bio-processors for the other types of IUUB materials that remain to be systematically managed as resources for feeding. The gross estimates include (1) 15–25 Mt food and beverage processing residues (Type 1) at small-scale processing facilities, assumed to be 15%–25% of Type 1 byproducts; (2) 30–35 Mt pre-consumer food discards (Type 2), based on the estimated 20 Mt *edible* food loss in the retail sector^[5] and assuming the inedible part to be 50%–75% of the edible amount; (3) 60–70 Mt post-consumer food waste (Type 3), considering the 40 Mt *edible* food loss by consumers^[6] and assuming the inedible part to be 50% to 75% of the edible amount. Taken together, there could be 105–130 Mt IUUB materials (as-is basis, with substantial dry matter variation) in the USA on an annual basis that remain as untapped resources to be reclaimed for potential feeding. The

USA situation could be similar to many other developed economies.

Importantly, IUUB materials can differ substantially in nutritional attributes, feeding quality and management challenges. Different animal species have distinct capacities as bioprocessors. Also, collecting IUUB materials for feed production may or may not be the best option in all cases. To strategically and systemically evaluate IUUB materials for prioritized end-use, such as animal feeding versus composting or anaerobic digestion (all more preferable than disposal at landfills), closing current data gaps is a critical first step. Only with a better understanding based on detailed data on the nature, amount, location and seasonality of residue production can society and businesses make informed decisions and take concrete action for recovery and proper reuse of IUUB materials. Furthermore, it is vitally important to safeguard animal health, which is closely connected with food safety and public health. Therefore, innovative technologies are needed for converting IUUB materials into feeds that are free of infectious disease agents or other contamination. Such technologies can also help change the longstanding stereotypical image of garbage-feeding with *new* feeds that are aesthetically acceptable and socially appealing as sustainable and climate-smart products. In this regard, research to quantitatively define the resource-environmental-climate implications (positive or negative) of producing new feeds from IUUB is needed. Relevant socioeconomic impacts will need to be addressed via multidisciplinary research as well. Better knowledge with systems-based comprehensive analyses is a prerequisite to inform and influence public policies and business decision-making toward a circular food system with greater efficiency, resilience and sustainability.

The domestication of farm animals more than ten thousand years ago enabled human to extend their food-acquiring capacities to combat food scarcity and hunger, as these animals helped to maximize the use of biomass available in an otherwise-primitive ecosystem. Today, the capacity of food provisioning through agriculture has vastly expanded, but the challenges that humans face are unprecedented and multidimensional, e.g., the growing appetite for meat, milk and eggs in developing economies, widespread water pollution and soil degradation, climate change and finite resources plus competition for land and water from non-agricultural sectors. Leveraging livestock, the gift of domestication from our ancestors, to maximize the beneficial use of agricultural biomass while minimizing unintended consequences is a viable path toward addressing the pressing challenges.

Compliance with ethics guidelines

Zhengxia Dou declare that she has no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by the author.

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