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FROM THE EDITOR

Foods of animal origin: a prescription for global health

Eric P. Berg
Department of Animal Sciences, North Dakota State University, Fargo, ND

Most often we associate malnutrition with undernutrition. The World Health Organization (WHO, 2019) describes undernutrition as wasting (low body weight relative to height), stunting (low height relative to age), and underweight (low body weight for a given age). However, the WHO also classifies malnutrition as inadequate or excess vitamins/minerals, overweight, and obesity. Anemia (iron and B12 deficiency) and indispensible amino acid malnutrition are physically manifested as wasting, stunting, and underweight as well as overweight and obesity.

This issue of Animal Frontiers is titled “Foods of Animal Origin: A Prescription for Global Health.” This phraseology was selected because “global health” can mean different things to different people. For example, it can mean the physical health of an individual to positively affect their ability to thrive, or global health can mean the environmental health of the planet and its ability to sustain all life. The balance between providing for human health without compromising environmental health must be addressed. This issue includes articles that provide evidence for consuming nutrient-dense foods of animal origin to prevent/cure the most common global nutrition-related conditions and articles that address the social, cultural, environmental, and ethical considerations of consuming animal-sourced foods (Figure 1).

The paper by Tang (2019) addresses the importance of correct food selection during the first 5 to 12 mo of age when solid foods are progressively introduced to infants. The foods selected for “complementary feeding” during this period can have a significant impact on food choices later in life as well as susceptibility to overweight/obesity and obesity-related metabolic disorders. The foods first introduced to children in transition are often cereal-based and low in high-quality protein with baby food meats being consumed the least. Anemia is a concern in early childhood and infant iron deficiencies may be prevented by the consumption of meat (especially “red” meat) as a complementary food. Furthermore, early research suggests that consumption of nutrient-dense muscle foods may provide beneficial substrates that promote development of a positive gut microbiome that becomes established during the transition period from breastmilk/formula to complementary foods.

Establishing good nutrition choices early in life provides the basis for lifelong dietary patterns that will improve an individual’s ability to thrive later in life. Hackney et al. (2019) describe the contribution of foods of animal origin for the prevention of muscle wasting later in life. The aging population often avoid meat (specifically “red” meat). As muscles age, there is a greater protein turnover and if protein degradation is greater than protein synthesis, then muscle tissue shrinks (metabolically termed wasting). Loss of muscle mass leads to loss of strength and greater susceptibility to falls and injury. Muscle serves as a metabolic sink for energy and a loss in muscle mass can also lead to development of obesity. Foods of animal origin are a high-quality source of highly digestible nutrients that can aid in maintenance of muscle health, providing more nutrients from fewer calories.

The Food and Agriculture Organization (FAO) convened a consortium of human nutrition experts that recommended (FAO, 2013): a) Dietary amino acids should be treated as individual nutrients whereby food labels should include information about digestible or bioavailability of individual amino acids and b) Quality of protein will be defined as a measure of digestible indispensable amino acid score (DIAAS). The FAO (2013) further stated that “Digestibility should be based on the true ileal digestibility of each amino acid preferably determined in humans, but if this is not possible, in growing pigs or in growing rats in that order (FAO, 2013).” Bailey and Stein (2019) describe the process for determination of true ileal digestibility of various animal-sourced foods. Most foods of animal origin are excellent sources of digestible protein, making them an important complimentary food with other foods possessing a lower DIASS, such as grains.

There is a growing ethical debate regarding how our food choices affect global environmental health. Alonso et al. (2019) present the case that meat, milk, and eggs consumed during the first 1,000 d of life (from conception, through pregnancy, to 2 yr of age) can significantly improve an individuals’ ability to thrive later in life. The authors also caution that as economic status improves and demand increases for foods of animal origin, history has shown that populations will demand greater quantities of that good thing. Left unregulated, this can lead to...
overproduction and abuse within the system that can include mistreatment of animals, land, natural resources, and people (employees).

On the surface, it may seem biologically impossible for obesity to be associated with malnutrition. Dasi et al. (2019) address the “double burden of malnutrition” where nutrient deficiencies lead to muscle wasting and a simultaneous increase in adiposity. In India, one in four urban adults over the age of 55 have been diagnosed with diabetes. Populations of low economic status often subsist on cereal-based diets deficient in such essential nutrients as vitamin B12, heme-iron, and many indispensable amino acids. Poor nutritional education in these parts of the world results in food choices that over-index starches (carbohydrates) and under-index high-quality proteins. Introduction of affordable animal sourced foods and nutrition education programs can improve the ability of these populations to thrive, especially for children.

We are often instructed to choose dietary patterns that include foods that are part of “sustainable” agriculture. Varijakshapanicker et al. (2019) address the balance between providing optimal nutrition and sustainability. The authors define sustainability as “a holistic concept that jointly considers ecological, social, and economic dimensions of a system or intervention for long-lasting prosperity.” They describe how livestock can be utilized in a sustainable system because they will consume plants that are not eaten by humans or they graze lands that are unable to sustain crops. Livestock are net contributors to human protein requirements because the grains, grasses, or forages they consume would not provide the same quality of bioavailable protein as animal-sourced foods. Furthermore, women play a very important role in livestock production in low- and middle-income countries. Management of such an economically important asset such as livestock has led to greater empowerment of women within the community.

A person’s ability to thrive in life is definitely dependent on their physical health, but mental health is also vital. Brain development, the ability to reason, make decisions, and improve intellectually all hinge on choosing the correct nutrients and combination of nutrients in a healthy diet. Balehegn et al. (2019) describe how the same dietary imbalances or deficiencies that lead to conditions of stunting and wasting may also impair cognitive development. Furthermore, animal-sourced foods provide more bioavailable sources of iron, zinc, iodine, and vitamins B12, B6, folate, and riboflavin that are necessary for proper brain development including enhancement of neural integrity and neural connectivity.

This issue of Animal Frontiers provides excellent insight into reaching a sustainable balance between providing optimal nutrition for a growing human population while maintaining the environmental harmony of the earth. Achieving this balance will require environmental stewards that are of strong body and mind. Foods of animal origin are nutrient-dense foods that should be the dietary staple throughout the lifecycle allowing humankind to not just survive, but to thrive.

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The impact of complementary feeding foods of animal origin on growth and the risk of overweight in infants

Minghua Tang

Section of Nutrition, Department of Pediatrics, University of Colorado School of Medicine, University of Colorado Anschutz Medical Campus, Aurora, CO 80045

Key Words: animal protein, growth, microbiome

Introduction

Evidence-based consensus holds that the first year of life is critical in obesity programming and unfavorable infant growth patterns, namely, excessive weight gain in relation to length gain or increased weight-for-length Z score, is strongly associated with obesity in young children and adolescents. Given the current obesity rates in U.S. children, identifying modifiable risk factors underpinning excessive weight and adiposity gain early in life are urgently needed. Although extensive research has been done on infant formula consumption and risk of overweight, a significant knowledge gap exists in the effects of complementary feeding on growth and risk of overweight during late infancy, especially regarding protein-rich foods. This review will present current literature on the impact of complementary foods of animal origin on growth trajectory and the risk of overweight in infants and discuss the potential mechanisms linking protein-rich complementary foods to infant growth and future research recommendations.

Protein Intake in Infant Formula and the Risk of Overweight

It was first reported by Rolland et al. (Rolland-Cachera et al., 1995) that protein intake at 2 yr of age, not carbohydrate or fat, was positively associated with body mass index at 8 yr of age. The DARLING study (Dewey et al., 1992) was one of the first to demonstrate that formula-fed infants had a greater weight-for-length score compared with breastfed infants. In this study, breastfed and formula-fed infants were followed from birth to 18 mo of age. Findings from this study showed that the mean weight-for-length score, the parameter of risk of overweight from 0 to 24 mo, became significantly higher in formula-fed infants starting at 6 mo and continued until the end of the observation. Because standard infant formula has a 46% higher protein than breastmilk (~2.2 vs. ~1.5 g protein/100 kcal of formula), this discrepancy has been considered the key contributor to greater weight-for-length score and increased risk of overweight in formula-fed infants. Indeed, a large-scale randomized controlled trial conducted in Europe (Koletzko et al., 2009) compared iso-caloric infant formula with high- and low-protein from birth to 12 mo. Results showed that the high-protein formula led to more rapid weight gain, adiposity, and a higher weight-for-length score compared with the low-protein formula, despite same energy intakes. These differences were also persistent at school age (Totzauer et al., 2018).

Current consensus holds that the high protein content in formula contributes to early rapid weight gain and increased risk of overweight in infants. The current recommendation proposed by the European Society for Pediatric Gastroenterology, Hepatology, and Nutrition is to limit protein during infancy to ≤15% of energy, without clear distinction for sources. Although

Implications

- Evidence-based dietary recommendations during early complementary feeding are lacking. Despite extensive research of protein intake in infant formula on growth and risk of overweight, research focusing on the impact of protein intake during early complementary feeding is needed.
- Current literature, although limited, showed a potential effect of meat intake to promote infant linear growth (length gain), which in turn led to a decreased risk of overweight in some studies.
- Possible mechanisms regarding protein intake and infant growth are not clear and the early protein hypothesis cannot explain the differential effect of various sources of protein on infant growth during early complementary feeding. Emerging animal studies showed that the gut microbiome may mediate the dietary impact on infant growth.

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the premise of this recommendation was based primarily on infant formula studies, the recommendation concerns both liquid diet and complementary feeding phases. A significant knowledge gap exists in the effects of common types of protein-rich foods on growth during early complementary feeding. As in dietary recommendations for adults, recommendations during complementary feeding need to distinguish between types of protein-rich foods, because dairy is no longer the sole protein source available.

**Importance of Complementary Feeding**

Early complementary feeding (~5 to 12 mo) represents the time when solid foods are progressively introduced to infants who no longer rely solely on breastmilk or formula (Figure 1). It is a unique and malleable period to establish lifelong dietary patterns and food preference, and a window of opportunity to develop interventions to prevent risk of overweight and obesity later in life. Different from toddlerhood (13 to 24 mo) when the individual is fully exposed to table foods and family meals, early complementary feeding has less food diversity, which makes it challenging and yet critical to provide evidence-based recommendations to meet nutrient needs while preventing undesired growth patterns. However, current complementary feeding recommendations are largely driven by tradition and marketing rather than a sound evidence base. Both the National Institute of Health and United States Department of Agriculture recognized the pressing knowledge gaps and emphasized the need for evidence-based dietary guidance during complementary feeding. The current Dietary Guidelines for Americans have minimal guidance for infants because of insufficient research available. The B-24 (birth to 24 mo) project was thus initiated to evaluate evidence and encourage research in high priority topics. In particular, “differences in protein intake, total amount and source” on growth, overweight, and obesity is listed as the first research priority topic for older infants (6 to 12 mo of age).

![Figure 1. Complementary feeding begins around 5 to 12 mo of age and represents the time when solid foods are progressively introduced to infants who no longer rely solely on breastmilk or formula.](image_url)

**Consumption of Animal-Based Complementary Foods**

Current national surveys indicate an overall low protein intake from animal origins in older infants. The Feeding Infants and Toddlers Study (FITS) is the largest dietary intake survey of infants and toddlers in the United States. FITS 2008 showed that less than 10% of older infants consumed meat which accounted for <5% of total energy (Reidy et al., 2017). The recently published FITS 2016 data also showed <5% of older U.S. infants consumed baby-food meats (Bailey et al., 2018) and similar patterns were found in Canadian infants (Makrides et al., 1998; Y eung and Zlotkin, 2000; Krebs et al., 2006; Dube et al., 2010; Tang et al., 2018). Specifically, in 4- to 6-mo-old U.S. infants, baby-food meats were the least consumed complementary foods while infant cereal was the most commonly consumed. In 6- to 12-mo-old infants, the exposure to meat and dairy foods increased to 41% of participants surveyed (one single 24-h recall) and the mean total protein intake was 9.2% of total calories (Bailey et al., 2018). Likewise, National Health and Nutrition Examination Survey 2009 to 2012 data on nutrient intakes also showed that the average total protein intake in 6- to 11-mo-old infants were 10% or 2 g/kg/d, without specifying protein source. Overall, older U.S. infants, on average, do not consume meat as the primary protein source of complementary foods and the low meat intake may at least partially contribute to the increased percentage of infants falling short on recommended iron intake (18% in 2016).

Effects of animal-based protein-rich foods during complementary feeding on infant growth and risk of overweight have not been thoroughly studied and available randomized controlled trials were primarily focused on meat (Engelmann et al., 1998; Makrides et al., 1998; Yeung and Zlotkin, 2000; Krebs et al., 2006; Dube et al., 2010; Tang et al., 2018). Unfortunately, the majority of these randomized controlled trials did not have infant growth as the primary outcome, but rather micronutrient homeostasis, such as iron and zinc. One randomized controlled trial in Germany (Dube et al., 2010) compared two complementary feeding interventions with high (12%) and low (8%) meat content as a good source of dietary iron. Results showed no differences in terms of infant weight or length gain from 4 to 10 mo of age between groups. Although the sample size was relatively decent (n = 50 per group), the small differences in meat intake between groups (12% vs. 8%) could have contributed to the nonsignificant findings. Some other studies (Engelmann et al., 1998; Makrides et al., 1998; Krebs et al., 2006) showing no effect of meat on infant growth also had short durations (~2 to 3 mo). One small randomized controlled trial (Tang and Krebs, 2014) found that compared with a plant/cereal based complementary diet (9% protein), a meat-based complementary diet (17% energy) promoted length gain from 6 to 9 mo in breastfed U.S. infants without increasing the risk of overweight (e.g., weight-for-length score). Another larger trial in China (Tang et al., 2014) showed that meat consumption reduced stunting, namely, increased linear growth, in older infants. Several observational studies also looked at meat intake and the risk of overweight and obesity. Garden et al. (Garden et al., 2011; Garden et al., 2012) showed that the highest quintile of meat intake was significantly associated with greater
The same studies (Garden et al., 2011; Garden et al., 2012) also found that dairy products (combined milk and milk products such as yogurt and cheese) at 18 mo were negatively associated with adiposity at 8 yr. Studies that compared various dietary patterns during complementary feeding were primarily observational and results are mixed. One population-based study showed that compared with an omnivorous diet of meat, dairy, and fish, infants consumed a macrobiotic diet of rice, pulses and vegetables that had retarded growth, fat, and muscle wasting. A recently published systematic review that included all the above-referenced studies by the B-24 project committee concluded that there is insufficient evidence to determine a relation between meat, dairy intakes, or various dietary patterns and incidence of overweight or obesity in older infants (English et al., 2019).

Research in adults and animal models showed that types of protein-rich foods differentially affect various health indicators, including insulin resistance, cancer risk, and bone health. When considering the potential differential effects of types of protein-rich foods on infant growth, findings are extremely limited. One observational study from Germany using diet records showed that dairy intake at 12 mo of age was associated with body mass index at 7 yr, whereas meat, plant, or cereal was not, after controlling for confounders (Gunther et al., 2007). To determine the impact of types of protein on infant growth and risk of overweight, randomized controlled trials are preferred with growth parameters as the primary outcome and evaluates direct comparison of different types of protein-rich foods. One recently published randomized controlled trial compared two types of protein: meat and dairy during early complementary feeding on U.S. infant growth (Tang et al., 2018). In brief, formula-fed infants from the metro Denver area were randomized to a meat- (n = 32) or dairy-based (n = 32) complementary diet from 5 to 12 mo of age. Total protein intake during the intervention was considered high at 15% of energy (~3 g/kg/d). The meat group consumed pureed beef, pork, and poultry (provided) and the dairy group consumed yogurt and cheese (provided). The same infant formula was provided for both treatments and fruits and vegetable consumptions were not restricted. Both groups consumed comparable amounts of total protein and minimum protein from the assigned (Tang et al., 2018). Intakes of energy, formula, fruits, and vegetables also did not differ during the intervention. Results showed that the length-for-age Z score (LAZ, the parameter of linear growth) increased in the meat group and decreased in the dairy group over the course of the intervention, which resulted in half-inch (2.5% or 1.8 cm) longer length in the meat group at 12 mo (Tang et al., 2018). Because both groups gained comparable amounts of weight, this deceleration of linear growth in the dairy group led to a significant increase of weight-for-length score of 0.76 from 5 to 12 mo, which was considered accelerated gain and increased risk of overweight. Importantly, these growth patterns from 5 to 12 mo also persisted at 24 mo, 1 yr after the dietary intervention ended (Tang et al., 2019). Specifically, the difference in length between meat and dairy groups remained at 1.9 cm at 24 mo. Participants from both groups consumed comparable amounts of protein from a mixture of meat, dairy, and plant. These findings suggest the long-term impact of early complementary feeding on growth and risk of overweight (Tang et al., 2019).

Overall, the current literature provides insufficient evidence to advise dietary recommendations during complementary feeding, especially regarding protein-rich foods, on infant growth, and the risk of overweight. A limited number of randomized controlled trials showed that meat may be beneficial in terms of promoting length gain in infants, which subsequently reduced the risk of overweight. However, available randomized controlled trials of complementary feeding primarily focused on outcomes other than growth, and findings on body composition (% body fat) are scarce.

The Early Protein Hypothesis

The mechanisms linking protein intake and infant growth remain unclear. The Early Protein Hypothesis explained the observations that high-protein intakes accelerate weight gain in formula-fed infants. This hypothesis proposed that high protein intake may increase the secretion of insulin and insulin-like growth factor 1 (IGF-1) and result in rapid weight and fat gain in infants. The European Childhood Obesity Project tested this hypothesis in their multicountry randomized controlled trial using high- vs. low-protein infant formula (Koletzko et al., 2009) and showed that IGF-I concentration was 40% higher in the high-protein formula group compared with the lower-protein formula group at 6 mo of age (Figure 2). Weight-for-length at 6, 12, and 24 mo was also positively associated with IGF-1 at 6 mo (Socha et al., 2011). However, in the randomized controlled trial that compared meat and dairy proteins in formula-fed U.S. infants, IGF-1 significantly increased in both Meat and Dairy groups from 5 to 12 mo without group differences (Tang et al., 2018), which was expected because both groups had a similar increased intake of protein quantity (2 to 3 g/kg/d). However, the increase of IGF-1 cannot explain the

Figure 2. The Early Protein Hypothesis suggests that high-protein intakes accelerate weight gain in formula-fed infants.
Decline of linear growth (LAZ). Moreover, IGF-1 is one of the most copious growth factors in human bone and both animal and human studies showed that IGF-1 is associated with bone growth. Thus, the early protein hypothesis of IGF-1 inducing excessive weight gain relative to length gain is not supported by the literature and needs further justification. Emerging animal research suggests that the gut microbiome could play an important role in regulating growth trajectories.

Effects of Complementary Foods on the Gut Microbiome

The role of the gut microbiome in human health and disease has been extensively examined, especially concerning body weight. A lower Bacteroidetes to Firmicutes ratio has been demonstrated as an “obesogenic” gut microbial profile and colonization of germ-free mice with “obesogenic” gut microbiota resulted in a significantly greater body fat increase than colonization with a “lean” microbiota. In preschool children, the dominating bacterial community tended to be less diverse in the obese/overweight children compared with those with normal BMI. Overall, the gut microbiota appears to have a significant impact on body weight regulation, as demonstrated in both human and animal studies.

Infancy is a life stage when the gut microbiota has low stability and high responsiveness to influencing factors, such as diet. Diet has significant implications for gut microbiota colonization (Laursen et al., 2016). Besides maternal impact, the infant’s gut is quickly colonized depending on feeding mode: breastmilk, infant formula, or both beginning at birth (Figure 3). Among breastfed infants, bifidobacteria can account for over 60% of the total fecal microbiota, while formula-fed infants tend to have more Bacteroides and Clostridium (Collado et al., 2012). Early complementary feeding is also a critical period of shaping the gut microbiome. After the “single food” phase of breastmilk or formula, complementary feeding is an important transition point that drives the pattern of maturation towards “adult” gut microbiome (Charbonneau et al., 2016). However, despite comprehensive research on breastfeeding and the gut microbiome, very few studies have addressed the impact of complementary foods on the infant gut microbiota development. Magne et al. (Magne et al., 2006) followed 11 infants longitudinally. Ruminococcus sp. was detected in one infant out of 11 during exclusive breastfeeding, and this number increased to 6 during weaning and postweaning period, suggesting the introduction of solid foods can change the gut microbiota. Another more recent cohort study (Laursen et al., 2016) compared infants of both normal weight and obese mothers and found that protein and fiber intakes during early complementary feeding (9 mo of age) were associated with gut microbiota richness (alpha diversity). This study also found that protein intake was positively associated with increased abundance of Roseburia and Ruminococcus, independent of maternal BMI, delivery mode, or gestational age (Laursen et al., 2016). Both Ruminococcus and Roseburia are considered key producers of extracellular glycosidases that degrade polysaccharides and produce short-chain fatty acids (Magne et al., 2006). There are many health benefits of short-chain fatty acids that are well documented (Byrne et al., 2015). Besides the beneficial impact on colon health, short-chain fatty acids are reported to activate G-protein coupled receptors (GRP41 and 43), which regulate fat accumulation and energy expenditure of the host (Kimura et al., 2014). Emerging research also showed that short-chain fatty acids directly regulate bone metabolism in mice and prevents inflammation-induced bone loss (Lucas et al., 2018). Overall, complementary feeding presents new energy and nutrient sources for gut microbes during late infancy and could result in selective advantages for specific microbes to establish in the gut (Laursen et al., 2016).

Effects of different types of protein-rich foods on the gut microbiome are still being explored. One animal study (Zhu et al., 2015) compared proteins extracted from meat, dairy, and plant on the gut microbiota and found significant differences in gut microbial profiles between the three protein sources. At the family level, Lactobacillaceae and Ruminococcaceae were the characteristic bacteria in rats fed with red meat proteins. Another earlier study by our group (Krebs et al., 2013) in 6- to 9-mo-old infants showed that compared with a low-protein, cereal-based complementary diet (9% energy from protein), a high-protein, meat-based diet (17% energy from protein), infant formula, or both beginning at birth. Emerging research suggests that gut microbiota may affect infant growth.

Figure 3. The infant’s gut is quickly colonized depending on feeding mode: breastmilk, infant formula, or both beginning at birth.
protein) increased the abundance of butyrate-producing strain *Lachnospiraceae*. These studies, although limited, suggest that besides dietary fiber, protein from animal origins, such as meat, may also promote the growth of short-chain fatty acids producing bacteria.

Plausible speculation of the differential impact of protein sources on the gut microbiome could be due to differences in substrate exposure. Ten percent or more of the ingested protein can reach the colon, and this amount is at least partially dependent on protein quality. According to the WHO, the digestible indispensable amino acid score (DIAAS) is the best method for evaluating protein quality (higher DIAAS suggests greater digestibility). The DIAAS is 143 for dairy (e.g., whole milk powder) 111 for beef, and even lower for plants (e.g., 47 for barley and 10 for cereal). Different DIAAS between dairy, beef, and plants suggest that at the same protein quantity, different types of protein may result in different amounts of substrates available for the gut microbiota. Amino acid compositions for various protein sources also differ. For example, meat, dairy, and plant proteins have varying amounts of branched-chain amino acids, with dairy being the highest. Branched-chain amino acid supplementation in mice increased the abundance of *Bifidobacterium* (Yang *et al.*, 2016). Moreover, undigested proteins and amino acids in the colon may serve as an additional substrate for short-chain fatty acid production next to nondigestible carbohydrates (Rasmussen *et al.*, 1988). One study (Zhu *et al.*, 2016) compared meat, dairy, and plant-protein extracts on short-chain fatty acid production and showed plant-protein led to the highest short-chain fatty acid production in mice. These differences in protein quality and amino acid compositions may at least partially contribute to the differential impact of protein source on the gut microbiome. When studying protein-rich foods, other compounds in these whole foods may also contribute to the outcome measures (e.g., the gut microbiome). Future studies that employ –omic-based analysis on protein-rich foods could further decipher food components that drive the health benefits, at the molecular level.

**The Gut Microbiome and Infant Growth**

Besides having a significant impact on body weight and obesity in adults, emerging research suggests that the gut microbiota may also affect infant growth. A cohort study (Forbes *et al.*, 2018) showed that exposures of breastmilk or formula differentially stimulated the gut microbiota changes, which are associated with the risk of overweight in Canadian infants. A landmark study (Blanton *et al.*, 2016) identified bacterial species whose proportional representation defines a healthy and mature gut microbiota during the first year of life in Malawian infants. Specifically, deviation from the normal gut microbial composition resulted in “immature” gut microbiota and growth impairment (Blanton *et al.*, 2016). Moreover, transplanting the gut microbiota from stunted infants to germ-free mice also transmitted impaired growth phenotypes, and adding back two growth-discriminatory species (*Ruminococcus gnavus, Clostridium symbiosum*) could ameliorate the growth impairment in mice (Blanton *et al.*, 2016). Another animal study (Schwarzer *et al.*, 2016) found that the gut microbiota interacts with the somatotropic hormone axis to drive growth during the juvenile period, and *Lactobacillus plantarum* promoted juvenile growth in a strain-dependent manner. Interestingly, one animal study (Zhu *et al.*, 2016) showed that intake of meat protein extracts substantially increased *Lactobacillus* abundance in rats, which may partially contribute to some previous findings of meat promoting linear growth in infants. Overall, these studies suggest that the gut microbiota may have a direct impact on infant growth and could be a potential mediator linking the complementary feeding to infant growth trajectories.

**Future Directions**

Early complementary feeding is a critical growth period that affects the etiology of obesity development. However, evidence-based dietary recommendations during early complementary feeding are lacking and more high-quality research is needed (Figure 4). Specifically, randomized controlled studies of dietary interventions with primary outcomes on infant growth and the risk of overweight are needed. Given the critical role of protein intake in infant growth and research priorities by the B-24 committee, dietary interventions on protein intake, both quantity and source, should be made a high priority. Infant outcomes also need to consider including not only growth Z score, but also body composition and neurodevelopment assessments. More importantly, mechanistic investigations of the impact of protein intake on infant growth are also lacking. Although emerging animal research showed a potential mediating effect of the gut microbiome in diet and growth, more human clinical studies that include longitudinal gut microbiome assessment are necessary.

![Figure 4. Early complementary feeding is a critical growth period that affects the etiology of obesity development. However, evidence-based dietary recommendations during early complementary feeding are lacking and more high-quality research is needed.](image)
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Feature Article

Protein and muscle health during aging: benefits and concerns related to animal-based protein

Kyle J. Hackney, Kara Trautman, Nathaniel Johnson, Ryan McGrath, and Sherri Stastny
Department of Health, Nutrition, and Exercise Sciences, North Dakota State University, Fargo, ND 58108

Implications

- Individuals aged at least 65 years are a fast-growing segment of the population.
- Age-related loss of muscle mass and strength will continue to have a significant economic impact unless dietary or exercise interventions are implemented.
- Increasing the ratio of animal-based protein relative to plant-based protein in the diet may help to mitigate age-related losses of muscle mass and strength.
- Animal-based protein sources, especially those that are lean or nutrient dense, are the most anabolic per gram.
- Additional health and environmental considerations are needed prior to increasing animal-based protein intake recommendations in the United States and globally.

Keywords: aging, animal-based protein, muscle size, plant-based protein, sarcopenia

Introduction

It is estimated that by 2060, nearly one in four individuals in the United States (94 million) will be over the age of 65 (Vespa et al., 2018). A well-known consequence of aging is the loss of skeletal muscle mass and strength, which are often referred to as sarcopenia and dynapenia, respectively (Clark and Manini, 2008). Collectively, sarcopenia and dynapenia can alter energy metabolism and lead to the loss of physical function, ultimately manifesting as functional disability. Skeletal muscle wasting specifically, occurs at a rate of 1% to 2% per year beginning at age 50 yr and may significantly affect up to 45% of older adults (Baumgartner et al., 1998). For example, Figure 1 shows a magnetic resonance imaging axial scan of the left upper leg muscles in (Figure 1A) a younger, active male and (Figure 1B) an older, inactive male. When analyzed via color thresholding for various tissue types and concentrations, notice the dramatic decrease in muscular area (dark gray color) in the inactive, older adult, which is accompanied by an increase in lipid infiltration and fibrous tissue (white color) within the muscle area relative to the active, younger adult. Although this is not the same individual, it is recognized that nearly all humans will have a similar profile over time unless an intervention (physical activity, exercise, dietary, pharmacological) occurs to slow the progression of skeletal muscle loss and adipose tissue infiltration. As a result, sarcopenia may lead to a greater economic burden related to treatments associated with loss of muscle mass and physical function (Janssen et al., 2004).

Skeletal muscle mass is governed by the daily balance between the rates of muscle protein synthesis and muscle protein degradation. Shifting the balance toward protein synthesis results in the addition of muscle protein, whereas shifting the balance toward protein degradation results in the loss of muscle protein (Phillips et al., 2009). Vigorous physical activity and exercise act as stimuli for muscle protein synthesis, which can last for several days following each bout (MacDougall et al., 1995), especially if the intensity is high enough to trigger anabolic hormone production (e.g., growth hormone, insulin-like growth factor 1) and cell-signaling cascades within muscle tissue. Food intake, in particular, dietary protein, is also a potent stimulator for muscle protein synthesis; however, it is more short-lived lasting only 4 to 5 h following ingestion (Fujita et al., 2007). The essential amino acids, especially leucine, appear to be the primary triggers for the initiation of muscle protein synthesis by way of mammalian target of rapamycin complex (mTORC1) phosphorylation and downstream markers that increase translation efficiency (Drummond et al., 2009).

Given this mechanistic evidence, elevated protein intake has been extensively studied to help preserve age-related muscle mass loss. For example, the recommended daily allowance for protein, or the daily amount sufficient to meet nutrition requirements for 97% to 98% of the population is 0.8 g per kg body mass (Institute of Medicine, 2005). To increase muscle health during the aging process, others have recommended 1.0 to 1.6 g per kg body mass, which is nearly a doubling for the current recommended daily allowance (Deutz et al., 2014). Older adults, especially women, often do not meet the recommended daily allowance for total protein. There are many reasons why protein intake could go down during aging. These include but are not limited to low appetite, dentition and other medical conditions, functional limitations.
that limit shopping, lack of knowledge on food preparation, and food insecurity (Deutz et al., 2014). Data from our Muscle, Metabolism, and Ergogenic workgroup suggest a significant and positive association with total protein intake from the diet and muscle cross-sectional area of the quadriceps muscles in younger and middle-aged adults (Figure 2). Therefore, providing specific recommendations that highlight protein type and quality is an important first step for providing aging adults with a protein intake level that emphasizes optimal consumption, instead of minimal intake, for muscle health.

Total protein intake from the diet or supplementation is categorized into two basic types: 1) plant-based protein sources (e.g., soy, rice, pea, oat, wheat, rice, legumes, beans, nuts) and 2) animal-based protein sources (e.g., meat, whey, poultry, fish, eggs, and milk). Adults aged 51 to 70 yr in the United States consume about 65% of protein from animal sources and approximately 35% from plant-based sources (Berner et al., 2013). Most (20%) of this animal-based protein was from red meat (14% beef and remainder pork, lamb, game, or beef/pork combined with other meats), 18% from dairy (including milk and cheese with less than 2% yogurt), 14% from poultry (95% chicken), and the remainder distributed among seafood, fish, and eggs. Accordingly, beef, pork, and chicken represent the majority of animal-based protein consumed in the United States. The more recent NHANES data (2015 to 2016) reveal increased consumption of poultry (47 g/wk), decreased consumption of

**Figure 1.** Representative MRI images of the upper leg showing muscle area (dark gray), inter/intramuscular adipose/fibrous tissue (white area within and between muscles), and subcutaneous adipose tissue (white area around all the muscle groups) in (A) younger, active and (B) older, inactive male. Muscle area is increased in the younger, active male by 55% compared with the older, active male (82.21 cm² vs. 52.87 cm²), whereas lipid/fibrous area is increased 7× in the older, inactive male compared with the younger, active male (11.50 cm² vs. 1.64 cm²).

**Figure 2.** Association between total protein intake and muscle cross-sectional area of the quadriceps muscle group in healthy younger and middle-aged adults.
unprocessed red meat (from 340 g/wk 1999 to 2000 to 284 g/wk 2015 to 2016), and no change in consumption patterns for processed red meats (182 g/wk; Zeng et al., 2019). van Vliet et al. (2015) recently provided an excellent critical review in relation to animal- and plant-based protein in relation to anabolic potential in skeletal muscle. In brief, Protein Digestibility Amino Acid Scores for milk, whey, egg, soy protein isolate, and casein are 1.00; soy and beef ranged from 0.91 to 0.92; and whole wheat, oat, and pea ranged from 0.45 to 0.67 (van Vliet et al., 2015). Thus, some animal and plant proteins were reported to have similar anabolic potential. However, there are limitations with the Protein Digestibility Amino Acid Scores (index may be replaced by Digestible Indispensable Amino Acid Score; Wolfe et al., 2016) given anabolic potential in skeletal muscle may vary based on essential amino acid content, digestibility, and absorption (Phillips, 2012). For instance, when stimulation of post-prandial muscle protein synthesis has been evaluated by stable isotope tracers methodology in combination with resistance exercise, whey (Yang et al., 2012), milk (Wilkinson et al., 2007), and beef (Phillips, 2012) appear to be superior to soy proteins, which suggests beneficial prediction of muscle mass with animal-based protein sources. Thus, animal-based proteins appear more anabolic than a similar dose of plant proteins.

There is additional cross-sectional evidence that indicates protein intake from animal sources are associated with increased muscle mass with aging. Lord et al. (2007) found animal-based protein intake was an independent predictor of an index of muscle mass (fat-free mass/height squared) in women >60 yr of age (Lord et al., 2007). Higher beef intake was also significantly associated with greater appendicular muscle mass index in nonobese males ≥50 yr of age (Morris and Jacques, 2013). Furthermore, leg lean mass was higher for participants in the highest quartiles of total protein and animal-based protein compared with those in the lowest quartiles (Sahni et al., 2015). Animal-based proteins generally are greater sources of lysine, leucine, and methionine relative to plant-based sources; thus, even larger amounts of plant-based protein are needed to have a similar influence on muscle size compared with animal-based proteins (Figure 3).

**Key Nutrients Associated with Animal-Based Protein**

Lean beef is particularly interesting for older adults. There are 29 cuts of beef that meet the labeling requirements for “lean” or “extra lean” (5 g or less fat and 2 g or less of saturated fat). A lean 3 ounce serving of beef, 6 cups of cooked brown rice, and 1 scoop of whey-protein all contribute about 2.15 g of leucine, whereas a 1/2 cup of almonds or soybeans has about 0.4 g of leucine. A 3-ounce portion of lean meat also provides about 10% of recommended daily calories, 37% of vitamin B12, 33% of zinc, 25% of niacin, plus over 10% of recommended iron, riboflavin, and other nutrients. Beef is, therefore, an example of a nutrient-rich food, important for those limiting or limited in their daily consumption of total calories. Iron, although not a nutrient of value for older adults, is instead very important as a nutrient of interest (shortfall nutrient) for premenopausal females, children, and during pregnancy. Meat foods provide heme iron, which is more bioavailable than nonheme plant-based iron. There is a high prevalence of vitamin B12 deficiency among older adults. A deficiency may be associated with confusion and other conditions that hurt quality of life (Stover, 2010).

**Animal-Based Protein Sources and General Health**

Although there is general support for increasing animal-based protein intake from the diet for preserving muscle mass during aging, animal-based protein consumption has recently become a highly debated topic in scientific literature and popular media. Animal-based proteins may be associated with chronic diseases such as heart disease, colorectal cancer, breast cancers, prostate cancers, and bone demineralization (Cho et al., 2006; Kaluzka et al., 2015; Isanejad et al., 2017; Diallo et al., 2018). However, additional studies published conflicting results, which further muddle our understanding on how animal-based proteins are related to human health needs (Hannan et al., 2000; Lin et al., 2004; Sanjoaquin et al., 2004; Alexander et al., 2009). It is likely that a person can live a reasonably healthy, low-risk life while consuming meat. To do so, one must consider that the mechanisms of the diseases and conditions listed above are multifaceted and that nutrition is only a single facet. For example, the high-fat content in animal-based proteins has been linked to cancers and cardiovascular disease incidence, but some of the fats found in lean meats and low-fat dairy (e.g., monounsaturated fatty acids) have shown to be beneficial (Lin et al., 2004; Diallo et al., 2018). Further investigation has suggested that carbohydrate intake may be a larger contributor in these conditions even more than saturated fats (Barclay et al., 2008).

Fat content is not the only concern that researchers have with meat. The difference between processed meat and unprocessed meat in regard to disease risk has been highly debated as increased nitrates, phosphate-containing preservatives, hydrocarbons, and sulfates are potential carcinogens (Lin et al., 2004; Cho et al., 2006; Diallo et al., 2018). In one study, women who...
consumed more than three servings per week of red meat as processed meats were 2.3 times more likely to develop hormone-positive breast cancers than women consuming less than one serving per month (Cho et al., 2006). Another study showed that consuming >50 g of processed meat per day was associated with a 23% increase in the risk of developing heart failure (Kaluza et al., 2015). However, it does not seem that processed meats are the only concerns as unprocessed meat has also been associated with a 23% higher risk of stroke (Bernstein et al., 2012). In addition, it does not seem that red meats are the only animal-based product that have been related to chronic illness. Egg intake of more than two eggs per week has been associated with breast and prostate cancers through hormonal mechanisms related to insulin-like growth factor 1, dioxine, and/or choline (Wu et al., 2016; Marcondes et al., 2019). Although these risks are concerning upon first glance, comparisons between vegetarians and their counterparts have reported no significant differences in the associations of colorectal cancer, fat free mass, fat mass, muscle size, muscle strength, phospho-creatine, creatine, or resting energy expenditure (Haub et al., 2002; Sanjoaquin et al., 2004). Protein has also been beneficial in bone maintenance regardless of hypotheses regarding potential renal acid load due to high sulfates leading to decreased urinary calcium through bone calcium buffering (Hannan et al., 2000; Isanejad et al., 2017). Although others have shown total protein intake is within the recommended daily allowance of 0.8 g/kg/day has been associated with lower femoral neck, lumbar spine, and total bone mineral density and bone mineral content (Isanejad et al., 2017). Overall, though there are risks associated with eating larger amounts of animal-based protein, they are less risky than using tobacco, drinking alcohol, and consuming large amounts of white bread (Sanjoaquin et al., 2004). Thus, the decision to incorporate animal-based products is a personal choice but can be done so safely by consuming a diet rich in fruits and vegetables and swapping out fried and/or processed foods for healthy, low-fat, calcium-containing alternatives (e.g., cottage cheese or yogurt for bacon at breakfast; Heaney and Layman, 2008; Astrup et al., 2011). In addition, increasing physical activity is associated with the reduction in cardiovascular disease (Lear et al., 2017) and various cancers (Moore et al., 2016) and therefore should be incorporated within a diet composed of higher animal-based proteins.

Animal-Based Protein and the Environment

Another concern related to elevating the promotion and intake of animal-based proteins is the effect that their production has on the environment and whether elevated production is sustainable. Animal-based proteins require a greater amount of energy, water, and land than plant-based proteins (Pimentel and Pimentel, 2003). For example, it has been estimated that on average 6 kg of plant protein is needed to produce 1 kg of animal protein (Pimentel and Pimentel, 2003). Similarly, others have projected that 1 kg of beef protein requires five times more water to produce compared with 1 kg of cereal protein (Mekonnen and Hoekstra, 2012). The increased demands of producing...
animal proteins can lead to nutrient depletion of soil (Menzi et al., 2010) and environmental pollution (Steinfeld et al., 2006). Additionally, the production of animal proteins is related to the emission of greenhouse gasses (Lesschen et al., 2011), and this problem is exasperated by increased deforestation for food production (Steinfeld et al., 2006). It is estimated that a shift from a Western diet, characterized by high intake of animal proteins, is a more sustainable dietary practice for reducing greenhouse gas emissions and land use by 70%, and water use by 50% (Alesandrowicz et al., 2016). For more detailed discussion, Grossi et al. (2019) recently published a review that addresses the effects that livestock production has on the environment.

**Conclusions**

The loss of muscle mass and strength within the rapidly growing aging population is an emerging public health epidemic. Increase in dietary protein intake above the recommended daily allowance is recommended for skeletal muscle preservation, but the ratio of animal-based proteins to plant-based proteins selected by the consumer is an individual choice filled with various ethical, economical, and environmental decisions. Regardless of protein selection, physical activity participation is also recommended in combination with increased fruit and vegetable intake as part of a balanced diet to not only enhance muscle health, but also increase longevity.

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Can the digestible indispensable amino acid score methodology decrease protein malnutrition

Hannah M. Bailey and Hans H. Stein
Division of Nutritional Sciences, University of Illinois, Urbana, IL 61801

Introduction

The characterization of proteins based on their nutritional value and optimization in human diets has been a lasting discussion over the years. Research focusing on protein malnutrition was largely conducted after the identification of kwashiorkor and the realization that many children globally are suffering from subclinical protein malnutrition. To address protein malnutrition, the composition and digestibility of proteins must be determined. Proteins consist of individual amino acids and the sequence and digestibility of each AA varies among proteins. The Food and Agriculture Organization of the United Nations (FAO) has developed methods to evaluate the protein quality of food items and, in 2011, the Digestible Indispensable Amino Acid Score (DIAAS) was recommended as the successor to their previous method: Protein Digestibility Corrected Amino Acid Score (PDCAAS). In the new DIAAS system, each indispensable amino acid is recognized as an individual nutrient and use of the DIAAS system offers a number of advantages in preparation of meals that are adequate in amino acids.

Implications

- The new system for estimating protein quality of human foods, which is called “Digestible Indispensable Amino Acid Score” or DIAAS, allows for calculation of the amino acid quality of food proteins that are based on ileal digestibility rather than total tract digestibility and values for each amino acid may be calculated.
- By recognizing the pig as an appropriate model for determining DIAAS values in human food proteins, a procedure for the standardized measurement of DIAAS values in a large number of food proteins has been established.
- Because digestibility values for amino acids in individual food proteins are additive in mixed meals, DIAAS values for mixed meals may be calculated. By comparing DIAAS values of mixed meals to the requirements for digestible indispensable amino acid, the amino adequacy of the meal may be calculated.
- Animal proteins such as meat and milk have greater DIAAS values than plant proteins, but by complementing plant proteins with low DIAAS values with animal proteins with greater DIAAS values, balanced meals that are adequate in all amino acids can be provided.

Indispensable Amino Acid Malnutrition

An estimated 815 million people globally are affected by undernutrition with one in four children under the age of 5 suffering from chronic undernutrition (FAO et al., 2017). The cost of undernutrition is approximately 2.1 trillion USD per year (FAO, 2014). Undernutrition is a global issue; however, sub-Saharan Africa and Southern Asia are among the countries with the greatest prevalence of child chronic malnutrition (FAO et al., 2017). These regions heavily rely on diets composed of cereal grains, such as sorghum, wheat, rice, or maize, which are limiting in indispensable amino acids such as lysine (Cervantes-Pahm et al., 2014; Shaheen et al., 2016; FAO et al., 2017; Abelilla et al., 2018). Cereal grains also undergo a variety of processing methods prior to consumption, which may decrease protein and amino acid digestibility (Duodu et al., 2002; FAO, 2013).

In 1933, a severe disease related to protein deficiency was identified by Cicely Williams: kwashiorkor (Williams, 1933). Kwashiorkor is nearly exclusive to children 1 to 2 yr of age and is characterized by general edema, swollen abdomens, and flaky skin (Williams, 1933). In addition, it was noted that kwashiorkor was mainly associated with children being weaned on maize-based diets (Williams, 1933), which are limiting in lysine.
Kwashiorkor is a very severe form of protein deficiency; however, there are many children suffering from subclinical protein malnutrition (Semba, 2016). Around 1970, the study of undernourished children shifted from focusing on protein and amino acids to energy and micronutrients under the assumption that the majority of children are consuming adequate amounts of protein (Semba et al., 2016). However, protein and amino acid deficiencies continued to be addressed by researchers and in 2016, a relationship was identified between chronic undernutrition of children (or stunted children) and low serum levels of all nine indispensable amino acids (Semba et al., 2016). In addition, Ghosh et al. (2012) calculated the risk of protein inadequacy in different countries using estimates of total protein and utilizable (digestible) protein. The risk of protein inadequacy ranged from 0.7% in North America to 37.2% in East and South Africa (Ghosh et al., 2012). These data contributed to reemphasize the need for providing meals that are adequate in all indispensable amino acids. However, to provide meals that are adequate in all indispensable amino acids, the quality of the protein in each food item needs to be determined and mixed meals need to be adjusted for protein quality by complementing low-quality proteins with higher quality proteins. The quality of protein in a food item is primarily determined by the concentration of the first limiting indispensable amino acid and the prececal—or ileal—digestibility of all indispensable amino acids.

**Diaas Principles**

The DIAAS methodology was developed to overcome multiple limitations of the previous method, PDCAAS, used to evaluate protein quality (Figure 1). A number of reviews outlining the limitations of the PDCAAS method have been published (WHO, 2007; Boye et al., 2012; Gilani, 2012; Schaafsma, 2012; FAO, 2013); however, PDCAAS will continue to be used until a sufficient database of ileal digestibility and DIAAS values are generated for commonly consumed human foods. There is therefore a need to generate DIAAS values for food proteins commonly consumed in different areas of the world.

**Pig vs. rat animal model**

The human is considered the best subject to determine ileal amino acids digestibility values for humans; however, the FAO has recognized that when values cannot be determined in the human, the growing pig is the more appropriate animal model compared with the growing rat (FAO, 2013). The pig is superior to the rat because it is a meal-eating species, similar to humans (Gilani, 2012). In addition, the gastrointestinal anatomy of the pig is similar to that of humans, and the physiology and metabolism response to nutrients ingested by pigs are comparable to humans (Gilani, 2012). In addition, the rat has a unique requirement for sulfur containing amino acids because of the high concentration of cysteine in the fur, but this is not the case for the pig (Deglaire and Moughan, 2012). It is, therefore, recommended that DIAAS values of food proteins are determined from ileal digestibility values of amino acids that are obtained in the growing pig if values cannot be determined in humans (FAO, 2013).

**Amino acid vs. protein digestibility**

The DIAAS methodology determines the digestibility of each individual amino acid. This is arguably the most significant change in the transition from PDCAAS to DIAAS because the potential differences of individual amino acid digestibility are now considered. This is especially important for food items that have been processed or heated, as well as for food items that have a high concentration of antinutritional factors. Processing, heating, and antinutritional factors can decrease the bioavailability or digestibility of different amino acids (Moughan, 2003; Gilani et al., 2012). As an example, the epsilon amino group of lysine is very susceptible to reacting with a reducing sugar at high temperatures and the associated Maillard reactions will reduce the concentration as well as the digestibility of lysine (Moughan, 2003). This is extremely relevant when determining the protein quality of diets based on a mixture of food proteins. For example, a mixed diet based on cereal grains may appear to meet the crude protein requirement for an age group; however, certain amino acids may not be present in adequate amounts and diets based primarily on cereal

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**Figure 1.** Differences between the protein digestibility corrected amino acid score (PDCAAS) system and the digestible indispensable amino acid score (DIAAS) system.
grains do usually not meet the requirement for digestible lysine. Therefore, it is important to treat each individual amino acid as a single nutrient when evaluating the digestibility and quality of a protein.

**Ileal vs. total tract digestibility**

Amino acid absorption takes place entirely in the small intestine of pigs, humans, and all other animals (Moughan, 2003; Stein et al., 2007). However, the PDCAAS methodology determined protein digestibility from fecal samples (FAO, 1991). Proteins synthesized by microbes and other nondietary proteins also end up in fecal contents, which will result in an overestimation of PDCAAS for low-quality proteins (Mathai et al., 2017). Therefore, the DIAAS methodology recommends amino acid digestibility be measured at the end of the small intestine (FAO, 2013). The most common method to measure this in pigs is by surgically inserting a T-cannula into the end of the small intestine (Stein et al., 1998). This method is effective and is being used across the globe to determine the ileal digestibility of amino acids associated with many foods and food ingredients. By collecting digesta at the end of the small intestine, it is also possible to directly calculate the small intestinal digestibility of each individual amino acid and, therefore, apply unique digestibility values to each amino acid. In contrast, fecal collections, as used in the PDCAAS methodology, only allow calculation of the digestibility of crude protein. This value is then applied to all amino acids assuming that the digestibility of all amino acids is the same, which has been demonstrated not to be a correct assumption (Mathai et al., 2017).

**Values greater than 100 vs. truncation**

The PDCAAS methodology requires values greater than 100% to be truncated to 100% (FAO, 2013), due to the assumption that consuming amino acids at a concentration greater than the human amino acids requirement does not provide addition nutritional benefit (Schaafsma, 2012). However, this approach fails to recognize the ability of high-quality proteins to complement low-quality proteins in mixed meals. Humans almost always consume a combination of ingredients during each meal and under such conditions, high-quality proteins are used to balance low-quality proteins to provide a complete meal that is nutritionally adequate in all amino acids.

Therefore, the DIAAS methodology does not truncate values at 100% and an example of the benefit of this is a mixed meal of milk and wheat (Figure 2). Wheat has a DIAAS value of 45 (Mathai et al., 2017); however, when wheat is processed in the form of a breakfast cereal, it may only have a DIAAS value of 1 (Rutherfurd et al., 2015). In contrast, milk has a DIAAS value of 118 (Rutherfurd et al., 2015). The calculated DIAAS value of a mixed meal of 60% milk and 40% breakfast cereal is 107 (Rutherfurd et al., 2015), demonstrating the ability of milk to complement wheat resulting in a balanced meal that meet the requirement for all indispensable AA. Likewise, it was recently demonstrated that milk and eggs are efficient in complementing low-quality plant proteins to improve the DIAAS value (Shivakumar et al., 2019). Although legumes generally have a greater DIAAS value than cereal grains, they are limiting in methionine and may contain antinutritional factors that often reduce the absorption of amino acids or micronutrients (Rutherfurd et al., 2015, Shivakumar et al., 2019). Consequently, animal proteins are more effective in increasing the protein quality of mixed meals and meeting human amino acid requirements than proteins from legumes.

**Protein Claims**

Based on the FAO recommendation, DIAAS values can be calculated for three age groups; 1) infants from birth to 6 mo, 2) children from 6 mo to 3 yr, and 3) children older than 3 yr, adolescents, and adults (FAO, 2013). Upon determination of DIAAS for a specific food item and age group, a protein claim can be made and added to its food label (FAO, 2013). This claim is based on the determined DIAAS value and, therefore, takes into account the bioavailability of amino acids and amino acid concentrations relative to human amino acids requirements. If a food item has a DIAAS value greater than 100, it can be considered an “excellent” quality protein source for the specific age group. A food item can be considered a “good” quality protein source if the DIAAS value is between 75 and 99. However, a food item with a DIAAS value less than 75 cannot have a claim made for protein (FAO, 2013). Generally, animal proteins (i.e., dairy, eggs, and meat) are considered “excellent” quality proteins with DIAAS values greater than 100 (Table 1; Rutherfurd et al., 2015; Mathai et al., 2017; Hodgkinson et al., 2018). In contrast, plant proteins and cereal grains generally have DIAAS values that are less than 75, with the exception of soy protein that usually has a DIAAS value between 75 and 100 and oats with a DIAAS value around 75 (Cervantes-Pahn et al., 2014; Rutherfurd et al., 2015; Mathai et al., 2017; Abelilla et al., 2018; Han et al., 2019).

A DIAAS value greater than 100 indicates that if the food item is consumed in an amount equivalent to the estimated average requirement for protein (i.e., 0.66 g kg⁻¹ d⁻¹; IOM, 2002/2005), 100% or more of the human amino acid requirements will be met for the day. However, the protein content listed on the food label is not indicative of the quality of amino acids in the food (Figure 3). For example, peas may have a high quantity of protein, but with a DIAAS value of approximately 64 it has a low quality, whereas milk has both a high quantity of protein and high quality of amino acids with a DIAAS of 122. As a consequence, an individual would have to consume more than twice as much pea protein compared with milk protein to meet the human amino acid requirements. This illustrates that both the quantity and the quality of protein are important when using DIAAS to formulate meals adequate in all amino acids.

**Protein Complementation**

The DIAAS methodology enables the determination of complementary proteins (FAO, 2013). Values for DIAAS in
individual ingredients are calculated by first determining the standardized ileal digestibility of each amino acid in a food protein. This value is then multiplied by the concentration of that amino acid in the protein to calculate mg digestible amino acid per g protein. A digestible indispensable amino acid reference value is then calculated for each amino acid by dividing the concentration of digestible amino acid by the reference value for a specific age group. The DIAAS value is subsequently determined as the least value among the digestible indispensable amino acid values for the digestible indispensable amino acids (Figure 4).

In addition, the protein quality of mixed meals can be determined due to the additivity of DIAAS values calculated for ingredients (FAO, 2013). These two aspects of the DIAAS methodology are useful in evaluating and recommending diets consumed in developing countries that may not be adequate in amino acids. For example, polished rice (DIAAS of approximately 60) is limiting in lysine, but has a high concentration of digestible sulfur amino acids. As a consequence, rice may complement peas (DIAAS of approximately 58) that are limiting in digestible sulfur amino acids and high in lysine (Rutherfurd et al., 2015). The combination of these two ingredients may provide a balanced amino acid pattern in a mixed meal. Another example is how meat, a good-quality protein with a DIAAS of approximately 99 (Hodgkinson et al., 2018), can complement wheat, a cereal grain limiting in lysine with a DIAAS of approximately 54 (Mathai et al., 2017), to provide all amino acids that are greater than or equal to human AA requirements. Table 1 summarizes DIAAS values for common ingredients that have been published and determined in the growing rat or the growing pig. Han et al. (2019) determined DIAAS values in cereal grains commonly produced in China. However, DIAAS values need to be determined in ingredients commonly consumed in developing countries to accurately determine the protein quality of diets consumed. This will make it possible to make recommendations on how meals that are balanced in amino acids can be prepared, which will contribute to reducing the prevalence of protein malnutrition.

**Summary**

Protein undernutrition is a serious global problem that results in stunted growth, disease, and premature death in millions of people annually. Protein deficiency is caused by a deficiency in specific indispensable amino acids and efforts to alleviate protein malnutrition, therefore, need to focus on the provision of adequate quantities of digestible indispensable amino acids. The digestibility of amino acids is most correctly determined at the end of the small intestine, and digestibility values obtained using this approach are termed “ileal digestibility values.” The total protein provision to an individual is based on the sum of digestible indispensable amino acids consumed in a meal. The protein quality of a single ingredient is less important than the quality of the mixed meal that is consumed. To assist in calculating the protein quality of meals for humans, the FAO recommends that a system called the “Digestible Indispensable Amino Acid Score” or DIAAS be used. This system is based on the ileal digestibility of each amino acid in individual protein foods, but allows for the calculation of the quality of a meal consisting of a number of protein foods. The system can then be used to assess the quality of total protein intake consumed as a meal. Comparison of this value to the requirements for indispensable amino acids by humans can be used to estimate an individual’s protein status.

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Table 1. Digestible indispensable amino acid scores (DIAAS) and first-limiting amino acid (AA) in parentheses determined for human foods using the pig or rat model

| Reference protein pattern | Animal model | Infants (0 to 6 mo) | Young children (6 months to 3 yr) | Older children, adolescents, and adults | Reference |
|---------------------------|--------------|---------------------|-----------------------------------|----------------------------------------|-----------|
| Cereal grains             |              |                     |                                   |                                        |           |
| Corn, yellow dent, raw    | Pig          | –                   | 10 (lysine)                       | 48 (lysine)                            | Cervantes-Pahn et al., 2014 |
| Millet, cooked            | Rat          | –                   | 54 (lysine)                       | –                                      | Han et al., 2019 |
| Oats, rolled, cooked      | Rat          | –                   | 37 (lysine)                       | –                                      | Rutherfurd et al., 2015 |
| Rice, polished, cooked   | Rat          | –                   | 29 (lysine)                       | –                                      | Han et al., 2019 |
| Sorghum, raw              | Pig          | 37 (lysine)         | 45 (lysine)                       | 54 (lysine)                            | Mathai et al., 2017 |
| Wheat, raw                | Pig          | 59 (SAA)            | 84 (SAA)                          | 98 (SAA)                               | Mathai et al., 2017 |
| Wheat, whole, cooked      | Rat          | –                   | 20 (lysine)                       | –                                      | Han et al., 2019 |
| Plant proteins            |              |                     |                                   |                                        |           |
| Kidney beans, cooked      | Rat          | –                   | 59 (SAA)                          | –                                      | Rutherfurd et al., 2015 |
| Peas, cooked              | Rat          | –                   | 58 (SAA)                          | –                                      | Rutherfurd et al., 2015 |
| Soy protein isolate       | Pig          | 68 (SAA)            | 84 (SAA)                          | 98 (SAA)                               | Mathai et al., 2017 |
| Dairy proteins            |              |                     |                                   |                                        |           |
| Milk protein concentrate  | Pig          | 85 (tryptophan)     | 120 (SAA)                         | 141 (SAA)                              | Mathai et al., 2017 |
| Skimmed milk powder       | Pig          | 81 (threonine)      | 105 (SAA)                         | 123 (SAA)                              | Mathai et al., 2017 |
| Whey protein concentrate  | Pig          | 71 (AAA)            | 107 (histidine)                   | 133 (histidine)                       | Mathai et al., 2017 |
| Meat proteins             |              |                     |                                   |                                        |           |
| Beef, raw                 | Pig          | –                   | 97 (valine)                       | –                                      | Hodgkinson et al., 2018 |
| Beef, boiled, 71 °C       | Pig          | –                   | 99 (valine)                       | –                                      | Hodgkinson et al., 2018 |
| Beef, roasted, 71 °C      | Pig          | –                   | 91 (valine)                       | –                                      | Hodgkinson et al., 2018 |

First-limiting amino acid (AA) is in parentheses. Unreported DIAAS values for certain reference patterns are noted by “–.” SAA = sulfur AA; AAA = aromatic AA.

Figure 3. Example of the use of digestible indispensable amino acid score (DIAAS) values in making protein quality claims and how it differs from protein quantity claims. Adopted from FAO, 2013.

Figure 4. Steps in calculating digestible indispensable amino acid score (DIAAS) values. First, the standardized ileal digestibility (SID) of amino acid (AA) in the test food is determined in the human, pig, or rat. Then, this value (SID of AA in Test Food) is multiplied by the analyzed concentration (mg) of the same AA in a g of crude protein (CP) for the test food. Lastly, the calculated mg SID of each AA per gram of CP is divided by the same AA requirement level for a specific age group. This results in a calculated digestible indispensable AA (DIAAA) reference value for each AA and the AA in least concentration is the DIAAS value assigned to the test food.
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Feature Article

The role of livestock products for nutrition in the first 1,000 days of life

Silvia Alonso, Paula Dominguez-Salas, and Delia Grace

Animal and Human Health Program, International Livestock Research Institute, Addis Ababa, Ethiopia
Faculty of Epidemiology and Population Health, London School of Hygiene and Tropical Medicine, London, UK
Animal and Human Health Program, International Livestock Research Institute, Nairobi, Kenya

Corresponding author: S.Alonso@cgiar.org

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Introduction

Dietary patterns across the world are extremely diverse, with diets of most people in low- and middle-income countries being suboptimal from a nutritional standpoint. It is in these countries that the highest levels of undernutrition are recorded, with children being the most affected. Although stunting (i.e., children short for their age) rates are declining globally and regionally, significant disparities in such rates exist between and within countries. Moreover, the absolute number of stunted children in Africa continues to increase (Development Initiatives, 2018). Iron-deficient anemia has risen to 32.8% globally and nutrient intakes are typically deficient in poor settings. Poor people in poor countries often subsist on suboptimal diets based on cheap staples and have limited access to nutrient-dense foods such as pulses, fruit, or meat (Murphy and Allen, 2003; Thompson and Meerman, 2010; Muhii et al., 2012). As a result of these circumstances, individuals do not receive sufficient nutrient intakes to sustain optimal well-being. Some research has shown that it is not unusual to begin feeding children livestock-derived food (particularly milk) before 6 mo of age when they should be exclusively breastfeeding (Micere et al., 2016). With that said, recent surveys confirmed that almost 40% of children above 6 mo living in informal settlements in peri-urban Nairobi did not consume cow’s milk daily. Furthermore, meat and other livestock-derived products were each eaten by less than 5% of these children and only in very small amounts (Grace et al., 2018). This is not an uncommon reality in Africa.

Over the past decades, investments have been made to address the various forms of undernutrition present in many countries across the world. The shift from food security (access to enough food) to nutrition security (access to enough nutritious food) has prompted the development of interventions to increase nutrient intake. These interventions include food fortification as a means to improving the nutrient content of diets. Little attention has been given, however, to the specific role of livestock products such as meat, milk, and eggs (and their derived products) on nutrition and their potential to help achieve nutrition security goals. Media outlets in recent years, primarily in high-income countries, have increasingly been flooded with reports that are critical of the role of meat, in particular, and livestock-derived foods (e.g., milk and eggs), in general, as part of diets. Their environmental footprint, as well as their suggested negative effects on health, are ostensible arguments used to promote a shift to diets containing little to no animal-sourced foods. Environmental and sustainability concerns exist related to livestock production that require serious reflection relative to the evolution of farming systems and dietary patterns in industrialized countries (Willett et al., 2019). Underlying this may be more fundamental and immutable concerns over the use of animals (Perry and Grace, 2015). Nonetheless, in many low- and middle-income countries, the livestock sector is a key contributor to national economies (representing between 15% and 80% of agricultural domestic product) and represents a potential pathway out of poverty and an essential livelihood for millions of people (World Economic Forum, 2019). In countries where high volumes of livestock production accompany important undernutrition problems, it would represent a significant missed

Implications

• Meat, milk, and eggs are nutrient-rich products that could efficiently boost nutrient-poor diets either as part of the normal diet or if access is increased through interventions.
• The scientific evidence for the role of livestock products in improving nutrition is limited, especially during the first 1,000 d of life in low- and middle-income countries.
• Beyond producing food, the livestock sector has additional positive and negative impacts on human health, the environment, societies, and economies that must be understood and managed.

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opportunity to not harvest livestock-derived food products to optimize the nutrition of the most vulnerable. This article will summarize the current state of knowledge on the role of livestock products for nutrition, with emphasis on the first 1,000 d of life for individuals living in low-income countries. The nutritional importance of livestock products, the evidence base for their impact on health and nutrition, and the major externalities concerned with their production will be considered.

**Nutritional Importance of Livestock-Derived Foods**

Livestock-derived foods possess a specific nutrient composition that matches well the human body's needs, particularly during the critical first 1,000 d of life covering the period from conception through pregnancy up to 2 yr of age (Dror and Allen, 2011). Livestock-derived foods could have an important role in reducing stunting and some key micronutrient deficiencies. Indeed, eggs, milk, meat, and offal are all nutrient-dense food products that contain high-quality proteins and several highly bioavailable vitamins (e.g., vitamin B12, only available in foods of animal origin, preformed vitamin A, and vitamin D) and minerals (e.g., iron, zinc, and calcium). Animal-source foods provide these nutrients at sufficient levels and with a great degree of digestibility, what makes them particularly adequate for young children as well as pregnant and lactating women who are in stages of rapid growth and development and have high micronutrient requirements but small intake volumes (Grace et al., 2018). Animal protein is a high quality, easily digested protein that possesses a high biological value, which is conducive for greater net protein utilization compared with nonanimal proteins. Animal proteins have a more balanced essential amino-acid profile relative to human tissues (WHO, 2007). A study in Malawi found that stunted children had lower serum levels of several essential amino acids commonly deficient in nonanimal proteins (Semba et al., 2016) which are the most common type of proteins in the diets of the poor in low-income countries. In addition, different studies have found that intake of milk and meat can have positive effects on nutrition and functional outcomes such as cognitive development, as shown in the next section. For all these reasons, livestock-derived foods can be interesting targets for interventions to reduce the biological impact of malnutrition, including poor growth or micronutrient deficiencies (Figure 1).

On the other hand, livestock-derived foods are controversial from a nutritional point of view. In recent years, there have been warnings against consumption of livestock-derived products owed to their suggested negative health effects. Although there is a general agreement on the need to avoid overconsumption, some of the recommendations to dramatically reduce consumption, for example of eggs or milk, have been later nuanced, whereas others, for example those about consumption of red and processed meat, remain strong, although far from contested (WCRF/AICR, 2007; Red meat and processed meat / IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, 2018; Willett et al., 2019). Chronic, noncommunicable diseases, such as cardiovascular disease or cancer, have risen sharply around the globe over the past few decades. Different studies have reported associations between consumption of livestock-derived foods and prevalence of obesity, cardiovascular disease, and diabetes; however, the data remain inconclusive, inconsistent, and not sufficient to explore effects in different life stages or nutritional contexts.

There is a significant dearth of scientific information examining the impact and trade-off of livestock-derived food consumption during the first 1,000 d of life in poor populations. The World Health Organization promotes “healthy diets” that protect against under- and overnutrition as well as noncommunicable diseases, by recommending higher intakes of fruits and vegetables and lower intake of animal fat (WHO, 2015). However, for a majority of the poor populations of low- and middle-income countries, the intake of livestock-derived food is so limited that the potential benefits of an increase in intake likely outweigh any potential health risks, provided intakes remain within healthy limits.

**Contribution of Livestock Products to Nutrition in Low- and Middle-Income Countries**

There is little debate about the fact that livestock products are a good source of highly bioavailable essential micronutrients.
and, as such, diets containing these foods are believed to be well placed to help achieve required micronutrient intakes. The scientific literature reveals a relatively large body of literature confirming the link between intake of livestock products and positive nutritional outcomes. The majority of this evidence is however derived from observational studies, which cannot prove a “causal link” exists between intake and the observed improvement in nutritional indicators. In other words, the research does not demonstrate that the observed change in nutritional indicators was undoubtedly due to meat, milk, or eggs consumed, although they may indicate it strongly. On the contrary, available randomized controlled experimental studies can provide more conclusive evidence. Unfortunately, these studies are few, likely due to the complex nature of feeding interventions and difficulties to ascertain compliance with treatment, the complex design of such studies, the required large sample size necessary to detect meaningful effects, and their potential ethical implications. Furthermore, the effect that consumption of nutrient-rich livestock products has on nutrition is affected by the composition of the entire diet, and therefore is context specific. Results from trials conducted in high-income countries, where diets are more diverse and nutrient-rich, will not necessarily speak to the role livestock products play with regard to nutritional status of individuals in low- and middle-income countries. Also, although determining the absolute effect of supplementing diets with livestock products compared with diets without them is relevant, it would be equally important to determine the relative effect of their consumption compared with other nonlivestock products (Figure 2).

Various authors have tried to consolidate the findings of randomized controlled trials to provide understanding relative to whether livestock products can be claimed as essential for nutrition for the young. Grace et al. (2018) provide a summary of the existing literature on the topic with the focus on Africa and South/South-east Asia. A more recent review by Shapiro et al. (2019) examined the role of animal-sourced foods on stunting and other nutritional indicators. Compared to the earlier review, the latter identified the latter identified only three additional articles for research conducted in Ecuador, China, the Democratic Republic of Congo, Guatemala, Pakistan, and Zambia (Shapiro et al., 2019). Both reviews presented similar studies and reached similar conclusions. An overview of the findings is presented in this section.

**Effects on the first 1,000 d of life**

Adequate quantity and quality of nutrients are necessary for the period of time from conception, through pregnancy, and up to 2 yr of age for individuals to not only survive, but to thrive throughout life (McDonald and Thorne-Lyman, 2017). The potential impact of consuming nutrient-rich livestock products at this age is of utmost importance for adequate development, especially in contexts were diets are little diverse and nutrient poor.

Inadequate micronutrient intake during gestation has far-reaching adverse consequences through fetal programming (e.g., impaired growth of fetuses and infants and high risk of metabolic syndrome). Micronutrient supplementation can reduce the risk of being born with low birth weight but there is virtually no literature investigating the role of livestock product consumption relative to nutritional outcomes of pregnant women or their off-spring in Africa and South/Southeast Asia. Old studies conducted in Asia have reported direct effects of animal protein intake on milk output of breastfeeding women and infant breastmilk consumption. For example, a study in Burma (Khin-Maung-Naing and Tin-Tin-Oo, 1987)
found that women consuming diets supplemented with unspecified animal protein (twice a day for 2 wk) have higher milk output and their babies ingest more milk than women without such supplementation. In Sri Lanka, women consuming skim milk powder during lactation had longer duration of exclusive breastfeeding. Although not specifically stated by the authors, the longer duration of breastfeeding could be attributed to a higher milk output stimulated from supplemental milk powder (Tennekoon et al., 1996). The evidence is weak and outdated, so further research on the benefits of consumption of livestock products for pregnant and lactating women is warranted.

Randomized control trials relative to the impact livestock products have on the first 2 yr of life are also limited. The scarce literature seems to suggest that, at these early stages of life, intake of milk is particularly important for linear growth. One of the largest randomized control trials conducted to date showed that toddlers in rural areas of Kenya whose diets were supplemented with cow’s milk grew taller than children consuming the usual diet or a diet supplemented with beef (Neumann et al., 2013). A very recent study in Ecuador by Iannotti et al. (2017) showed that supplementing nutrient-scarce diets of children 3 to 9 mo of age with one egg per day for 6 mo increased child height. The study also found increased concentrations of essential micronutrients in the plasma and the prevalence of stunting was reduced by 47% in the egg-supplemented children compared with children on the traditional diet (Iannotti et al., 2017).

The available evidence for the role of livestock products consumed by pregnant and lactating mothers and children during the first 2 yr of age in low- and middle-income countries is relatively limited. That said, many studies have found positive associations with various nutritional outcomes. Although excess intake of protein could be an issue for health, the studies reviewed did not expose any potential adverse impact of consuming moderate amounts of foods of animal origin during this critical period of growth and development. Most studies however have weak designs which limit their capacity to accurately evaluate the impact of animal foods. Conducting research and, particularly randomized control trials, among these groups is particularly difficult due to stringent ethical considerations and health risks that make it challenging to design studies that will provide robust, sufficient scientific evidence.

**Effects on children and adolescents**

More research has been conducted targeting school-aged children, revealing results that are mixed. Several studies have recorded improvements in nutritional outcomes from diets supplemented with livestock products compared with the base diet. Milk is believed to improve linear growth in children (particularly in malnourished children), mediated by the stimulation of insulin-like growth factor (Hoppe et al., 2006; Dror and Allen, 2011). Consumption of livestock-derived foods has also shown positive impact on functional outcomes. For example, research looking at the effects of meat supplementation in children has suggested that consuming meat could improve cognitive development. The improvements in cognitive ability could be a result of meat providing a highly bioavailable source of the necessary combination of micronutrients that may have been missing or undersupplied by the traditional diet (Gupta, 2016).

Milk supplementation has been associated in various studies with improved height. This was demonstrated in a study by Mathews et al. (1974) conducted in New Guinea among children 8 to 12.5 yr of age who were fed 25 g of skim milk powder daily for 8 mo. After 8 mo of supplementation, the children had greater height and weight compared with the control group. On the other hand, diet supplementation with 500 mL of plain milk over 6 mo in Vietnam led to improvements in weight and a reduction in underweight prevalence (Lien et al., 2009). The idea that milk stimulates growth had already been suggested by De Beer (2012) based on the results of a meta-analysis of studies examining milk supplementation and linear growth. De Beer concluded that there was moderate evidence to suggest that dairy product supplementation stimulated growth. The most likely effect was 0.4 cm per annum additional growth associated with 245 mL of milk daily (De Beer, 2012).

The amount of meat, milk, or eggs consumed, and the duration of supplementation are likely critical factors behind the observed effects. Intake of high amounts of livestock products for sustained periods has resulted in a positive influence on micronutrient status. The study on milk supplementation in Vietnam (Lien et al., 2009) found improved levels of ferritin and reductions in vitamin A and zinc deficiencies after daily supplementation with regular milk over 6 mo.

A large randomized control trial in Kenya (Grillenberger et al., 2003; Siekmann et al., 2003; Hulett et al., 2014) among primary-school children (6 to 14 yr of age) assessed the effects of milk, meat, or energy supplementation on micronutrient status and a variety of anthropometric and development outcomes. The study found a negligible influence of milk on child linear growth; however, younger (≤6 yr) and stunted children showed a greater rate of height gain, indicating that milk supplementation may have limited impact on growth among healthy children, yet the influence of milk consumption can be more prominent among younger and (or) ill children. After 1 yr of the intervention, only the levels of vitamin B12 (but no other micronutrients) in blood experienced a noticeable increase (Siekmann et al., 2003) compared with the control group. Specifically, these meat and milk supplementation interventions led to a marked decrease in prevalence of low plasma vitamin B12 diagnosis among participants (i.e., 8.9% in the milk group and 4.5% in the meat group, compared with the baseline prevalence of 40.2% and 56.2%, respectively). Meat and milk are among the few products that contain vitamin B12, which is a key element to support cognitive development. Also in this study, meat improved cognitive performance, school test performance, leadership behavior, and physical activity (Whaley et al., 2003; Sigman et al., 2005; Neumann et al., 2007). The influence of meat on cognitive development is thought to be related to greater intake of vitamin B12 and a more bioavailable source of iron and zinc. Together with high-quality protein, these may facilitate specific mechanisms such as the speed of information processing in learning tasks.
Globally, the livestock sector is one of the most important in terms of land-use, economic value, employment, and use of animals. Unsurprisingly, livestock production can have many impacts, both positive and negative, on societies and ecosystems beyond providing food. Livestock production brings a range of economic, societal, and environmental benefits, some of which are summarized in Table 1. Most of those impacts are particularly important in low- and middle-income countries, where livestock production is the primary source of income and livelihoods for many families, especially in rural areas (Swanepeol et al., 2010).

Although this paper focuses on the nutritional benefits of livestock products in the first 1,000 d of life, a balanced discussion must also pay attention to the negative impacts associated with livestock production. Unsurprisingly, these are the issues that have received most attention over the past decades. Although it is difficult to bring these issues to a common metric, it is likely that the impact of foodborne disease may have the highest ongoing burden, whereas the greatest potential for catastrophic loss (or existential risk) may stem from the contribution of livestock production to climate change and to the emergence of global pandemics. The landmark first assessment of the global burden of foodborne disease (Havelaar et al., 2015) conducted by the World Health Organization considered 31 food-related hazards. It concluded that foodborne disease has a health burden comparable to malaria, HIV/AIDS, or tuberculosis. Most of this burden (98%) falls on developing countries and 40% on children less than 5 yr of age. Although information on source attribution (that is, what foods are responsible) is weak, livestock products are disproportionately represented as causes of foodborne illness (Grace, 2015; Hoffmann et al., 2017). Foodborne disease and health hazards found in livestock products (such as aflatoxins) may also directly contribute to poor nutritional status in infants in low- and middle-income countries. A 9-country study found that 25% of stunting could be attributed to experiencing more than four episodes of diarrhea before the age of 24 mo (Checkley et al., 2008). Studies find a strong peak in diarrhea after the introduction of supplementary foods and find that weaning foods often have high levels of microbial contamination and adulteration (Kumi et al., 2014). Aflatoxins may directly contribute to stunting, and there are demonstrated associations between higher toxin levels in food and poorer growth in several contexts, including children consuming milk with aflatoxins in Kenya, although a causal relation is yet unproven (Leroy, 2013; Hoffmann et al., 2017).

Livestock production, especially in intensive systems and if accompanied by land-use change, can lead to the emergence of zoonotic diseases (Taylor et al., 2001; Jones et al., 2013). Around 75% of new and emerging human diseases (including many antimicrobial resistant organisms) are zoonotic (Blancou et al., 2005). These have the potential to sicken and kill large numbers of people and to damage economies. Emerging pandemics are considered to represent one of the few important risks to societal collapse (Taylor et al., 2001).

Another existential threat to humanity is climate catastrophe, which, under the most extreme scenarios, could make large parts of the world uninhabitable. Although estimates vary, the livestock sector is made responsible for up to 14.5% of anthropogenic greenhouse gas emission (Gerber et al., 2013). Livestock production also has implications for other planetary boundaries, notably biosphere integrity, freshwater consumption, land system change, and nitrogen and phosphorus flows (Rockstrom et al., 2009; Steffen et al., 2015). Production of other foods, especially those requiring high levels of inputs and of low nutritional value (e.g., greenhouse grown, irrigated lettuce), also has environmental effects but a review of the scientific literature seems to suggest that many experts in the sustainable-diets field consider diets low in livestock products and high in fruit, vegetables, and legumes offer the greatest co-benefits in terms of human nutritional outcomes and environmental sustainability (Grace et al., 2018; Willett et al., 2019).

As well as environmental, there are important societal impacts of livestock production. Animal welfare is an increasing public concern raised by consumers, especially in high-income countries. Animal welfare conditions currently vary across countries and production systems, and depend on socio-economic and regulatory settings, as well as on religious and cultural traditions, consumer and civil society organizations pressure. However, animal welfare is often especially problematic in intensive systems of low- and middle-income countries. Other social consequences of intensification include rural abandonment, poor working conditions, low wages, vulnerability of migrant labor, and occupational hazards (HLPE, 2016). These can be exacerbated by economic risks in the form of dependence on external inputs, including feed and energy, market concentration, price volatility, inequitable distribution of value added, as well as the difficulty of internalizing externalities in price signals.

**Table 1.**

| Benefits of keeping livestock beyond their involvement in food production |
|---------------------------------------------------------------|
| **Economic**                                        | **Environmental**                                   | **Social**                                     |
| Obtain access to credit                                | Provision manure                                    | Psycho-social well being                       |
| Draft power                                           | Nutrient manure                                     | Biophilia                                      |
| Transport                                              | Landscape amenity                                   | Traditional foods                             |
| Asset accumulation                                     | Improving pasture land                              | Cultural events                               |
| Household energy production                            | Carbon sequestration                                 | Ritual and religion                           |
| Non-edible byproducts (hides, horns, fiber, etc.)     |                                                   | Exercise                                       |
| Construction material                                  |                                                   | Sport and recreation                           |

As well as environmental, there are important societal impacts of livestock production. Animal welfare is an increasing public concern raised by consumers, especially in high-income countries. Animal welfare conditions currently vary across countries and production systems, and depend on socio-economic and regulatory settings, as well as on religious and cultural traditions, consumer and civil society organizations pressure. However, animal welfare is often especially problematic in intensive systems of low- and middle-income countries. Other social consequences of intensification include rural abandonment, poor working conditions, low wages, vulnerability of migrant labor, and occupational hazards (HLPE, 2016). These can be exacerbated by economic risks in the form of dependence on external inputs, including feed and energy, market concentration, price volatility, inequitable distribution of value added, as well as the difficulty of internalizing externalities in price signals.
Understanding the optimal role of livestock products in diets in the first 1,000 d of life requires a holistic understanding of all the positive and negative impacts of the production and consumption of meat, milk, and eggs. Few studies to date have examined comprehensively the links between production and consumption of livestock products and economic, social, or health sustainability in low- and middle-income countries or the trade-offs between the different aspects of sustainability. For example, advocates for action against climate change recommend shifting from red meat to chicken as this is associated with less greenhouse gas emitted per kilogram of meat produced. Furthermore, white meat (such as poultry breast meat) is often claimed to be healthier than red meat (such as beef or pork). Yet, according to Scherer et al. (2018), the shift to poultry consumption will bring increases in net animal suffering. As mentioned earlier, intensively kept livestock, as is often the case in poultry systems, are associated with disease emergence. One recent study estimated that the annual cost of an influenza pandemic was equivalent to the cost of climate change (Fan et al., 2016). This implies, a shift towards increased poultry meat consumption at scale could result in nonnegligible increased risk of pandemic and their associated animal suffering and economic loss. None of these aspects of sustainability are considered in recent long-standing recommendations to shift consumption from red meat to poultry.

Towards Promotion of Meat, Milk, and Egg Consumption in the First 1,000 d of Life in Low-Income Countries

There is limited robust evidence regarding the effect of consuming livestock products during the first 1,000 d of life, particularly in low- and middle-income countries. That said, evidence from studies on older children and the fact that foods of animal origin represent the most significant source of specific nutrients such as vitamin B12 suggest that consumption of these products would provide nutritional benefits during the first 1,000-d period, possibly without any negative health effects (if intakes are not excessive). Furthermore, it is believed that even low amounts of meat, milk, or eggs can make a difference for these individuals with high nutrient requirements. Yet, the scientific evidence-base to support these claims is far from optimal. Greater capital should be invested into well-designed research projects that possess sufficient power to determine optimal amounts of these foods to achieve the largest benefit to human development and well-being. It is also imperative to determine the relative importance of nutrients derived from foods of livestock origin versus other food products and their contribution to human nutritional outcomes.

Moreover, beyond the nutritional considerations, promoting intake of livestock products among resource-limited populations will require specific feasibility and sustainability studies to be conducted to ensure those foods are available and affordable to the target populations. Drawing policy recommendations on consumption of livestock products for nutrition of vulnerable women and children will require an analysis of the relationship between price of a food and its likely consumption among poor populations. Intake of meat, milk, and eggs in low-income countries is driven primarily by affordability.

About the Authors

Silvia Alonso is a senior scientist at the International Livestock Research Institute (ILRI), based in Addis Ababa, Ethiopia. She has more than 10 yr of experience in public health research, both in Europe and internationally, focusing on the impacts of livestock production on human health. Her current research explores how to leverage livestock value chains to improve health and nutrition. She is leading the first large-scale field trial of an intervention in informal markets to improve food safety and child nutrition in peri-urban Nairobi. She is a Diplomate of the European College of Veterinary Public Health and the Chair of the ethics IRB at ILRI.

Correspondence: salonso@cgiar.org.

Paula Dominguez-Salas is a veterinarian and a public health nutritionist with a focus in developing countries. She now works as a human nutritionist to optimize the impact of livestock development programs at the International Livestock Research Institute (ILRI) in Nairobi, Kenya, and is assistant professor in nutrition-sensitive agriculture at the London School of Hygiene and Tropical Medicine, from where she also graduated. Her research interests are micronutrients, dietary practices, food safety, and gender. Her professional experience is mostly in East and West Africa and Latin America.

Delia Grace is an epidemiologist and veterinarian with more than 20 yr experience in developing countries. She graduated from several leading universities and currently co-leads research on human and animal health at the International Livestock Research Institute (ILRI) based in Nairobi, Kenya. Her research interests include food safety, emerging diseases, gender studies, and animal welfare. Her career has spanned the private sector, field-level community development, and aid management. Her research program focuses on the design and promotion of risk-based approaches to food safety in livestock products. She is also a key player on ILRI’s Ecohealth/One health approach to the control of zoonotic emerging infectious diseases and agriculture-associated antimicrobial resistance.
constraints—these foods are an expensive commodity that is consumed often in small amounts and only in special occasions in accordance with cultural acceptability. These products are also often subject to food proscription. Promotion of their consumption will require tailored recommendations that respect cultural habits and strategies to promote the availability and reduce the cost of these products. The growing differences in meat and milk intake between children in richer (who may already be eating high amounts already) and poorer families in those countries should also be dealt with to avoid exacerbating the double burden already experienced by many low-income countries (WHO, 2017). Finally, promoting the consumption of livestock products cannot occur without accounting for the possible health, environmental, and economic externalities. Investments in sustainable and environmentally friendly livestock production systems and strong food safety systems are required in these countries to holistically maximize the utility of livestock food for nutrition.

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Feature Article

Animal source foods for the alleviation of double burden of malnutrition in countries undergoing nutrition transition

Teena Dasi,† Kiruthika Selvaraj,† Raghu Pullakhandam,‡ and Bharati Kulkarni†,•

†Clinical Division, National Institute of Nutrition, Hyderabad 500007, India
‡Division of Biochemistry, National Institute of Nutrition, Hyderabad 500007, India

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Introduction

The double burden of undernutrition and obesity-related chronic diseases in countries undergoing nutrition transition is a significant impediment to sustainable development. For instance, recent reports from the ICMR-INDIAB study in India showed that almost one in four urban adults over 55 yr of age were diabetic (Anjana et al., 2017). This is coupled with a steep rise in the proportion of overweight and obese adults in the last decade (from 10% in 2005 to 2006 to 20% in 2015 to 2016) as per the third and fourth rounds of the National Family Health Surveys. Rapidly burgeoning chronic disease burden coexists with high burden of undernutrition in adults and children, as indicated by almost 20% prevalence of chronic energy deficiency (body mass index [BMI] less than 18.5 kg/m²) in adults and around 38% prevalence of stunting in children under 5 yr of age, which represents an enormous policy challenge.

There has been increasing recognition that tackling this complex challenge needs “double-duty” actions in terms of policies and interventions that have the ability to simultaneously reduce the undernutrition and overweight/obesity; the two seemingly contrasting forms of malnutrition (Hawkes et al., 2017). Identifying the “shared drivers” between different forms of malnutrition and then targeting interventions to these shared drivers would help reduce all forms of malnutrition. Understanding childhood undernutrition and adult overnutrition as a continuum rather than mutually exclusive problems is particularly useful in this regard.

A substantial body of evidence suggests that body composition with low muscle mass throughout life may be an important link to explain the coexistence of high prevalence of childhood undernutrition and adult-onset chronic diseases in countries undergoing nutrition and epidemiological transition. A number of studies from India and other Asian countries have shown increased cardiometabolic risk within a normal (less than 18.5 to 25 kg/m²) BMI range (Vikram et al., 2003), which has been mainly attributed to the peculiar body composition with high fat and low muscle mass in Asians compared with the other ethnic groups (Misra et al., 2015). Another line of evidence based on a large number of studies has demonstrated that lower birth weight and growth faltering during infancy programs the body toward a lower lean body mass and muscle mass in adulthood (Kulkarni et al., 2014). Childhood undernutrition thus coexists with adipose body composition in adults, especially in South Asian countries. On this background of chronic muscle mass deficit, increasingly obesogenic environment linked with nutrition transition, particularly the excessive intake of processed foods and reduced energy expenditure, results

Implications

• Double burden of undernutrition in children and adults along with high prevalence of obesity-related chronic diseases in adults in developing countries undergoing nutrition transition is an enormous policy challenge.
• Interventions that promote childhood growth and help maintenance of muscle mass in later life would be the key to tackle the double burden of malnutrition.
• Animal source foods could have an important role in combating the double burden of malnutrition in low-income countries where diets are predominantly cereal based with very low intakes of animal source foods.
• In the settings where childhood undernutrition is highly prevalent, affordable animal source foods should be explicitly promoted as a part of guidelines on infant and young child feeding.
• Nutrition counseling needs to be coupled with enhancing the affordability and access to animal source foods for low-income households through macro- and micro-level policy interventions.

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in fat accretion with elevated risk of obesity and metabolic syndrome.

Low muscle mass increases the risk of fat accretion and insulin resistance in multiple ways. The skeletal muscle is a major site for glucose disposal at rest, and reduced skeletal muscle mass and function is associated with decreased insulin sensitivity. Moreover, the low muscle mass itself may predispose to fat accretion due to its significant effect on energy balance as the synthesis and breakdown of muscle protein are largely responsible for the energy expenditure of resting muscle. Wolfe (2006) estimated that an approximate 10-kg deficit in muscle mass translates to conservation of ≈100 kcal/d in energy expenditure, which in turn may result in accumulation of 4.7-kg fat mass in a year. In addition, a number of energy-sparing mechanisms may take place in nutritionally stunted children who have low muscle mass including impaired fat oxidation and preferential oxidation of carbohydrate (Martins et al., 2011). As oxidation of 1 g of carbohydrate is equivalent to 4 kcal compared with 9 kcal with the oxidation of 1 g of fat, the tendency to store fat is enhanced with this adaptation, especially in an environment where physical activity is low.

Dietary intake of important nutrients such as high-quality protein, essential fatty acids, and micronutrients including iron, zinc, vitamin A, and calcium influence the intrauterine and childhood growth. These nutrients are also important for the development and maintenance of adult lean body mass and muscle mass. Suboptimal diets lacking these important nutrients, therefore, could be the main reason underlying the double burden of childhood undernutrition and adiposity during adulthood. Focusing on food systems to enhance availability and access to diverse diets rich in the above nutrients would address the “shared drivers” of the double burden of undernutrition and overnutrition.

**Role of Animal Source Foods**

In resource-poor settings of the developing countries, higher proportion of dietary energy is consumed as low-cost cereals (e.g., rice, maize, wheat, sorghum) or root crops such as cassava (Figure 1). The proportion of energy provided by animal source foods typically varies from 5% to 10% in low-income countries compared with >30% in industrialized countries. Animal source foods, being rich source of high-quality protein, essential fatty acids, and highly bioavailable micronutrients including zinc, iron, calcium, vitamin A, and B12 could contribute substantially to reducing childhood undernutrition and optimal development and maintenance of muscle mass throughout life, thereby reducing the double burden of malnutrition.

In the following sections, we provide a brief appraisal of evidence on the relationship of animal source foods intake with 1) stunting and muscle mass in children and 2) lean body mass and muscle mass in adults particularly focusing on studies conducted in developing countries. Because a comprehensive review of this evidence is beyond the scope of this article, this review is illustrative rather than exhaustive. It is also important to note that the discussion in following sections is largely relevant in the context of developing countries such as India, where the diets are predominantly cereal based with very low intake of animal source foods (Figure 2).

**Animal Source Food Intake and Child Nutrition**

A number of observational and intervention studies have demonstrated the beneficial effects of including animal source foods in children’s diets for improving linear growth as well as micronutrient status.

**Observational studies**

Many observational studies in infants and children which examined the relationship between animal source foods intake and childhood nutrition, especially linear growth, have shown a strong association of higher animal source foods...
consumption with reduced stunting as well as wasting. For example, a cross-sectional study in 3,150 infants and toddlers from Democratic Republic of Congo, Zambia, Guatemala, and Pakistan showed that consumption of meat and fish was associated with reduced likelihood of stunting as well as wasting after controlling for relevant confounders (Krebs et al., 2011). Another independent household survey in more than 2,500 Indian children showed that the odds of severe stunting were 60% higher in children of mothers who did not consume milk or dairy products at least once weekly during pregnancy, whereas low consumption of eggs was associated with a two-fold increase in the odds of stunting in children (Aguayo et al., 2016). Similarly, the SEANUTS study, which examined the associations between dairy consumption and nutritional status in more than 12,000 children from Indonesia, Malaysia, Thailand, and Vietnam, found that the prevalence of stunting was almost double in nondairy consuming children compared with those who consumed dairy on a daily basis (21.4% vs. 10%; Nguyen Bao et al., 2018). In addition, a review based on data on 74,548 children (6 to 23 mo old) from 39 countries showed that children whose diet did not include any animal source foods had 1.44 higher odds of being stunted compared with children who consumed all three types of animal source foods—meat, egg, and dairy (Krasevec et al., 2017).

**Intervention studies**

The findings of the observational studies are in line with the intervention studies although only a few high-quality randomized controlled trials evaluating the impact of animal source foods supplementation on growth and body composition of children have been reported. Most of these studies were conducted in African countries, with scarce information available from Asian countries. For example, a randomized controlled trial from Ecuador in children aged 6 to 9 mo demonstrated that egg supplementation (one per day) for 6 mo reduced prevalence of stunting by 47% and underweight by 74% compared with children in the control arm who received no intervention (Iannotti et al., 2017). Another study from rural Uganda assessed the impact of egg supplementation on growth of primary school children (6 to 9 yr) attending a school feeding program (5 d/wk for 6 mo). The researchers found that children receiving 2 eggs/d had a greater increase in height and weight compared with those who received either 1 egg/d or no eggs. Moreover, participants receiving either one or two eggs per day had a significantly higher increase in mid-upper-arm circumference, indicating large gain in muscle mass, compared with those not receiving eggs (Baum et al., 2017). Similar findings were observed in a study from Kenya which examined the growth and muscle mass of 6- to 14-yr-old schoolchildren from two cohorts with over 900 children after supplementation with meat, milk, or energy for two academic years compared with a control group without a supplement (Neumann et al., 2013). The results showed that children in the meat group had significantly higher gain in mid-upper-arm muscle area than the other groups. To a lesser extent, children who received the milk or energy supplement also gained more mid-upper-arm muscle area than the controls. Importantly, of all groups, the meat group showed the least increase in mid-upper-arm fat area alleviating the concerns about increased adiposity. A systematic review which assessed the impact of supplementing usual diet with dairy products on physical growth estimated benefit of approximately 0.4 cm per annum additional growth per 245 mL of milk consumed daily (de Beer 2012). However, the majority of studies included in this systematic review were conducted in developed countries as very few efficacy trials of dairy supplementation for growth improvement in infants or young children have been reported from developing countries.

A few studies, on the other hand, do not support the above evidence. For instance, a large cluster randomized efficacy trial conducted in Democratic Republic of Congo, Zambia, Guatemala, and Pakistan with over 1,000 subjects comparing the daily provision of 30 to 45 g of lyophilized beef with micronutrient fortified rice-soy cereal product from 6 to 18 mo of age did not find a positive impact for either intervention to prevent progressive linear growth faltering in these settings with high baseline rates of stunting (Krebs et al., 2012). Another recent meta-analysis which assessed the effectiveness of animal source foods compared with other feeding interventions or no intervention regarding improving growth and developmental outcomes in children reported uncertainty regarding the beneficial effects of the animal source foods supplementation due to low quality of the evidence (Eaton et al., 2019).

Given the high nutrient density of animal source foods, promotion of livestock production is considered as a strategy to enhance diet quality and improve child nutrition. The empirical evidence to support the impact of these interventions is, however, limited. For example, by evaluating the impact of Heifer International’s dairy cow and meat goat donation programs in Rwanda, Rawlins et al. (2014) reported that, in households that received pregnant cows, height-for-age z-scores of children under the age of five increased by about 0.5 standard deviations. Similarly, using data from rural Bangladesh, Choudhury and Headey showed that household dairy production was associated with 0.52 standard deviation increase in height-for-age z-scores in the critical 6- to 23-mo growth window. These findings have been corroborated by studies from Uganda (Fierstein et al., 2017) and eastern Africa (Mosites et al., 2017). A community-based dietary diversification intervention, which promoted animal source foods (especially soft-boned fish), showed enhanced z-scores, mid-upper-arm circumference and arm muscle area in 30- to 90-mo-old children in Malawi although there was no significant impact on weight or height gain (Gibson et al., 2003).

**Animal Source Foods Intake and Body Composition in Adults**

Apart from its beneficial role on linear growth and muscle mass development during childhood, animal source foods intake continues to exert positive influence on muscle mass throughout life due to the anabolic properties of dietary
proteins. Plant proteins have lower digestibility and are deficient in essential amino acids leucine, lysine, and methionine. Current evidence suggests that animal source foods proteins may be more anabolic than plant proteins as muscle protein synthesis requires availability of a complete amino acid profile (van Vliet et al., 2015). The majority of the studies exploring the role of animal source foods in muscle mass and function have been done with dairy products as both whey and casein proteins contain high amount of branched-chain amino acids and stimulate muscle protein synthesis. Whey protein, due to its rapid digestion and amino acid absorption kinetics, has been shown to stimulate muscle protein synthesis to a greater extent compared with casein in young adults and in older men (van Vliet et al., 2015).

Cross-sectional studies have shown that total protein and animal protein intake, but not plant protein intake, are positively associated with muscle mass index and leg lean mass (Skau et al., 2015). In addition, longitudinal studies have shown that higher intakes of total protein and animal protein are associated with a reduced loss of lean mass over 3 yr of follow-up (Isanejad et al., 2015).

**Impact of Animal Source Foods on Body Composition: Underlying Mechanisms**

The positive impact of animal source foods on childhood growth and adult muscle mass seen in observational and intervention studies could be linked with multiple mechanisms as summarized in Figure 3. Optimal body composition depends on age appropriate bone and muscle growth in childhood and adolescence, and maintenance of muscle mass in later life. The positive impact of animal source foods on body composition is mediated by key signaling mechanisms affecting linear growth and muscle synthesis as well as by the impact of dietary proteins on the satiety, thereby influencing calorie intakes.

Although animal source foods, in general, are a rich source of bioavailable micronutrients, their superior protein density and quality stands out in comparison to plant proteins. It is well known that essential amino acid content and digestibility of animal source food proteins is far superior to that of plant proteins. Recent studies using stable isotopic methods have shown that quality of protein as determined by availability of indispensable amino acids is quite lower (20% to 30% for lysine and leucine) for legumes compared with eggs or meat (Devi et al., 2018; Kashyap et al., 2018). It is well known that protein intake induces an increase in serum IGF1 levels, and restriction of dietary proteins leads to its reduction via increased clearance (Bonjour et al., 1997). Studies have shown that the positive impact of milk consumption on child growth may be mediated through higher serum IGF1 levels among children (Hoppe et al., 2004). Furthermore, supplementation of essential amino acids also increased serum IGF1 levels and protein synthesis in human participants suggesting that the quality of protein is critical in achieving desired body composition changes (Dillon et al., 2009). A metabolomic study among 12- to 59-mo-old children demonstrated a decline in serum essential amino acid

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**Figure 3.** Role of animal source foods in development and maintenance of optimal body composition.
levels in stunted children, of which leucine showed the strongest association with growth (Semba et al., 2016). Thus, the positive association of animal source foods intake with growth could be, at least in part, due to higher protein quality.

Linear growth is regulated by complex interwoven genetic and hormone-mediated cell signaling mechanisms, which are nutrition sensitive. Physiologically, nutrients are divided into types 1 and 2. The deficiency of type 1 nutrients such as iron and B-vitamins manifests in biochemical changes without affecting the linear growth, whereas the deficiency of type 2 nutrients (such as protein, zinc, magnesium, phosphorus, and potassium) manifests in growth faltering with no change observed in blood levels (King, 2011). The beneficial effect of animal source foods on linear growth in childhood could also be due to the higher density and bioavailability of type 2 nutrients such as zinc and protein in animal source foods compared with plant foods as independent studies have shown the positive impact of supplementation of these nutrients on lean mass (Seino et al., 2018).

In mammals, the mechanistic target of rapamycin (mTOR) appears to be the master regulator of anabolic reactions. Interestingly, the hormonal (growth factors), metabolic (energy and oxygen), and nutritional factors (essential amino acids, i.e., leucine, lysine, etc.) appear to converge in regulating the mTOR pathway (Laplante et al., 2012). The essential amino acids leucine and arginine not only stimulate the activity of the mTOR pathway, but also are absolutely required for growth factor-induced mTOR activation. In fact, emerging evidence suggests that leucine supplementation along with dietary protein improves the muscle mass, reduces weight gain, and improves protein synthesis in animal models and humans (Churchward-Venne et al., 2014).

Higher protein intake also appears to help in weight management in overweight individuals because replacing other macronutrients with high-quality proteins has been shown to reduce body weight. Studies have shown that increasing the protein intake from 15% to 30% by reducing equivalent amount of fat resulted in sustained reduction in appetite, ad libitum calorie intake and reduced body weight among healthy adults (Weigle et al., 2005; Veldhorst et al., 2008). Furthermore, an inverse relationship between serum amino acids and appetite has also been reported (Mellinkoff et al., 1956). The increase in the serum amino acid concentration following oral or parenteral supplementation resulted in decreased appetite and a corresponding decline in serum amino acids restored the appetite, implying that the effect was specific to amino acids. Therefore, it appears that beneficial...
The double burden of undernutrition and overnutrition in transitioning societies represents an enormous challenge to tackle the two seemingly contrasting forms of malnutrition. Interventions to reduce childhood as well as adult undernutrition through food supplementation programs might simply aggravate another problem of increasing obesity if the food supplements are not well balanced in terms of protein quality. Dealing with the complex problem of the double burden of malnutrition requires actions that have the potential to reduce undernutrition without producing a substantial increase in obesity. Improving childhood growth and maintenance of optimal body composition with higher muscle mass later in life seems to be the key to addressing the double burden of malnutrition. As shown by a large body of evidence, animal source foods have an important role in this context due to their effect of promoting childhood growth and maintaining optimal muscle mass in later life.

In the settings where childhood undernutrition is highly prevalent, affordable animal source foods should, therefore, be explicitly promoted as a part of guidelines for infant and young child feeding. But for the nutrition counseling interventions to be effective, these efforts need to be coupled with enhancing the affordability and access to animal source foods for low-income households through macro- and micro-level policy interventions. Finally, it is important to consider that promoting increased production and intake of animal source foods creates another challenge in terms of increased environmental costs. It is, therefore, necessary to carefully balance improved nutrient density of diets with sustainable strategies of livestock production.

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Feature Article

Sustainable livestock systems to improve human health, nutrition, and economic status

Padmakumar Varijakshapanicker, † Sarah McKune,‡,‖ Laurie Miller, § Saskia Hendrickx,‖,¶ Mulubrhan Balehegn,‖,** Geoffrey E. Dahl,‖,¶ and Adegbola T. Adesogan‖,¶

†International Livestock Research Institute, Hyderabad, India
‡Department for Public Health and Health Professions, University of Florida, Gainesville, FL 32611
‖Feed the Future Innovation Lab for Livestock Systems, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL 32611
§School of Medicine, Friedman School of Nutrition Science and Policy, and Eliot-Pearson Department of Child Study and Human Development, Tufts University, Boston, MA 02111
¶Department of Animal Sciences, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL 32611
**Department of Animal, Rangeland and Wildlife Sciences, Mekelle University, Mekelle, Tigray, Ethiopia

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Introduction

The most common words associated with sustainability are “environment,” “social,” and “economic.” Thus, sustainability is a holistic concept that jointly considers ecological, social, and economic dimensions of a system or intervention for long-lasting prosperity. Experience shows that economic development at the cost of ecology does not last; therefore, it is critical to harmonize ecology with development. This also applies to livestock systems, which should be economically viable for farmers, environmentally friendly or at least neutral, and socially acceptable in order to be considered sustainable.

There are different types of livestock production systems, depending on availability of resources, environmental conditions, and social and economic contexts, and they vary considerably in sustainability. These livestock systems include the grassland-based extensive systems, intensive landless systems, and mixed farming systems among others. These systems contribute significantly to human nutrition and livelihoods and provide important ecosystem services. However, if not properly managed, they can also cause nutrient and environmental pollution and land degradation.

With increasing global awareness about climate change and studies indicating that livestock is one of the contributors to greenhouse gases, environmental degradation, and loss of biodiversity, various concerted efforts have been aimed at developing and or ensuring the sustainability of livestock systems that deliver economic and ecosystems services without compromising the future integrity, health, and welfare of the environment, humans, and animals. Increasing competition for the requisite resources for feed and food production, especially under more intensive livestock production systems, has raised concerns about the economic and environmental sustainability of some livestock production systems. Feed production and

Implications

- Sustainable livestock systems contribute to food security, economic and environmental stewardship, and sociocultural needs and are vital for achieving most of the United Nation’s Sustainable Development Goals.
- Livestock production contributes to sustainability through use of uncultivable land for food production, conversion of energy and protein sources that cannot be used by humans into highly nutritious animal-sourced food and reduction of environmental pollution with agroindustrial by-products, while generating income and supporting livelihoods of millions of people all over the world.
- Some livestock systems are particularly effective at carbon sequestration and hence reducing greenhouse gas emissions that contribute to global warming.
- Livestock production offers the greatest potential to reduce greenhouse gas emissions from agriculture and animal scientists have devised several effective strategies that can reduce such emissions from livestock systems by up to 30%.
- Most of the current discourse on sustainability focuses on one albeit important factor—the environment. Equally important factors are the need to ensure food and nutritional security for the growing global population in a culturally acceptable manner that ensures its accessibility, affordability, and safety.
- While livestock systems generally contribute to sustainability, poorly managed livestock systems may have adverse effects on the environment and human and animal health and welfare.

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processing, and enteric fermentation of feed contribute to 45% and 39%, respectively, of the total emissions from agriculture (Steinfeld et al., 2006). About 90% of livestock emissions are produced by ruminants through enteric fermentation (188 million tons) and the remaining 10% from manure (Swamy and Bhattacharya, 2006). In addition, inadequately managed livestock production systems may cause negative environmental consequences such as eutrophication in intensive high input systems, overgrazing, and soil and rangeland degradation in extensive systems and negative human health outcomes.

Even though inadequately managed livestock systems may have adverse effects on the environment, widely quoted statistics about their contribution are misleading. Most do not reflect the diversity of livestock production systems or differences between production systems dominant in various countries even for a given species. For instance, an often-cited statistic is that livestock contribute 18% of greenhouse gases globally (Steinfeld et al., 2006), more than that for the transportation industry, but that analysis is incorrect and has been corrected by the authors (Mottet and Steinfeld, 2018). Moreover, interventions can help reduce the carbon footprint of livestock production, while improving productivity. For example, with improved management and feeding strategies, the carbon footprint per billion kilograms of beef produced in 2007 was reduced by 16.3% compared with equivalent beef production in 1977 (Capper, 2011).

When comparing greenhouse gas emissions of various livestock production systems, it is critical to take the need for environmental stewardship as well as food security into account to ensure the sustainability of the system. An index which takes both into account is the emissions intensity measure, which relates greenhouse gas emissions to food produced by the system. This important index shows that methane production per unit of food produced in several low- and middle-income countries is much greater than in some developed countries (Figure 1). This does not imply that the production systems in the developed countries should be copied entirely by low- and middle-income countries; rather, each country should evaluate and implement the aspects of developed country production systems that will sustainably intensify their production systems and thereby increase food production while reducing greenhouse gas emissions.

Often ignored is the fact that livestock systems contribute to global sustainability by providing various ecosystem services. For instance, a recent meta-analysis of 86 studies that examined various agroforestry systems revealed that net accumulation of soil carbon or sink of greenhouse gases was greatest when grassland was converted to silvo-pastures combining trees, forage, and livestock (Feliciano et al., 2018). Land maintained for livestock grazing has lower greenhouse gas emission than the same land converted for crop production. Rates of soil loss in U.S. croplands are more than four times that of grazing lands. Grazing lands sequester more carbon per unit area compared with cultivated croplands (Diaz et al., 2012). Furthermore, globally more than half (57%) of the 2.5 billion hectares of land used for producing forage is unsuitable for food production (Mottet et al., 2017).

Thus, forage crops make productive use of noncultivable land. In addition, since only 14% of the feed consumed by livestock is edible by humans, the remaining 86%, including by-products, crop residues, and grasses or fodder, is converted into human food contributing to incomes and avoiding environmental pollution from burning or dumping the residues and by-products (Mottet et al., 2017). Even when livestock consume human-edible proteins, their net protein contribution is positive. For example, in U.S. beef production systems, the ratio of human-edible protein in animal-source foods to that in animal feed is always greater than one (Baber et al., 2018). Thus, livestock are net contributors to human protein requirements (Baber et al., 2018) and in fact livestock contribute to 13% and 28% of the global protein and energy, respectively (FAO, 2009).

Animal scientists have developed nutritional, genetic, health, and management strategies to reduce greenhouse gas emission intensities by as much as 30% (Gerber et al., 2013). Indeed, the concept of sustainable diets that are profitable, ethically and socio-culturally acceptable, and environmentally benign is emerging as one of the key solutions to ensuring the sustainability of livestock production systems. Considering the competition between feed and food systems, the concept of sustainable diets stipulates that future feed systems should focus on increased efficiency of conversion of fibrous feeds such as crop residues with high content of poorly digestible structural carbohydrates (lignin and cellulose) into human-consumable animal products. Sustainable diets and feed systems, therefore, have a potential for maintaining profitability of feed systems while reducing their negative environmental and social impacts (Bocquier and González-García, 2010). The adoption of such sustainable animal diets will require multidisciplinary input into the development of objective indicators. Future research into sustainable livestock diets should target both animal physiology and farmers’ practices to develop an integral, dynamic, and flexible conceptual perspective (Bocquier and González-García, 2010).

**Sustainable Livestock Production for Human Nutrition**

Assessment of sustainability of livestock food systems usually focuses on GHG emissions from the foods produced. However, this approach does not account for the nutritional, health, and other benefits livestock provide in various production systems. These benefits offset the greenhouse gas they produce, which are declining because of the introduction of improved livestock management systems (Capper, 2011). The larger carbon footprint generated by livestock compared with other food sources are necessary trade-offs because livestock systems provide nutrient-rich products that are vital for health and wellbeing (White and Hall, 2018).

**Human nutrition, malnutrition, and stunting**

The nutrient requirements of human beings include macronutrients (carbohydrates, protein, and fat) and micronutrients
(vitamins and minerals). Malnutrition is defined as a deficiency, excess, or imbalance in nutrient intake versus nutrient requirements. Both undernutrition and overnutrition may have serious consequences. Undernutrition during infancy and childhood is widespread in low- and middle-income countries and is most commonly classified as stunting (low height-for-age) or wasting (low weight-for-height). Stunting usually reflects chronic malnutrition and frequent infections while wasting indicates acute significant food shortages and/or diseased status, and is a strong predictor of mortality. About 1 in 5 or 151 million children in the world are stunted, and more than 50 million are wasted (UNICEF, 2018).

Stunting rates are highest in several sub-Saharan Africa and south Asian countries, where the prevalence often exceeds 30%. In young children, stunting is associated with reduced physical and cognitive development, increased risk of infection, lower school achievement, and greater behavioral problems. Adults who were malnourished in childhood have less economic productivity, poorer maternal reproductive outcomes, and increased incidence of hypertension and glucose intolerance (UNICEF, 2018). Indeed, World Bank researchers reported that childhood stunting reduces the gross domestic product of affected countries by about 7% on average and by 10% for African and Asian countries, with the reduction being as high as 16% for certain countries (Galasso et al., 2016).

Stunting abounds among the poor in low-income settings where diets are cereal-based and lack diversity. The limited gastric capacity of infants, particularly infants, makes it difficult for them to ingest adequate nutrients needed to support rapid growth. Stunting is often associated with micronutrient deficiencies. For instance, 38% of children in India are stunted because young children mainly consume cereal-based food, which lacks easily digested protein and key bioavailable micronutrients (Shivakumar et al., 2019). These micronutrient deficiencies increase the risk of diseases such as diarrhea, malaria, and measles, further diminishing child growth and cognitive development. Micronutrient deficiencies in childhood are also associated with later reductions in work productivity, as well as poorer reproductive outcomes for women (Neumann et al., 2002).
Importance of animal-sourced foods versus plant foods in meeting nutrient requirements

Compared with plant foods, animal-sourced foods provide dense and readily bioavailable sources of energy, protein, minerals, and vitamins. Animal-sourced foods are particularly valuable for infants in the first 1000 d of life when the small gastric size and rapid growth rate demand dense and bioavailable nutrient sources. The World Health Organization notes that animal-sourced foods are the best nutrient-dense foods for children aged 6 to 23 mo. Animal-derived proteins provide a balanced profile of amino acids that are readily digested, whereas plant-derived proteins often lack one or more amino acids critical for growth and other metabolic functions and are less digestible. For example, a recent study compared the digestibility of amino acids in rice, finger millet, mung dal, and eggs. The amino acid digestibility (measured by the digestible Indispensable Amino Acid Scores) was least for mung dal (65%), highest for eggs (87%), and intermediate for rice and finger millet (Shivakumar et al., 2019).

Dietary quality, rather than the quantity of food energy and protein, has been cited as a significant predictor of children’s cognitive development (Whaley et al., 2003). Intake of animal-sourced foods also improves growth, and physical activity of children, and leads to better pregnancy outcomes and reduced morbidity from illness (Neumann et al., 2002). Animal-sourced foods are important contributors to diet quality. For example, meat is rich in amino acids, iron, zinc, riboflavin, vitamin B12, vitamin B6, essential polyunsaturated fatty acids, and other micronutrients essential for cognitive function and normal growth. Milk (Figure 2) is a good source of vitamin A, calcium, vitamin B12, riboflavin, essential polyunsaturated fatty acids, folate (except goat’s milk which is folate deficient), and is perhaps the best source of bioavailable iodine. Eggs are good sources of amino acids (Figure 3), vitamins A, B2, B12, iodine, choline, folate, zinc, iron, and fatty acids such as docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA). Therefore, animal-sourced foods provide many of the nutrients that are completely lacking (or less bioavailable) in plant-based foods.

Animal-sourced foods also provide multiple micronutrients simultaneously. This can be important in the diets of the poor in low- and middle-income countries, which typically lack several nutrients. For example, about one-third of women globally are anemic; the prevalence is greatest in low- and middle-income countries (McLean et al., 2009). Vitamin A and riboflavin are both needed for iron mobilization and hemoglobin synthesis; therefore, iron supplementation or fortification alone may not successfully treat anemia if these other nutrients are deficient (Allen, 1995).

Consumption of even small amounts of animal-sourced foods contributes substantially to ensuring dietary quality. In fact, a woman would have to eat about 8 and over 3 times as much spinach as liver and beef to meet her daily iron needs, respectively (Gupta, 2016; Figure 4). Protein-energy malnutrition, iron-deficiency anemia, and vitamin A deficiency can be prevented if enough animal-sourced foods are included in the diet of the poor in low- and middle-income countries.
diet. This applies in low- and middle-income countries as well as developed countries; if animal-sourced foods are omitted from U.S. diets, micronutrient deficiencies will prevail (White and Hall, 2018). This is also evident from Figure 5 which compares nutrient deficiencies in meat eaters, vegetarians, and vegans in the United Kingdom (Sobiecki et al., 2016).

The foregoing clearly indicates that animal-sourced foods can significantly enhance nutritional quality and reduce malnutrition for vulnerable populations in low- and middle-income countries, especially young children and pregnant and lactating women. Animal-sourced foods are also important in meeting the nutrient needs of those in developed countries and moderate intakes may reduce the high rates of obesity and diabetes due to consumption of “empty” calories based on carbohydrate-dense foods in some of such countries.

**Evidence of the nutritional benefits of animal-sourced foods consumption**

Research indicates that consumption of animal-sourced foods improves growth, cognition, and other nutrition outcomes in children. Consumption of various animal-sourced foods may affect these outcomes differently. For example, in some studies, milk was particularly associated with better linear growth and meat with better cognition (Neumann et al., 2007). Meat is a particularly good source of bioavailable iron, which is critically important for motor development and neurological functioning including learning and memory (Nyaradi et al., 2013). In a randomized controlled trial of dietary supplements for Kenyan school children, those whose diets were supplemented with meat outperformed children who received supplements of milk or oil (for energy) on cognitive performance and tests of arithmetic ability. The meat-supplemented group children had test scores 45% relative to baseline when their performance was averaged over five school semesters and all subjects, whereas those supplemented with milk, oil, and nothing (control) were 28% greater and 7% and 10% less, relative to baseline, respectively (Hulett et al., 2014). Iron-containing complementary foods like meat are especially important among infants who have insufficient iron stores or inadequate intake, as concluded in a recent systematic review (Obbagy et al., 2019).

There is increasing evidence on the importance of animal-sourced foods in reducing stunting. A meta-analysis (De Beer, 2012) showed that dairy consumption increased child growth, with a pooled effect increase in height of 0.4 cm per annum for additional consumption of 245 mL of milk daily. In Ecuador, adding one egg per day to the diet of young infants reduced stunting rates by nearly half (Iannotti et al., 2017). In India, adding an egg or milk to the diet reduced stunting in young

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**Figure 4.** Amount of various types of foods that provide the same amount of iron. Figure provided by Gupta (2016).

**Figure 5.** Incidence of common nutrient deficiencies among people consuming meat-, vegetarian-, or vegan-dominated diet patterns. Data are expressed as the percentage of subjects with deficiencies of protein, vitamins (A, B2, and B12), and minerals (calcium, iron, zinc, selenium, and iodine). Adapted from (Sobiecki et al., 2016; n = 24,000).
Health Benefits of Animal-Sourced Foods

In addition to beneficial effects on growth and development, animal-sourced foods provide micronutrients and other elements important for human health. Iron and zinc are important for optimal function of the immune system and iodine is essential for thyroid function. Therefore, animal-sourced foods that contain these nutrients can contribute to enhanced immune systems. Cow milk is a source of potassium, which can enhance vasodilation and reduce blood pressure in adults. Calcium in milk is also important for bone health, blood clotting and wound healing, maintaining normal blood pressure, and muscle contractions including heartbeat. Dairy consumption improves bone health during childhood and adolescence and reduces the risk of osteoporosis and type 2 diabetes (Rozenberg et al., 2016). Dairy consumption has also been associated with reduced blood pressure, arterial stiffness, cardiovascular diseases, rickets, and hip fracture (Fekete, 2016). However, a systematic literature review on the effects of milk and dairy product consumption on prostate cancer risk and mortality (Lopez-Plaza et al., 2019) concluded that although there are some data indicating that higher consumption of dairy products could increase the risk of prostate cancer, the evidence is not consistent. In addition, meta-analysis by Guo et al. (2017) was not conclusive about the health benefits of milk consumption, further indicating the need for more studies. Similar equivocations also exist on the health benefits of meat and other animal-sourced foods indicating the need for further large scale, controlled, and longitudinal research studies for developing food guidelines.

Economic Impacts of Sustainable Livestock Systems

Livestock products (meat, milk, and eggs) are among the top 10 globally traded commodities with a value of approximately US$6.5 million (FAOSTAT, 2017). Livestock generate income for farmers of all categories via sale of animals and livestock products. In low- and middle-income countries, millions of farmers keep livestock as a status symbol, with more indicating greater status or as insurance against emergencies and sell them to meet cash needs; the animals are commonly referred to as a “savings bank on hooves” (Figure 6). Livestock also provide opportunities to capitalize on underutilized family labor. As the income from livestock is less seasonal (compared with crops), farmers, particularly women, depend on these animals as a vital source of income for household essentials, including payment of school fees and medical expenses. Livestock also serve to empower women who have important and varied roles in raising them in many low- and middle-income countries. The manure and draft power from livestock represent assets that can be used or sold as fuel for cooking or heating or building materials, or exchanged for needed commodities, respectively. Furthermore, income from livestock allows farmers to make better dietary and health choices and provide the necessary resources to pay for medical care.

According to the International Labor Organization, the livestock sector is an integral part of agriculture, which contributes 60% to 70% of total employment in low- and middle-income countries, mainly in Africa and Asia. The jobs in the sector are not limited to just farm production but extend to include aggregation, processing/value addition, distribution, transportation, food storage, retailing, food marketing, etc. Studies in Bangladesh and India have shown that raw milk collection
and distribution creates 20 to 40 full time jobs per 1,000 liters of milk traded. Milk processing generates another 60 to 100 jobs per 1,000 liters of processed milk with around 15% of the traded milk being processed, leading to around 32 additional full-time jobs per 1,000 liters of marketed milk. It is to be noted that few comprehensive studies are currently available on the aggregate direct and indirect employment generation and socio-economic impacts of the livestock sector in low- and middle-income countries at the country or regional level.

Differences in Animal-Sourced Foods Consumption Patterns and Underlying Causes

Various factors determine animal-sourced foods consumption patterns among different groups of people. In India, per capita consumption of milk was higher in urban than in rural areas (Kumar et al., 2014). This holds true in many countries. Not surprisingly, richer households consume significantly more milk and milk products than poor households (Kumar et al., 2014). Notably, an increase in purchasing power is associated with a change in the food consumption patterns; people include more meat, eggs, and milk products in their diets when their income increases. In other words, consumption of animal-sourced foods is income-elastic.

Consumption of milk is generally associated with ownership of dairy animals. A review of six studies conducted by the Global Dairy Platform to identify potential impacts of dairy farming revealed that ownership of dairy cattle resulted in a substantial increase in household milk consumption. However, when animal productivity is increased, it does not necessarily result in increased consumption of animal-sourced foods by the household members, especially in a market-oriented production scenario (Masset et al., 2011). It is difficult to ensure that the animal-keeping households increase their animal-sourced foods consumption when productivity of their animals increase. For example, several projects aiming to introduce or improve animal production suggest that livestock and their products are more likely to be sold for income than consumed by poor households (Ruel et al., 2018). Various sociocultural factors including religion and traditional beliefs also affect animal-sourced foods consumption and these are discussed below.

Reasons for low/little consumption of animal-sourced foods

In several low- and middle-income countries, lack of access to animal-sourced foods is the main problem. This may be due to many reasons such as unavailability of animal-sourced foods at the right location, time, or form; lack of awareness about their importance in the diet; as well as poverty, gender dynamics, taboos, or other socio-cultural factors.

1) Awareness: Many of the poor who live in rural areas in low- and middle-income countries have little or no knowledge of nutrients and their importance to human health and well-being. Food consumption is mainly aimed at satisfying hunger; knowledge about the importance of animal-sourced foods in the diet is lacking.

2) Affordability/income: Compared with plant-based foods, animal-sourced foods are relatively expensive; thus, their consumption is income-dependent. Kumar et al. (2014) found that the per capita consumption of milk by rich households in India was 6.8 times higher than that of very poor households and 3.3 times higher than that of poor households. Similar trends are evident in other countries. In Ethiopia, the prices of dairy, eggs, and meat increased by about 30% over the last decade, whereas the price of grains, roots, and tubers did not increase (Bachewa et al., 2017). The relatively high cost of animal-sourced foods is a challenge for the poor who must make tough decisions on how to spend their scarce resources. Consequently, for many families, animal-sourced foods are not consumed at all, or only on rare occasions such as religious festivals.

3) Myths and taboos: Taboos associated with animal-source foods often create barriers to consumption of these foods. In Southern Ethiopia, consumption of animal-sourced foods by pregnant women is thought to be associated with a more difficult delivery (Demissie et al., 1998). Discussion with farmer/women groups in India and Nepal revealed that in some Indian communities it is believed that meat of scavenging poultry, buffalo, and pigs should not be consumed due to their dirty feeding habits. Some other communities believe that during menstruation, girls should not consume pure foods such as milk because they are impure. In Nepal, some people believe that milk is meant for consumption by evil spirits, and therefore, it should not be sold. In certain African countries, some people still believe that milk is for cats and not children, or that eating meat or eggs will make children steal, severely limiting animal-sourced food consumption.

   a) Religion: Members of the Hindu faith avoid beef consumption due to veneration of cows. The caste system also limits animal-sourced foods consumption. For instance, Brahmins in India and Nepal do not eat beef and may not consume milk if the milking was done by someone in a low caste like the Dalits. It is also a belief that if the milk is consumed by lower caste people, the productivity of animals will be reduced (Mamgain and Diwakar, 2012). Muslims avoid pork consumption for religious reasons. In Ethiopia, devout orthodox Christians practice “fasting,” defined in this context as avoiding animal-sourced foods, for up to 240 d a year, during which adults and children eat food of suboptimal protein and calorie content.

   b) Gender-based food allocation bias: There is ample evidence from all over the world to show that there is food allocation bias against females of all ages, and against younger household members. As a result, there are gender-based differences in the consumption of animal-sourced foods (Gittelsohn and Vastine, 2003). In South Asia, women, particularly pregnant, are discriminated against during allocation of food in households due to food insecurity or
socio-cultural factors (Gittelsohn and Vastine, 2003). This is also true in many sub-Saharan African countries where the man gets the choice portions of the meal followed by the children. In many of such situations, women often eat last and the least; they fast more frequently and have limited decision-making power over food-purchasing decisions. Women also limit themselves from consuming enough animal-sourced foods for fear of big babies and the risk is thought to increase as women approach childbirth (Gittelsohn and Vastine, 2003).

Pathways to promote consumption of animal-sourced foods among vulnerable groups

1) Education/training: Food choices are usually determined by availability, economic status, taste, convenience, social norms, etc., rather than nutritional knowledge. Therefore, creating awareness about healthy food options, especially during certain important stages of development (pregnancy, first 1000 d of life) is critical. Nutritional counseling and education can play a key role to promote good nutrition among the vulnerable in low- and middle-income countries. Proper education will also help us to address various taboos associated with consumption of animal-sourced foods. Community and religious leaders can assist in addressing cultural food allocation practices related to food type, gender, and age. Efforts are also needed to raise awareness among policy makers and researchers about the importance and benefits of animal-sourced foods consumption.

2) Increasing affordability: Since the high cost of animal-sourced foods is one of the main deterrents to their consumption, reducing their prices or improving the income of the poor would make them more accessible. The former can be achieved by increasing the efficiency and productivity of livestock, as well as the efficiency of actors along the livestock value chain (such as smallholder farmers, animal health workers, feed dealers, fodder producers, artificial insemination technicians, buck rearers, and marketing agents). This would increase the income of these groups of people. However, increased income and therefore increased affordability does not necessarily mean they will purchase and consume more animal-sourced foods. The households may choose other more expensive foods that do not supply the required nutrients. Therefore, nutritional interventions should include social behavioral change campaigns on the importance of animal-sourced foods in the diet.

3) Policies and programmes: As animal-sourced foods are relatively expensive, policies should be enacted and implemented to make livestock products more affordable or available for the poor. School lunch programs are one way this can be implemented. Similar efforts to improve the nutrition of school children in low- and middle-income countries with milk and eggs are being implemented by governments and nongovernmental organizations (NGOs) in various countries. Such efforts are commendable but inadequate. More nutrition-targeted subsidized programs

Figure 7. The role of livestock in achieving the United Nations sustainable development goals can be categorized into four main aspects including inclusive sustainable economic growth and equitable livelihoods (A) and improving nutrition and health, and sustainable ecosystems (B). Figure was adapted from Wright (2017).
About the Authors

Padmakumar Varjakshapanicker has been working with International Livestock Research Institute (ILRI) since 2009 and is currently managing the Asia hub of the Livestock System Innovation Lab, a Feed the Future Initiative of USAID. He is also the Acting Head of ILRI’s NIRS Feed Technology Platform at Patancheru, Hyderabad, India. Padmakumar graduated from the Centre for Tropical Veterinary Medicine, University of Edinburgh, UK. He has been working in the livestock sector for more than three decades and has research experience in India, Nepal, and Cambodia. Corresponding author: V.Padmakumar@cgiar.org

Sarah L. McKune is an Assistant Professor in the Department of Environmental and Global Health and the Center for African Studies at the University of Florida. She holds a BA in French and Sociology, a Master’s in Public Health, a PhD in Interdisciplinary Ecology, and was a postdoctoral fellow for the CGIAR’s research program on Climate Change, Agriculture, and Food Security. She is currently a visiting professor and researcher in the Department of Child Psychiatry at St. Anne’s Hospital in Paris.

Adgebola (Gbola) Adesogan is Director, Feed the Future Innovation Lab for Livestock Systems and Professor, Ruminant Nutrition at the University of Florida. His research interests include using animal-sourced foods to improve human health and nutrition; improving food and feed safety and quality; and devising sustainable strategies to optimize the performance, health, and welfare of livestock. Prior to his tenure at the University of Florida, he was an Assistant Professor of Animal Nutrition at the University of Wales, UK.

Laurie C. Miller is Professor of Pediatrics, Adjunct Professor of Nutrition and of Child Development, Tufts University (Boston, USA). She works with Heifer Nepal as an investigator in several projects supported by the USAID Nutrition Innovation Lab and the Innovation Lab for Livestock Systems. She also serves as a consultant on zoonotic diseases to a World Bank-funded project in Nepal.

Geoffrey E. Dahl is the Harriet B. Weeks Professor in the Department of Animal Sciences at the University of Florida, Gainesville. Geoff conducts applied and basic research with direct impact on dairy production, including effects of photoperiod manipulation on production and health, the impact of frequent milking in early lactation on milk production, and heat stress abatement during the dry period on cow and calf productivity and health. He has active Extension programs in Sri Lanka, Nepal, Rwanda, and Ethiopia. Geoff is Past-President of the American Dairy Science Association.

Saskia Hendrickx is the Deputy Director of the Feed the Future Innovation Lab for Livestock Systems at the University of Florida. Saskia is a veterinary epidemiologist by training with over 15 yr of experience in public health, livestock research, and project management in developing countries. Before joining the University of Florida in 2016, Saskia worked with the International Livestock Research Institute and the World Health Organization. Her research aims to improve surveillance of zoonotic diseases and improve livestock production to increase household income in sub-Saharan Africa and Asia.

Mulubrhan Balehgen Gebremikael is an Associate Professor of Livestock Production and Pastoralist Development at Mekelle University, Ethiopia. He holds a PhD in Animal nutrition from the Norwegian Institute of Life Sciences and an MSc in Livestock Production and Pastoralist Development from Mekelle University. His research interests include improving the quality and productivity of animal feeds toward improving the productivity and consumption of animal-sourced foods in developing countries. He is currently working as a research coordinator at the University of Florida. Before his current position, Dr. Mulubrhan was a postdoctoral fellow at the United Nations International Ecosystem Management Partnership and at the Research and Publication Office, Mekelle University, Ethiopia.

She is currently a visiting professor and researcher in the Department of Child Psychiatry at St. Anne’s Hospital in Paris.
foundations and earmarked funds as part of their Corporate Social Responsibility. Similar initiatives and more of such programs are needed. Home-rearing of location-appropriate livestock species has also been promoted as a possibly pathway to improve household animal-sourced foods consumption as well as income.

**Sustainable livestock systems and the UN Sustainable Development Goals**

The United Nations developed 17 Sustainable Development Goals (SDGs) as a blueprint to achieve a better and more sustainable future for all by 2030. The goals address global challenges including those related to poverty, inequality, climate, environmental degradation, prosperity, and peace and justice. Wright (2017) arranged the 17 SDGs into four groups (inclusive sustainable economic growth, equitable livelhoods, improving nutrition and health, and sustainable ecosystems) illustrating the critical roles livestock play in achieving the Sustainable Development Goals (Figure 7). These groupings and the associated descriptions of the role of livestock in each one indicate that achieving most of the SDGs without livestock is difficult and likely impossible.

**Conclusions**

Livestock production contributes to environmental sustainability through conversion of human-unusable energy into highly nutritious animal-sourced foods, thereby contributing to the reduction in organic waste and pollution in the world, but also provide food and nutrition security. However, the potential and actual contribution of various livestock production systems to environmental sustainability varies according to production system. Various nutritional, genetic, management, and health-related strategies exist for reducing the environmental impact of livestock and making them contribute positively to sustainable livelihoods. Livestock contribute directly and indirectly to environmental and economic sustainability via various pathways. Some livestock systems are particularly effective at carbon sequestration and hence reducing greenhouse gas emissions that contribute to global warming. Assessment of the impact of livestock on the environment and livelihood should not focus on single criteria such as greenhouse gas emissions, but should balance ecological, social, and nutritional costs and benefits. Sustainable livestock systems contribute to food security, economic, environmental stewardship, and sociocultural needs and are vital for achieving most of the UN SDGs. They are particularly important for improving human nutrition, health, and economic productivity. Concerted efforts are needed to promote such systems in low- and middle-income countries.

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Feature Article

Animal-sourced foods for improved cognitive development†

Mulubrhan Balehegn,†,‡ Zeleke Mekuriaw,|| Laurie Miller,§ Sarah McKune,‡,¶ and Adegbola T. Adesogan‡,**

†Mekelle University Department of Animal, Rangeland and Wildlife Sciences
‡Feed the Future Innovation Lab for Livestock Systems
||International Livestock Research Institute, Addis Ababa, Ethiopia
§School of Medicine, Friedman School of Nutrition Science and Policy, and Eliot-Pearson Department of Child Study and Human Development, Tufts University, Boston, MA 02111
¶Department for Public Health and Health Professions, University of Florida, Gainesville, FL 32611
**Department of Animal Sciences, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL 32611

Implications

• Animal-sourced foods are the best source of nutrient-rich foods for children aged 6 to 23 mo according to the World Health Organization.
• Studies on the role of animal-sourced foods on cognitive functions are limited, but consistently show compelling benefits.
• Animal-sourced food consumption can positively contribute to school performance in children, lifelong achievement, economic productivity, and social and community outcomes.
• More large-scale randomized controlled longitudinal studies are required to fully understand the link between consumption of animal-sourced foods and cognitive development.
• Improving production of animal-sourced foods does not guarantee increased consumption by children. Complex health, gender, cultural, financial, and religious barriers limit the consumption of animal-sourced food by children, particularly in low- and middle-income countries.
• To increase consumption of animal-source food by vulnerable children, affordability, acceptance, and access must be increased.

Key Words: animal-sourced foods, bioavailability, cognitive development, malnutrition

Introduction

Malnutrition continues to be an important problem, despite global increases in food production over the last century. Over 200 million children worldwide fail to meet their developmental potential because of malnutrition and other socio-environmental constraints. In 2018, more than one in five children were stunted and 7.3% suffered from wasting (UNICEF 2019). Although wasting (low weight-for-age) is a measure of acute malnutrition and is associated with mortality, stunting (low height-for-age) is a widely used measure of chronic malnutrition. Children who are stunted in early childhood, particularly in the first 1,000 d, experience reduced growth and physical development and suffer compromised cognitive development leading to lower Intelligence Quotients, worse school performance, greater susceptibility to chronic diseases, increased behavioral problems, and reduced earning potential as adults (De Onis and Branca 2016). In a recent World Bank report, countries where the workforce was stunted in childhood had reduced gross domestic products by about 7% on average globally and 10% to 17% in Africa and South East Asia (Galasso et al., 2016).

Stunting is caused by several interacting factors including poor hygiene and various health-related factors, but the most important cause is an inadequate diet (total calories and essential nutrients) especially during the first 1,000 d. These essential nutrients include iron, zinc, copper, chromium, selenium, iodine, manganese, and molybdenum, and 13 vitamins (vitamin A, vitamin B1, B2, B6 and B12, niacin, folate, pantothenic acid, vitamin C, vitamin D, biotin, vitamin E, and vitamin K). The prevalence of stunting among disadvantaged children in low- and middle-income countries is high and often exceeds 30% in many sub-Saharan and South East Asian countries. This is in part because of the high prevalence of starch-based diets that lack these essential nutrients. Even among the populations that supplement these diets with fruits and...
vegetables, stunting remains a problem partly because plant foods lack readily bioavailable forms of various micronutrients because they are bound to other compounds like phytate or fiber, markedly reducing their bioavailability (Gibson et al., 2018). Plant foods also completely lack other nutrients, such as vitamin B12, which predisposes people to megaloblastic anemia, developmental delays, failure to thrive, and poor growth in infants and insulin resistance (Williams et al., 2016). Due to widespread consumption of plant-based diets, vitamin B12 deficiency is relatively common, affecting ~40% of children and adults in Latin America, ~70% of children in Kenya, and ~80% of children in India (McLean et al., 2007). Vitamin B12 concentrations were deficient in the breastmilk of 89% of 286 nursing Kenyan women indicating that even though breastmilk is the ideal food for infants, its quality and in this case, B12 sufficiency, depends on the adequacy of animal-sourced foods in their diets (Williams et al., 2016).

The concentration of essential micronutrients in plant-based foods is also limited. For example, 2,400 g of spinach contains no more iron than 625 g of beef or 300 g of liver (Gupta 2016). This difference, combined with the greater bioavailability of iron in animal-sourced foods, implies that spinach would be the least favored source of supplying iron to young infants who need dense bioavailable nutrient sources because of the small size of their stomachs. Hence, plant-based foods have limited capacity to fully meet the nutritional needs of infants.

The most deficient micronutrients in human diets globally, iodine, vitamin A, iron, and zinc, are all present in animal-sourced foods. In addition, animal-sourced foods contain greater quantities of high-quality protein, due to their balanced or complete amino acid profile, compared with plant foods. Consequently, animal-sourced foods are ideal for stimulating muscle development and linear growth as well as enhancing cognitive development. These factors outline the vital importance of using animal-sourced foods to prevent or alleviate nutrient deficiencies.

**The Role of Animal-Sourced Foods in Brain Development**

There is limited understanding of the specific mechanisms by which animal-sourced foods contribute to improved cognitive development. Studies indicate that bioavailable nutrients in animal-sourced foods such as iron, zinc, iodine, and B vitamins (B12, B6, folate, and riboflavin) enhance cognitive development through their impact on structural brain development via enhancement of myelination, dendritic arborization, and synaptic connectivity (Lövblad et al., 1997). Studies that model brain development using neonatal pigs indicated that early life iron deficiency impairs brain development (Antonides et al., 2015).

Vitamin B12 increases iron and zinc absorption from fiber- and phytate-rich plant staples, contributing to their role in promoting cognitive development (Fairbanks, 1994). Choline and lecithin, found in eggs, are substrates for the synthesis of the neurotransmitter acetylcholine, a chemical known to improve memory (Hasselmo 2006). Animal-sourced foods also contain polyunsaturated fatty acids, such as arachidonic acid and docosahexanoic acid, which together account for about one-fifth of the brain’s dry weight. These fatty acids, along with eicosapentanoic acid, are essential for brain development and function (Bentsen 2017). The accumulation of these fatty acids in the brain is most intense during the third trimester of pregnancy. During the first 2 yr after birth, polyunsaturated fatty acid-dependent processes are involved in expansion of glial cells, neurons, axons, and dendrites and myelination of nerve fibers (Hadley et al., 2016). Furthermore, the high-quality proteins found in animal-sourced foods facilitate specific mechanisms, such as speed of information processing, that are involved in learning tasks such as problem-solving capacity (Neumann et al., 2007). Nevertheless, more research is needed to better understand the biochemical pathways by which consumption of animal-sourced foods positively contributes to cognitive development.

Animal-sourced foods are the best food-based strategy to prevent stunting and promote cognitive development (Figure 1). Alternatives to animal-sourced food-based provision of the missing nutrients include fortification, biofortification, or supplementation. Fortification and biofortification approaches are important and useful but tend to supply only one of several missing nutrients. Supplementation with missing nutrients is simply not feasible where needed most, such as in the rural areas of low- and middle-income countries due to their unavailability. Supplements would also be prohibitively expensive for the poor. Supplements and fortificants provided as part of research or development interventions do not offer sustainable solutions to these problems in low- and middle-income countries, as these are usually discontinued when donor or government funding ends.

Despite research evidence showing the importance of animal-sourced foods in children’s mental and physical development, diets in poor countries are dominated by starchy grains and legumes that provide an inadequate supply of bioavailable essential micronutrients. Animal-sourced foods constitute only

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Figure 1. Nepali school children give the thumbs up sign after learning about livestock disease prevention. Photo credit, Renu Shakya.
about 5% of the diet in sub-Saharan Africa, compared with about 20% in the United States (Allen 2006). Economic, socio-cultural, religious, and other reasons contribute to this lack of consumption. Research results, which clearly demonstrate the role of animal-sourced foods in children’s cognitive development and improvement in adult economic productivity, have unfortunately not been articulated, publicized, and disseminated sufficiently to influence policy and action in agriculture and nutrition (Martorell 2017). Consequently, even when production of animal-sourced food is increased, consumption by children is often not guaranteed due to ignorance about the benefits, cultural taboos against consumption of animal-sourced foods, and their high cost (Mohammed and Aboud 2019).

**Association of Consumption of Animal-Sourced Foods With Cognitive Development or Mental Health: The Evidence**

In this paper, via a review of existing evidence from eight intervention and 10 observational studies with data from 61,066 adults and 26,299 children (age range: 1–16 yr), across 11 countries, we substantiate the important role of animal-sourced foods in ensuring proper cognitive development of children, and the attendant implications.

Studies that evaluated the effect of inclusion of, or supplementation with, animal-sourced foods with a common or vegetarian-dominated diet on cognition and those that evaluated the association between animal-sourced food diets and cognitive development were included. Studies that did not specifically mention or examine the role of inclusion or supplementation with animal-sourced foods or that examined associations with factors excluding cognitive development were excluded. Databases examined included Google scholar and Science Web. Search terms included various combinations of animal-sourced foods, meat, milk, or eggs with cognition, cognitive development, intelligence quotient, school achievement, or exam scores. The total number of initial references retrieved was 30, of which, 18 were considered pertinent after closer review.

Before discussing the data, it is important to note that there are only a few randomized controlled interventional studies on the impact of animal-sourced foods on cognitive development, perhaps because of the logistical and ethical challenges associated with controlling what human subjects—especially children—consume. Consequently, most of the early evidence comes from animal studies. Available evidence from humans is mostly from cross-sectional or retrospective observational studies that attempt to relate cognitive functions to consumption patterns of animal-sourced food. Such studies are important in terms of developing a hypothesis of association but cannot definitively confirm associations between consumption of animal-sourced foods and cognition, as such studies fail to control for other confounding variables that might influence cognitive development. Over a hundred unique factors have been identified to influence cognitive development in children (Ruiz et al., 2016). Therefore, controlled interventional studies that try to accommodate for other confounding factors such as genetic, environmental, and social factors, are the best for generating robust evidence of association. When observational studies are undertaken, it is almost practically impossible to avoid all other confounding variables that influence cognitive development in children.

Despite the methodological limitations, the few observational and interventional studies that examined the association between consumption of animal-sourced foods and cognitive development identified a clear pattern of positive association. Moreover, many neurological studies involving physical examination and modeling of the human brain suggest the importance of animal-sourced foods or at least the micronutrients that animal-sourced foods supply readily and abundantly on brain development in infants and children.

In this review, studies spanned 12 countries and various age groups, with children dominating the interventional studies and adults in the observational studies. Results consistently show positive associations between consumption of animal-sourced foods and cognitive development. Sources of this evidence are summarized in Figure 2.

**Consumption of Animal-Sourced Foods and Cognitive Development**

Malnourished children usually exhibit compromised reasoning, perpetual reduced spatial functioning, poorer school grades, reduced attentiveness, and unresponsive play behavior compared with their well-nourished peers (McLean et al., 2007). A landmark study in Kenya assessed the impact of animal-sourced food supplementation in the diets of school-aged children through a feeding program comparing the impact of supplementation with meat, milk, or energy-equivalent (oil) in the school-based meals of children. This study found that animal-sourced food supplementation (Figure 3) increased exam scores by 45 (meat) and 28 (milk) when averaged across all subjects and school semesters and improved leadership skills and overall behavior of children (Hulett et al., 2014). In the same study, meat supplementation also resulted in improved performance in arithmetic tests, and initiative in leadership (Neumann et al., 2003). Furthermore, recent work demonstrates that consumption of animal-sourced foods by infants and pregnant women is positively associated with better child language, motor, personal, and social skills (Prado et al., 2016).

The various studies we reviewed indicate that supplementation with animal-sourced foods or animal-sourced food-dominated diet patterns increased cognitive functions (test and exam scores) by up to 20 fold and fluid intelligence and verbal skills by up to two-fold (Figures 4 and 5). For instance, children fed vegetarian diets had delays in gross motor development and in speech and language development compared with those fed omnivore diets (Louwman et al., 2000). In another study with elementary school students in Kenya, supplementation with meat resulted in significant improvement in cognitive ability among 555 school children (Black 2003). Supplementation with 8.8 g milk protein per day increased the percentage of correct pattern recognition memory by 5.5% by children when...
compared with those supplemented with 4.4-g milk protein in a rice-based diet in Ghana (Lee et al., 2018). In a longitudinal study on rural children in Nepal, 43% of the variation in head circumference (an indicator of brain development and cognitive function) was explained by weight for age scores and consumption of animal-sourced foods, with those consuming more animal-sourced foods having greater head circumference scores (Miller et al., 2016).

**Does Timing of Consumption of Animal-Sourced Foods Matter?**

Some evidence suggests that the negative effects of malnutrition at certain stages of growth may be irreversible (Levitsky and Strupp 1995) and that the first 1,000 d of life is a critically important window of opportunity for preventing the lifetime consequences of malnutrition. Methodologic constraints make this difficult to directly address. However, only a few studies have examined the impact of consumption of animal-sourced foods in early life on long-term outcomes. For example, improving consumption of animal-sourced foods among children and pregnant women was associated with improved cognitive functions and development in children even later in life (Prado et al., 2016). In the United Kingdom, children whose diets contained meat from 6 to 24 mo were associated with greater intelligence quotient scores at age 8 yr compared with those whose diets contained less meat (Smithers et al., 2012). In a study of more than 20,000 Chinese older adults, limited consumption of meat in childhood (ascertained retrospectively), regardless of animal-source food consumption as adults, was associated with poorer performance on the 10-word recall test (which examines new learning ability and screens for mild cognitive impairment; Heys et al., 2010). There is evidence that the effects of animal-sourced foods on cognitive development may be more pronounced in the long term than in the short term (Hoang et al., 2019). Supplementation with animal-sourced foods in childhood among Guatemalan subjects was associated with improved grade and economic achievement later in life (Maluccio et al., 2009). Cognitive impairment in stunted adults was twice than that of children, implying that the effect of consumption of

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Figure 2. Summary of reviewed evidence of the relationship between consumption of animal-sourced foods and cognitive development.

Figure 3. Effect of meat and milk supplementation to a githiri (corn and beans) diet consumed by school children in Kenya on changes in their examination scores averaged across all school subjects and five school terms (Adapted from Hulett et al., 2014).
animal-sourced food on cognitive development may be underestimated in the few existing studies (Hoang et al., 2019).

**Conclusions and Future Perspectives**

Studies on the relationship between consumption of animal-sourced food by children, and pregnant and lactating women mostly show improved cognitive development in children and even later in life. This is because animal-sourced food provide the best supply of bioavailable nutrients that are responsible for mental and cognitive development versus vegetarian or starch-based foods. Therefore, for proper cognitive development in children and all the consequent benefits for individuals and communities, children, and pregnant and lactating women, particularly those in low- and middle-income countries, should be provided with proper access to affordable animal-sourced foods.

Although mostly consistent, the evidence on the positive association of animal-sourced food consumption and cognitive development requires further validation. Notably, a few studies, sometimes with mitigating circumstances, found no association or even a negative association between animal-sourced food consumption and certain measures of cognitive development. For instance, soy protein supplementation resulted in greater improvement in nonverbal cognitive (fluid intelligence) in HIV-infected children compared with beef supplementation (Khee Loo et al., 2017). Such discrepancies can be attributed to experimental or other confounding factors, as cognition has been clearly demonstrated to be a result of interaction of a complex set of factors. The relationship between micronutrient deficiency and cognitive and behavioral functions is embedded in a host of other biological and psychosocial risk factors, making consumption of animal-sourced food a necessary, but

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**Figure 4.** Comparison of test scores and verbal intelligence between subjects supplemented with animal-sourced foods or have animal-sourced foods-dominated diet patterns and subjects supplemented or with diet patterns dominated by other foods. Results are from four studies; 1: (Hulett et al., 2014), 2 and 3: (Neumann et al, 2007), 5: (Mohammed & Aboud, 2019). Nine measures of cognitive development summarized include 1: Combined test scores (Arithmetic, English, Kiembu, Kiswahili, Geography, Sciences and Art); 2: End-of-term arithmetic scores (Raven's progressive Matrices test); 3: End-of-term total test scores over time (Raven's Progressive Matrices test); 4: Adjusted mean scores in mathematics and English.

**Figure 5.** Comparison of fluid intelligence and motor skills measures between subjects supplemented with animal-sourced foods or have animal-sourced foods-dominated diet patterns and subjects supplemented or with diet patterns dominated by other foods. Results are from five studies: 1: (Petrova et al., 2018), 2 and 3: (Heys et al., 2010), 4: (Khee Loo et al., 2017), 5: (Smithers et al., 2012). Five measures of fluid intelligence summarized include 1: Symbol/animal search; 2: 10 word-word recall; 3: 10 word-word recall (adjusted for age, sex and education); 4: Fluid intelligence (Ravens progressive matrices); 5: Intelligence Quotient (IQ).
insufficient, condition for producing cognitive benefits (Ruiz et al., 2016).

The biochemical mechanism by which denser proteins from animal-sourced foods improves cognitive facilities and brain function is not clear, and many studies on the required level of micronutrient supplementation have been inconclusive (Black 2003). Furthermore, there is no empirical evidence on the relative role of different animal-sourced foods such as milk, meat, and eggs on cognitive development and mental health (Neumann et al., 2003), or the optimal daily intakes for different age groups. This information is critical but challenging to acquire because animal-sourced foods improve cognitive function in different ways, making it difficult to establish guidelines (Neumann et al., 2007).

Questions also remain on the relationship between the timing of consumption of animal-sourced foods and long-term impacts on cognition, social development, and depressive symptoms, as most of the evidence is generated from short-term studies. The best way to conclusively establish the required relationships and thereby inform the development of proper dietary guidelines would be through controlled interventional and longitudinal studies that account for confounding and interactive factors. Many more of such studies are urgently needed.
The consistency of evidence on the role of animal-sourced foods on the cognitive development and lifelong achievement of individuals should have important implications on how animal-sourced foods are produced and consumed. Yet, studies on improving human nutrition, so far, have involved little or no discourse with the livestock production sector. Promotion of animal production does not always improve consumption of animal-sourced foods, as many complex factors including high prices, food safety, increased work burden on women, cultural and religious barriers limit the consumption of animal-sourced foods. Strategies and approaches should, therefore, focus on most direct ways for putting affordable animal-sourced foods on the tables of vulnerable families and communities such as smallholder farmers, pastoralists, women headed households, and pregnant and nursing women in low- and middle-income countries (Neumann et al., 2003). Smallholder producers should be supported to improve livestock productivity and efficiency in order to lower production costs and make animal-sourced foods more affordable by the poor. Efforts should also be directed at increasing accessibility to and hygienic preservation of animal-sourced foods for the poor as well as raising awareness about the importance of consumption of animal-sourced foods. The latter should involve highly regarded influencers such as religious leaders, celebrities, or village leaders to overcome cultural, religious, and market limitations. Extension services should specifically focus on educating women, as they are mostly directly involved in preparation, preservation, and serving of food (Neumann et al., 2007). Planned and tailored social marketing campaigns and strategic messaging tools should be employed to increase the consumption of animal-sourced foods. Pro-poor marketing and packaging that increase the availability of animal-sourced foods at the poor’s table such as, for example, selling smaller cuts of meat at lower cost would be preferable.

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American Meat Science Association News

The American Meat Science Association (AMSA) fosters community and professional development among individuals who create and apply science to efficiently provide safe and high quality meat.

AMSA Names Industry Veteran, Collette Kaster as the New AMSA CEO

AMSA announced the appointment of Collette Schultz Kaster as its new Chief Executive Officer on June 6, 2019. Kaster brings more than 25 years of technical experience in areas of food safety, quality assurance, and animal welfare and executive roles managing teams across livestock industry companies and organizations. Most recently, she has served as the Executive Director of the Professional Animal Auditor Certification Organization (PAACO).

“Collette is the right leader at the right time for AMSA and its future. She has extensive industry knowledge combined with her formidable experience managing successful teams and businesses. She understands our organization and has a vision to meet member needs in this growing association and provide content and context for the science and information demands of an expanding world,” stated Dr. Eric Berg, AMSA President.

Kaster is trained as a meat scientist, with degrees from South Dakota State University and the University of Nebraska. She has been a member of AMSA for 28 years and is a past President and holds the rank of AMSA Fellow. In addition to her new role with AMSA, Kaster will continue to lead PAACO as its Executive Director. To enable this dual role, PAACO has developed several highly experienced Training Specialists to meet the growing needs for animal auditor training, certification, and audit certification across all sectors of the livestock industry. Kaster began as the CEO for AMSA on July 1.

2019 Calendar of Events:

October 13 - American Royal Meat Judging Contest - Omaha, Nebraska

October 15 – National 4H Meat Judging and Identification Contest - Manhattan, Kansas

October 21–23- PORK 101 - Iowa State University - Ames, Iowa

October 27 - Cargill High Plains Meat Judging Contest - Friona, Texas

November 10 - International Intercollegiate Meat Judging Contest - Dakota City, Nebraska

Reciprocal Meat Conference 2019–2020

June 23–26, 2019 - Colorado State University - Fort Collins, Colorado

August 2–7, 2020 – RMC and ICoMST - Disney Coronado Springs Resort in Lake Buena Vista, Florida, USA
2019 ASAS Meetings

Nestled between lakes Mendota and Monona, Madison is one of only two major U.S. cities built on an isthmus.

Greater Madison is an eclectic mix of cultures, from college town to capital, from single students to families large and small. We’ve got a small town feel, and big city amenities. It’s no wonder we’ve earned national notoriety for some of the people and places that contribute to what makes our city so memorable.

Besides boasting natural beauty and outdoor recreation, Madison plays host to stimulating cultural offerings, distinctive restaurants, excellent music venues and unique shopping. Ours is a true college town, and the intellectual offerings of the University of Wisconsin-Madison and surrounding schools attract scholars from around the world.

The American Society of Animal Science fosters the discovery, sharing and application of scientific knowledge for the responsible use of animals to enhance human life and well-being.

2019 ASAS Meetings
Northeast Section Meeting • November 4 • Hershey, PA

ASAS Publications

*The Journal of Animal Science*, an official journal of the American Society of Animal Science, publishes research on animal production and genetics, nutrition, physiology and the utilization of animal products.

*Translational Animal Science*, an official journal of the American Society of Animal Science, encompasses a broad scope of research topics in animal science, focusing on translating basic science to innovation.

*Animal Frontiers*, an official journal of the American Society of Animal Science, publishes discussion and position papers that present several international perspectives on the status of a high-impact, global issues in animal agriculture.

*Junior Animal Scientist*, an official magazine of the American Society of Animal Science, offers elementary or middle school students a way to learn the real science behind pets, zoo animals and farm animals. A membership is offered and encompasses both the magazine and access to a special part of AnimalSmart.org. Sign your Junior Animal Scientist up today!

To access articles and learn more about ASAS Publications, visit asas.org.

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News from the Canadian Society of Animal Science

The 2018 joint annual meeting of the American and Canadian Societies of Animal Science took place in Austin, Texas in July this year. Canadians were well-represented with two Symposia featuring Canadian content, graduate student competitions, and participation of many scientists. We extend our gratitude to all our sponsors, in particular generous support from Canadian Science Publishing, Diamond V, Trouw Nutrition, Masterfeeds LLP, Dairy Farmers of Canada, and the Canadian Pork Council.

Our 2019-2020 executive committee was also named at the Annual Meeting, and we look forwarding to serving our society in the coming year! We also warmly welcome our new Student Ambassadors, Michaela Lièvre, University of Guelph and Cameron Olsen, University of Alberta, who will represent the students of Eastern and Western Canada, respectively, on our Executive board.

Graduate Student Awards at the 2019 Annual Meeting in Austin

The annual meeting provides an opportunity to recognize excellent science being done in Canada. Both students and professionals were recognized for their achievements with a number of CSAS Awards presented at the 2019 CSAS Awards Banquet. Student awards are sponsored by Canadian Science Publishing.

Graduate Student Travel Fellowship Winners:
- Qianru Hui, University of Manitoba; Cameron Olsen, University of Alberta; Kuechun Bai, University of Alberta; James Templeman, University of Guelph; Janghan Choi, University of Manitoba; Prince Opoku, University of Alberta; Stéphanie Bélanger-Naud, McGill University; Esther Ijiwad, University of Alberta

Graduate Student Poster Competition Winners:
- 1st: Ryley Vanderhout, University of Guelph;
- 2nd: Anouk Caron, Université Laval;
- 3rd: Paul Tamayao, University of Manitoba

MSc Oral Presentation Award Winners:
- 1st: Annemiek Wielborn, University of Guelph;
- 2nd: Nicole Briggs, University of Alberta;
- 3rd: Dakota Wightman – University of Saskatchewan

PhD Oral Presentation Award Winners:
- 1st: Christine Bone, University of Guelph;
- 2nd: Stephanie Terry, AAFC Lethbridge / University of Sydney;
- 3rd: Daniel Watanabe, University of Saskatchewan

Professional Member Awards

Canadian Society of Animal Science Fellowship:
Dr. Pierre Lacasse Agriculture and Agri-Food Canada;
Sponsored by Canadian Science Publishing

Technical Innovation in Enhancing Production of Safe and Affordable Food:
Dr. Trevor Devries University of Guelph;
Sponsored by Dairy Farmers of Canada, Canadian Pork Council, and The Canadian Society of Animal Science

Excellence in Nutrition and Meat Sciences:
Dr. Joshua Gong Agriculture and Agri-Food Canada;
Sponsored by Trouw Nutrition

Young Scientist Award:
Dr. Daniel Columbus Prairie Swine Centre;
Sponsored by the employees of Masterfeeds LLP

Join us at www.asas.org.CSAS!
EAAP is the International Federation of Animal Science for Europe and the Mediterranean. Join EAAP and become a member of the most exciting international animal science network and have access to many services that are indispensable for animal scientists worldwide. More information about the EAAP and its activities can be found at: www.eaap.org

The 71st Eaap Annual Meeting Will Be Held In Porto (Portugal) From 31st August To 4th September 2020

After 32 years, Portugal is honored to host the annual meeting of EAAP in Porto (classified as World Heritage by UNESCO in 1996). During the meeting themes such as societal challenges of animal production in a growing world, sustainability of livestock production systems, feeding the world and ensuring resource efficiency and sustainability, technology in animal production, mountain farming systems, adaptations to climate challenges, and animal product quality and safety will be discussed. The program will cover nutrition, genetics, physiology, animal health and welfare, livestock farming systems, precision livestock farming, insect production and use, cattle, horse pig, sheep and goat production.

The EAAP Annual Meeting gives an opportunity to apply new ideas of practice through many parallel sessions, a plenary meeting, poster presentations, and discussions about scientific achievements in livestock production all around the world. It is a privileged discussion forum where the research community meets with the industry, to discuss and plan for how to address the multiple challenges that animal science sector has to cope with in the upcoming years.

All these activities make the EAAP one of the largest animal science congresses in the world.

More than 1,500 participants from more than 50 countries are expected to attend. An excellent social program will also be organized, including the welcome ceremony, an unforgettable Portuguese night, a gala dinner, technical tours, and a program for accompanying persons. The lead organizer is the Portuguese Association of Animal Science (APEZ), with the patronage of the Ministry of Agriculture, Rural Development and Fisheries from the Portuguese Government.

Agriculture in Portugal is based on small to medium-sized family-owned dispersed units

Small scale animal production in Portugal is widely related to the local breeds. Portugal has a total of 22 registered local animal breeds, most of them ancient breeds and a genetic heritage of great importance.

Conference Information:
http://www.eaap2020.org
Conference local organizers eaap2020@skyros-congressos.com
Please follow us on Facebook and Twitter
https://www.facebook.com/EAAP.ORG
https://twitter.com/eaapofficial

INDIVIDUAL MEMBERSHIP OF EAAP

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