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Chapter 6

Managing Dietary Energy Intake by Broiler Chickens to Reduce Production Costs and Improve Product Quality

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Abstract

Feeding constitutes the highest variable cost in poultry production, accounting for at least 60% of such costs, especially in an intensive rearing system. Energy intake is an essential factor in broiler production because of its involvement in growth rate, carcass quality as well as its role in the development of certain metabolic diseases. Dietary energy is supplied in broiler nutrition through different feed resources. Dietary energy content strongly regulates feed consumption, and energy is the most expensive item in poultry diets. At the same time, excess energy intake may result in an increased fat deposition, which affects meat quality and consumer health. This chapter explores the implication of imbalance in energy intake, possible nutritional strategies to restrict energy intake without reducing performance and hence improving meat quality.

Keywords: broiler chickens, energy intake, health, meat quality, nutrition production cost

1. Introduction

One of the objectives of any poultry producer is to feed the chickens with balanced diet at least cost and also generate products that will attract premium prices in order to maximise profit. For many decades, farmers and feed manufacturers have been facing the challenge of effectively reducing the cost of poultry production and produce quality products. Several factors such as genotype, diet composition, digestible nutrient content, energy to protein ratio, feed form, feed processing, environment, and disease could affect the cost of production and

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poultry product quality through influencing feed intake, body weight gain and feed conversion ratio (FCR). Dietary management of energy intake has been reported to decrease the cost of production and improve product quality to a greater extent than the abovementioned factors [1]. However, most energy feed ingredients that will help in achieving improved performance, health, reduced production costs and improved product quality in poultry production are continuously becoming scarce and expensive for use in broiler production due to the stiff competition for available energy sources used by industries for biofuel and as food for humans. Feeds that provide the basic nutrients which help to achieve quality broiler carcass yield accounts for over 70% of the overall cost of poultry production, with energy sources being the largest in terms of quantity (40–70%) and invariably the most expensive [2–4].

The continuous increase in the cost of poultry feed ingredients (especially energy sources) has forced some farmers as well as feed manufacturers to use poor quality energy feed ingredients. This practice has resulted to poor feed intake, weight gain, FCR and meat quality [5]. The importance of dietary energy in poultry feeding cannot be over-emphasised because increasing or decreasing the dietary energy has been reported to affect feed intake in addition to promoting or undermining efficient feed utilisation and growth rate [6–9]. Singh and Panda [10] concluded that birds usually eat with the aim of satisfying their energy requirement, and once this aim is achieved, the birds will stop eating irrespective of the fact that other key nutrient requirements such as protein, minerals, and vitamins have not been met. This scenario tends to lead to malnutrition, poor performance, increased deposition of excess abdominal fat or carcass fat in broilers [9, 11], and this fat deposit is usually considered to be waste product when birds are processed. High fat deposition is regarded as an economic loss for poultry producers. Furthermore, energy intake is considered a fundamental factor in broiler production because it not only affects growth rate and carcass characteristics but also causes some metabolic diseases such as ascites and fatty liver syndrome in broiler chickens [12, 13].

Therefore, appropriate focus is usually placed on the inclusion levels of various dietary energy sources when formulating diets for broiler chickens since an increase or decrease of dietary energy could play a key factor in determining not just cost but also the final product quality [7–9]. The nutrient density in the diet should be adjusted to enable appropriate nutrient intake based on requirements and the actual feed intake. Based on these facts, several poultry researchers and nutritionists have over the years directed their research toward finding various strategies aimed at managing dietary energy intake in poultry birds in order to cut down on the cost of production and also improve the quality of poultry products. Results obtained so far have been conflicting, with some authors concluding that dietary energy content could be managed to influence broiler performance and carcass quality [8, 9, 14, 15]. Other authors report that changing the dietary energy content has no effect on broiler performance and carcass quality [16]. Kim et al. [17] reported different responses to energy concentration with different strains of broiler chickens. The management of dietary energy intake in broiler chicken production aimed at reducing production costs and improve the product quality of broiler birds has been practiced for many decades with varying outcomes. Research geared towards achieving both a reduction in the cost of production and improvement of quality broiler products has also been inconsistent so far. The variability when dietary energy strategies are applied could be due to various factors such as genotype, diet composition, digestible nutrient content, energy to protein ratio, feed form and feed processing, environment and disease. Suitable mechanisms to keep these sources of variation constant when dietary energy management is applied are worth considering. This chapter seeks to review the shortfall and progress that have been achieved in research into the management of energy content to reduce feed costs, sustain productivity and improve product quality. The nutritive value of energy sources for poultry, recent advances in understanding energy requirements of poultry, cost implications of energy sources, regulation of dietary energy and feed intake in poultry nutrition will also be discussed. The effect/implication of imbalance in energy intake on poultry (growth, fat deposition, potential disease disposition, meat quality), nutritional strategies to restrict energy intake and various implications/benefits of restricted energy intake in poultry production.

2. Dietary energy sources for poultry

Energy and protein are the second most important feed constituents after water and are needed to maintain health, growth, and production. This explains why energy and protein sources are the most important feed ingredients for poultry feeding. Oilseed cakes and animal protein meals are considered as secondary sources due to their substantial energy content [18]. Cereal grains provide 60–70% of dietary energy for poultry, while other energy and protein sources supply the rest. Although the interaction of protein sources with the main energy sources influences the overall energy supply and utilisation, it is important to determine precisely the energy values of diets containing vegetable sources, whether for least-cost formulation purposes or for adapting feed supply to energy requirements of animals [19]. Some data on global production of energy sources are shown in **Table 1**.

2.1. Cereals grains energy feed ingredients

Cereals are the grain-producing plants, which can be used as energy sources in animal and human food. These form the largest part of the energy source in poultry diets and consist of the highest inclusion level in a standard poultry diet. Corn, wheat, sorghum, barley, rye, oats, triticale and millet [34–38] represent the main cereal grains used as energy sources in broiler diets. Cereal grains are cultivated in large quantities and provide more starch worldwide in comparison with other types of crops. Recently, grain by-products such as distiller's dried grains with soluble (DDGS) have been used in poultry feeding. Starch constitutes the basis of energy in grains, which is highly digestible especially for poultry. The metabolisable energy content of frequently used grains for poultry ranges from 2734 kcal/kg in rye to 3300 kcal/kg in corn. The nutritional profiles of ground cereal grains vary according to type, location, season, cultivation, harvesting and handling conditions. Although they contain highly digestible starch, most of the grains contain anti-nutrients, which negatively affect the digestion, absorption, and availability of nutrients [39, 40].

Ingredient	Global production (m tonnes)	Top producers	References
Cereal grains			
Corn	1031.6	USA, China, Brazil, European Union, Argentina.	[20]
Wheat	2627	China, India, Russia, USA, France.	[21, 22]
Sorghum	59.34	USA, Nigeria, Mexico, India, Sudan	[23]
Barley	137.47	European Union, Russia, Australia, Canada, Ukraine.	[24]
Oat	23.3	European Union, Russia, Canada, Poland, Finland	[24]
Rye	12.6	European Union, Russia, Belarus, Ukraine, Turkey.	[24]
Triticale	5.2	Poland, Germany, Belarus, France, Russia.	[25]
Millet	29.9	India, Nigeria, Niger, China, Mali.	[26]
Root and tuber energy sources			
Cassava	27.0	Nigeria, Thailand, Indonesia, Brazil, Vietnam	[27]
Potato	393.75	China, India, Russia, Ukraine, USA.	[28]
Plant protein energy sources			
Soybean meal	345.9	USA, Brazil, Argentina, China, India	[29, 30]
Sunflower meal	45.6	Ukraine, Russia, European Union, Argentina, Turkey.	[31]
Cotton seed meal	13.9	India, China, Pakistan, Brazil, USA.	[32, 33]

Table 1. Global production and major producers of different energy feed sources (2017).

2.1.1. Corn

Corn, also called maize, was first grown in America by the American-Indians. According to the physical appearance of the kernel, there are seven types of corn worldwide, including flint, flour, dent, pop, sweet, waxy and pod. Nowadays, most of the grown corn is the hybrid, produced by crossing inbred lines through several generations. As a plant, corn is efficient at converting great amounts of sunlight into constant forms of energy and stored as starch, cellulose, and oil. The corn bushel approximately consists of 65.6% starch, 26% gluten feed, 5.2% gluten meal and 3.2% corn oil. Corn is the principal cereal grain for poultry feeds around the world, especially in the United States [41]. Due to its good energy content (3300 kcal/kg of energy for poultry), high starch digestibility and low fibre, it is extremely palatable and almost free from anti-nutritional factors (ANF). Corn is considered as the standard by which alternative grains are evaluated.

2.1.2. Wheat

China, India, the USA, the Russian Federation, France, Pakistan, Germany, Canada, and Turkey represent the main wheat producing countries. Generally, wheat is grown for human

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consumption. Wheat inclusion in animal feeds depends on seasonal production, price fluctuation during harvesting and the relative market prices of the other energy sources. Wheat is the premier source of energy for poultry diets in Canada, parts of Europe, Australia, and New Zealand [42]. Wheat has high starch content (about 70% DM), providing around 3153 kcal/kg energy for poultry. In addition to its high nutrient digestibility, rolled wheat is very palatable; therefore, it is considered an efficient energy source for all classes of poultry. Wheat has been classified into hard and soft varieties, depending on gluten content. Soft varieties are commonly used as main ingredients in poultry feeds [43].

2.1.3. Barley

Barley is one of the popular cereal grains. It is cultivated in more than 100 countries, almost across all continents. The USA, Canada, Australia, Russia, UK, France, Germany, Ukraine, Spain and Turkey produce around three-quarters of the total world production. This important seasonal plant is ranked fourth after maize, rice and wheat [42]. Barley provides around 2795 kcal/kg energy for poultry, with a low starch content, relatively high fibre content and some ANFs [44]. The lower metabolisable energy (ME) value limits the inclusion of barley in high-energy poultry diet formulation, and it is not included at high rates, particularly in diets for young birds [45].

2.1.4. Sorghum

Sorghum is mainly grown in warmer climates, especially in Africa, Asia and Central America. Kafir, Milo, Feterita, Durra and Hegari are the common African and Mediterranean varieties of sorghum, while Sballu, and Kaoliang are Asian types. United States varieties were originally produced from crossing Kafir and Milo. In addition, sorghum is classified according to the tannin content to high- and low-tannin types. Tannins are ANFs, which reduce the availability of protein during digestion [46]. The content of tannin in sorghum limits its use in poultry diets, although tannin-free varieties are available now but in inadequate amounts. Sorghum is considered the major source of energy for poultry feeds in some Asian and most African countries, due to its high energy content (3263 kcal/kg). Using rolled sorghum is a common practice in poultry feed formulation, although sometimes whole grain feeding is well known in rural areas [47].

2.1.5. Rye

Rye is originally a south-west Asian plant, but now it is growing in all Asia, Europe, Africa and North America (especially Canada). Rye contains high starch content (around 62%), with an energy content of about 2734 kcal/kg energy for poultry and has a low fibre content. Despite the rich nutrient profile, rye is not competitive as a source of energy for poultry because of the presence of ergotism, resorcinols and large amounts of soluble arabinoxylans, which decrease the nutrient bioavailability for birds, leading to a depression in growth and productivity. On the other hand, this composition makes it a good source of low-fibre energy diets. Rye is considered less palatable than other cereal grains [48].

2.1.6. Oats

Oats are one of the cool and high moisture area plants, also they can grow at high altitude of tropical areas. Russia and Canada are considered the main producers of oats followed by Poland and Australia, respectively. Undehulled oats are low in starch (around 40%), offering about 2756 kcal/kg energy for poultry, while the dehulled oats contain around 60% starch. The presence of ANF such as β-glucans and high fibre contents are the common constraints to the use of oats in poultry diets. In addition, the high oil content of oats can lead to development of off flavour in chicken meat. Inclusion of oats in low amounts is suitable for pullets and breeders [49].

2.1.7. Triticale

Triticale is the result of crossbreeding between wheat (mainly durum type) and rye, so it is a hybrid grain produced in German and Scottish laboratories in the nineteenth century. This crossing process introduced a new cereal grain species with wide adaptability, environmental tolerance, and improved nutritional value, to be grown in areas not proper for maize, rye and wheat around the world [50]. The currently developed varieties of triticale contain on average, 110 kcal/kg energy for poultry, with low fibre content; therefore, it has been included at rates up to 30% in broiler diets, and at slightly lower levels in layers diets. Furthermore, unlike the other cereal grains, different varieties of triticale almost similar in their energy content, which maintains consistent poultry performance [51].

2.2. Root and tubers

Starchy root and tuber crops are second only in importance to cereals [52]. Most of these roots and tubers are high in metabolisable energy, but their usage as poultry feed ingredients is limited because of the presence of anti-nutritional factors. However, these anti-nutrients are reduced or eliminated through adequate processing methods. Examples of these crops include cassava, cocoyam and potato [53–56].

2.3. Fats and oils

Fats and oils are collectively known as lipids. They provide significant amounts of energy to poultry diets, but there is a large variation in composition, quality, feeding value, and price. These notwithstanding, they are regularly used in poultry feeds to satisfy the energy need of the animal as lipids have more than twice the amount of ME than carbohydrates or proteins per kg weight. However, they are normally included at a maximum level of 4–5%. The commonly used types of fat in poultry diets include tallow, poultry fat, feed-grade animal fat and yellow grease. Animal fats provide an average ME of 8850 kcal/kg for poultry. Similarly, oils have a high content of energy, the average ME content of different types of vegetable oils ranging between 8300 and 8975 kcal/kg. The commonly used oils in broiler diets are soybean oil, canola oil, and palm oil. Besides the concentrated energy, including fats and oils in poultry diets improves the physical traits and palatability of diet, increases pellet durability and enhances the essential fatty acid contents of the diets, especially linoleic acid [57–59].

2.4. Energy from protein sources

While cereal grains provide 60–70% of dietary energy for poultry, protein sources also supply a considerable amount of energy. There are plant and animal protein sources. On their own, proteins are denser in energy than carbohydrates although they are not used as energy sources due to cost and physiological burden of excreting them from the body.

2.4.1. Plant protein sources

Although the energy value of various plant protein sources is not as high as the cereal or root and tuber energy ingredient source, they have a considerable amount of energy that helps in furnishing the required energy needed for optimum poultry performance and cost reduction. Examples include soybean meal, canola meal, cottonseed meal, sunflower meal, peas and lupin [36–38]. Geographical location of production, the season of production, method of cultivation, genetic and environmental impacts, as well as processing method and the amount of remaining oil are the main causes of differences in energy content between different vegetable protein sources.

2.4.2. Animal protein sources

Although they are major sources of protein, they also contain considerable amounts of energy. Examples include meat meal, fish meal, blood meal, feather meal and poultry by-product [36–38]. The differences in the energy content of animal protein sources may be attributed to animal species, part of the body, and processing methods. Soybean, canola, cottonseed and sunflower seed contain an average of 2557, 2000, 2350, 2205 kcal/kg ME for poultry, while meat and bone, meat, fish, poultry by-product contain around 2475, 2500, 2720, 2950 kcal/kg for poultry, respectively [60].

3. Nutritive value of energy sources in poultry

Feed formulation involves a prudent usage of various (available) feed ingredients to supply sufficient amount and proportions of several nutrients required by poultry. Poultry feed is made up of many ingredients, and these ingredients are grouped into those that provide energy (fats, oils, and carbohydrates), protein (amino acids), vitamins, and minerals. Among the feed nutrients, dietary energy is one of the most important because it influences the utilisation of other nutrients through its ability to regulate feed intake to a high degree. Formulating poultry diets should be done with the aim of achieving optimum energy level based on the composition of the feed ingredient to lower feed cost per unit of poultry product and produce quality end-products. In animal feeds, energy supply represents a major part of the cost of the formula. Since feed ingredients that supply energy in a standard broiler diet are in the highest amount (40–70%) in terms of inclusion level [2–4, 61], it is important to improve the knowledge of energy utilisation and energy requirement by the animal to better meet its energy needs. Therefore, having systems in place to evaluate the energy content of raw materials

Ingredients	Metabolisable energy (kcal/kg)	References
Cereal grains		
Corn	3300–3319	[34–38]
Wheat	3153–3430	[34, 37, 38]
Sorghum	3263–3550	[34–38]
Barley	2734–2760	[36–38]
Oat grain	2550–2756	[36–38]
Rye	2710–2734	[36, 38]
Triticale	3110–3150	[36–38]
Millet	3240	[36, 37]
Roots and tubers		
Cassava	3000–3279	[63, 64]
Cocoyam	3476	[55, 56]
Potato	2370–3190	[25, 26]
Plant proteins		
Soybean meal	2557	[36, 38]
Canola meal	2000–2186	[36–38, 65]
Sunflower meal	2205–2310	[36–38]
Cotton seed meal	2350–2640	[36–38]
Peas	2550	[38]
Lupine	3000	[36, 38]
Animal proteins		
Meat meal	2500–2685	[37, 38]
Blood meal	2690–3220	[36–38]
Fish meal	2600–2970	[37, 38]
Feather meal	2880–3016	[37, 38]
Poultry by products	2950	[38]
Fats and oils		
Animal tallow	6020–7780	[57, 59]
Lard	7200–9854	[57, 59, 66–68]
Soybean oil	8800–9659	[57, 59]
Canola oil	9000–9260	[57, 59]
Cotton seed oil	8160–8630	[57, 59]
Palm oil	5302–7810	[57, 59]
Fish oil	8270–8690	[57, 59]
Poultry fat	8020–10,212	[57, 59]
Molasses	900–1080	[36, 37]

Table 2. Metabolisable energy values of different energy sources for poultry nutrition.

and feeds is a determining factor in least-cost formulation. The energy requirement for broilers at different phases of growth and breeds are 3000 kcal ME/kg or 12.55 MJ/kg (starter); 3100 kcal ME/kg or 12.97 MJ/kg (growers) and 3200 kcal ME/kg or 13.39 MJ/kg (finisher) [62]. Since management of dietary energy could influence cost and product quality based on the inclusion levels of various feed ingredients, a summarised table showing various feed ingredients that supply high to moderate energy to show farmers and feed manufacturers that are interested in manipulating cost and achieving improved broiler products through the use of dietary energy will not only give the targeted audience a sense of direction but also save cost. The nutrient composition of various energy feedstuffs is shown in **Table 2**. Each energy source has a different composition due to factors such as regional location, manufacturing practices and climatic conditions [37].

Adequate knowledge of broiler nutritional requirements based on breed, the energy composition of a feed ingredient, availability and cost of these ingredients is fundamental in least cost formulation and achieving improved broiler performance. Manipulating dietary energy has been reported to influence feed intake with a resultant effect on performance and carcass quality. Poultry adjust their feed intake to accommodate a wide range of diets with differing energy contents at different ages and in response to various factors, including dietary energy [69]. Therefore, appropriately analysed information on different dietary energy contents of several energy-rich feedstuffs becomes important. However, the high cost of feed analysis makes it always difficult for farmers (especially for small-scale farmers) and feed manufacturers to analyse each batch of feedstuff for its nutrient content. Invariably, they usually rely on feedstuff composition data that have been compiled based on many laboratory analyses. Therefore, it becomes imperative to present a reasonable, accurate and summarised estimate of energy contents of feed ingredient for farmers, researchers and feed manufacturers, to enable them to cut down on cost and time that would have been taken to analyse and obtain more accurate laboratory data. The energy which a bird uses for maintenance and productive functions is obtained mainly from starches (carbohydrates), lipids and protein. Energy feed ingredients could be classified into cereal grains, root and tubers, plant protein sources, animal protein sources, fats and oil, as discussed in Section 2 of this chapter. These feed ingredients provide high to moderate dietary energy. Therefore, adequate knowledge and skills are required in using these ingredients to get the best possible least-cost formulation and achieve improved product quality.

4. Cost implications of energy sources

The poultry industry relies on a limited number of energy sources, mainly cereal grains and their by-products, in addition to oils and fats, which are normally included in small proportions in poultry diets [70]. Utilising the low-cost locally available energy sources to feed poultry is a nutritionally and economically proven way to reduce the cost and product inefficiency. Annual production, availability, cost of production, prices of other sources, productivity variations and the stiff competition with humans are the main factors affecting the prices of vital cereal grains needed for poultry feeding. Scientifically, assessing cost of feed ingredients depends on its quality evaluation, which is very important to specify ingredient suitability to meet the nutrient specification of poultry to such production type. The ingredient dry matter content and metabolisable energy concentration are crucial keys to evaluate the cereal grain quality and enable real calculation of energy cost for each source. In addition, poultry performance is highly correlated to energy intake, therefore the best energy source is that which supports the best products to maximise the returns [71].

Feed manufacturers target the available energy sources with reasonable price to use, so availability, price, competition, and quality represent the main handicaps that facing processors to produce cost-efficient and high quality feeds. Globally, corn is the premier energy source, but the high demand for it by humans and animals affects its price and availability. Therefore, to solve this problem, in the most consuming countries such as US, Brazil, and some Asian countries they have started to use a major co-product – distillers' dried grains with soluble (DDGS), because of its cost-effectiveness, good nutrient profile and ready availability. Wheat has been used to replace corn in some parts of the USA, China and India due to the price difference. The expansion in poultry production in the developing countries is forcing the producers to import feed ingredients, increasing the pressure on the prices and quality of feeds. In Australia, because of the low price of sorghum it has been used instead of expensive wheat in summer, while barley and rye are used in some European countries when their prices are lower [72, 73].

The principal goals of manipulations in use of energy sources are to adjust ingredient costs, to reduce the cost of production and maintain the sustainability of the poultry industry. This can be achieved by meeting the nutrient requirements of birds and producing low-cost meat and eggs to satisfy the consumer desire. The rate of inclusion of cereal grains in poultry diets mainly depends on their current costs and nutritive values, therefore changing and replacing energy sources should not be in huge and sudden, to prevent digestive upsets and feed intake depression, which will reduce birds' productivity and production efficiency. Likewise, the price of energy sources has an impact on the cost of poultry feed and a corresponding increase in the total cost of poultry production and the cost of poultry products. This dilemma has affected the profitability of poultry production globally, reducing the interest of existing and potential poultry farmers in the business. Furthermore, this situation, coupled with the increasing demand for animal protein by humans, has caused great concern globally [74].

5. Recent advances in understanding energy requirements of poultry

Meremikwu [75] reported that one of the technical constraints to successful poultry production in the tropics is strict adherence to nutritional standards. According to Meremikwu [75], nutritional standards such as NRC [57] may over-specify diets in many low-income, resource-poor countries (particularly those in the humid tropics) because of environmental constraints. For decades, the widely accepted theory was that birds eat to constant energy intake, irrespective of the energy level of the feed. However, with advances in genetic selection over the years, this understanding has shifted drastically. The continuous improvement of poultry birds, especially broiler chickens through genetic selection, initially developed by focusing on growth and laying rate, then, by taking other physiological aspects into account has reinforced the poultry bird's potential for better feed efficiency. From a nutritional perspective, such genetic selection has led to changes in nutrient requirements of improved birds, which

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infers that feed characteristics have had to be continuously changed by feed manufacturers [76], to possibly meet the demand imposed by this development. The performance of poultry in terms of feed conversion ratio is largely dependent on ME values of feed ingredients. While Pym [77] and Fairfull and Chambers [78] once postulated that the effect of genetic selection on ME is relatively insignificant, this theory requires a second look at recent studies indicate otherwise, with growing birds fed wheat-based diets showing high heritability of ME values [79]. The assumption is that birds selected for fast growth rate should require a higher energy. However, one possibility may be that broiler genetic improvement results in the consequent loss of sensitivity to control feed intake based on dietary energy level. Richards [80] reported that feed intake is not properly regulated voluntarily in broilers selected both for faster body weight gain and deposition of muscle according to energy level, as in an *ad libitum* program where compulsive appetite and excessive fat accumulation was observed. Hence, the energy concentration of diets used for broiler selection has remained unchanged over time, suggesting that selection has accustomed broilers to a diluted diet compared to the concentration required to support their growth rate [76]. Hence, determining the energy requirements of poultry with the recent improvement may require species-specific as well as selection information to obtain optimal energy requirement for birds.

6. Regulation of dietary energy and feed intake in poultry nutrition

The amount of feed consumed by an animal determines the amount of nutrient that is available to the animal for maintenance and production functions [81]. Feed intake tends to influence body weight gain, FCR, cost and carcass quality. Based on these facts, adequate regulation of feed intake using several strategies becomes a critical action aimed towards achieving quality product and controls the cost of poultry production. Factors such as dietary factors (dietary nutrient composition, feed formulation, feedstuff inclusion levels and pellet quality) and managerial factors (feed and water availability to the birds, environmental management, stocking density and disease regulation) individually or collectively influence feed intake in poultry production [1, 81]. Among the abovementioned factors, dietary factors (dietary nutrient composition) have been reported to have a great/significant effect, with dietary energy intake having the most predictable effect on feed intake when applied on poultry [1, 82]. Feed intake has been reported to increase or decrease as dietary energy intake decreases or increases, respectively [69]. This increase or decrease in feed intake in relationship to dietary energy content is influenced by the amount of feed in the gut or other physiological limitations. Dietary energy intake has been reported to also influence growth rate and carcass quality through its effect on feed intake [83]. The ability to sense energy status and adjust metabolic pathway activity in response is a basic function of cells in all animal species [84]. Energy-sensing pathways are present in the central nervous system (CNS) and peripheral tissues of birds, and they represent another set of regulatory mechanisms that are used to modulate peripheral tissue metabolic activity as well as regulate feed intake, energy expenditure to maintain energy balance and body weight [85]. To regulate feed intake, dietary energy intake must be balanced with energy expenditure in the birds. This is monitored/controlled by the hypothalamus [86]. The hypothalamus in the brain of poultry plays an essential role in interpreting all information and generating the appropriate responses in feed intake and energy requirement needed to maintain energy homeostasis [84]. As shown in **Figure 1**, the hypothalamic melanocortin system comprises the vital feeding regulatory neural circuitry, which consists of two groups of neurons, the first group expresses neuropeptide Y (**NPY**) and agouti-related protein (**AgRP**) while the second group expresses proopiomelanocortin (**POMC**), a precursor containing α-melanocyte-stimulating hormone. Stimulation of NPY/AgRP-expressing (anabolic) neurons mediates a net increase in feed intake and energy storage, whereas activation of the POMC-expressing (catabolic) neurons results in a net decrease in energy intake and storage. Initiation of AMPK in the hypothalamus in response to lowered energy status stimulates the activity of the NPY/AgRP-expressing (anabolic) neurons and thus leads to increased feed intake and reduced energy expenditure, which work together to increase energy status. On the other hand, activation of mTOR causes increased activity of the POMC-expressing (catabolic) neurons, which in turn causes a reduction in feed intake as a result of the presence of increased energy expenditure, thereby promoting the utilisation of energy for maintenance, growth, and reproduction. Thus, balance in the activity of hypothalamic melanocortin system

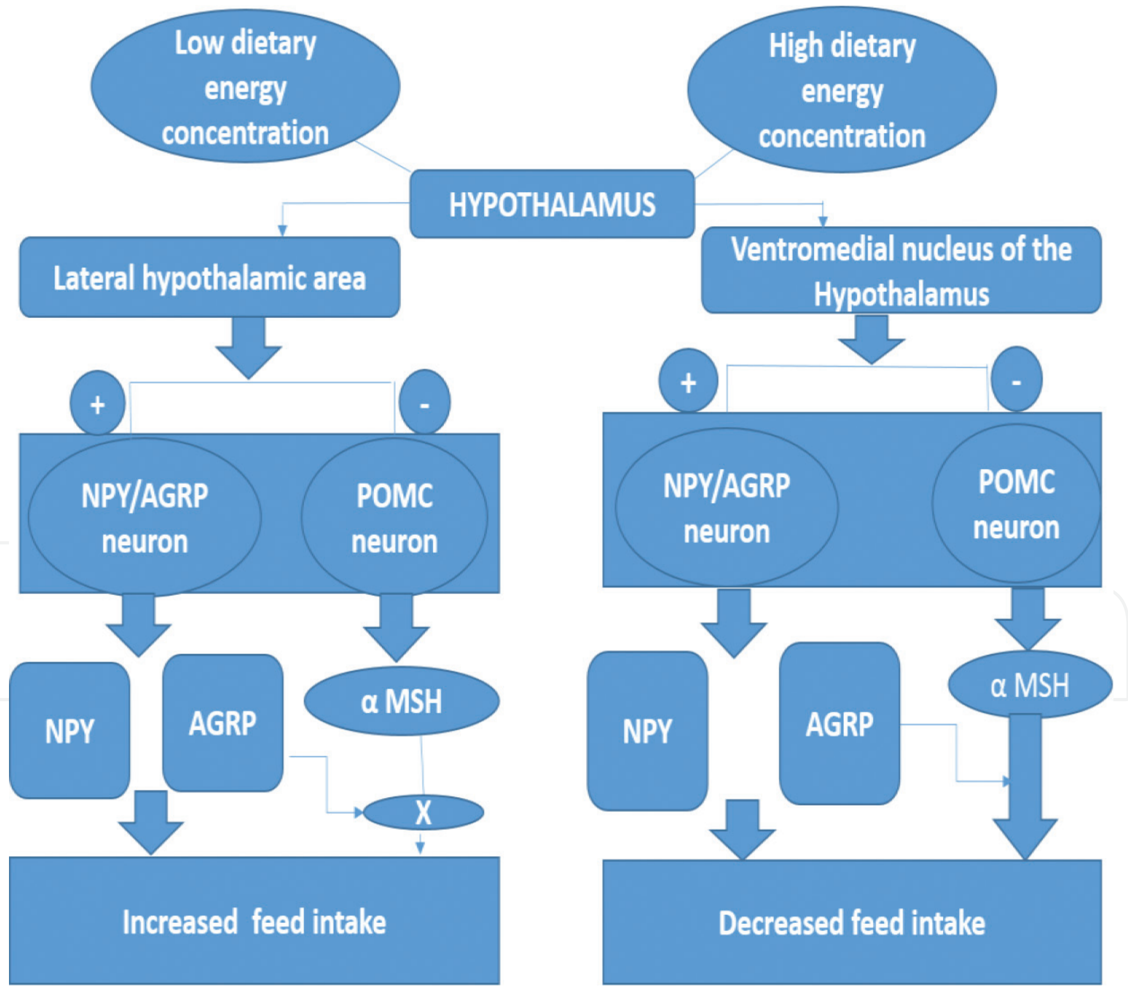

Figure 1. Diagram showing hypothalamic response in regulating feed intake when dietary energy intake is reduced or increased in poultry. Adopted and slightly modified from Bungo et al. [86]. NPY = neuropeptide Y; AGPR = agouti-related protein; POMC = pro-opiomelanocortin; α MSH = α-melanocyte – stimulating hormone; ARC = arcuate nucleus, + = activate; − = inhibit.

neurons is what ultimately determines feed intake considering dietary energy concentration and a resultant improvement in whole-body energy balance and body weight.

However, reports and research on the influence of dietary energy intake on feed intake in poultry have been conflicting. These inconsistencies could be due to differences in genotype/strain, environmental influence, stocking density, size of bird used, among other factors [81]. It is worthy to note that low-mass birds such as laying hens because of their size tend to adjust their feed intake in response to dietary energy concentration effectively than heavier birds such as broilers that maintain a constant feed intake, irrespective of the dietary energy concentration except this is limited by the gut content or other physiological factors [1]. Although there is a topic of great debate and discussion, a great number of research have reported the effect of high or low dietary energy in increasing or decreasing the feed intake in broiler chickens. It is well documented that most broiler chickens and laying hens tend to eat to satisfy their energy requirements or that they will consume a reduced amount of a feed greater in energy content than the one with a reduced energy concentration [87–89]. For instance, an earlier report by Sheriff et al. [90] indicated a higher feed consumption in broilers fed with low-energy diet. Moraes et al. [91] reported that high ME content results in low feed intake in laying hens. Almeida et al. [92] agreed with Moraes et al. [91] by also concluding that high dietary energy concentration led to a reduction in feed intake of commercial laying hen. Harms et al. [93] also observed that hens receiving the low-energy diet consumed significantly more feed than hens receiving the control and high-energy diets.

Van Krimpen et al. [94] concluded that hens that are fed low-energy diets or diets that are high in non-starch polysaccharides (NSP) spend more time on feed, compared with hens that were fed the normal control diets. Based on these facts, the authors concluded that laying hens adjust more rapidly to a decrease in dietary energy than to an increase in dietary energy. Compared to research results obtained using broilers and laying hens where an increase in dietary energy resulted to a decrease in feed intake and vice versa, Mbajiorgu et al. [81] observed an increase in feed intake when indigenous Venda chickens were fed increased dietary energy level. This difference in response between broiler chickens and laying hens compared to indigenous Venda chickens was attributed to the difference in intrinsic genetic limitations inherent in indigenous Venda chickens that may have led to the loss of sensitivity to influence feed intake when dietary energy regulatory strategy is applied [95]. Although there is a dearth of research on the nonsignificant effect of dietary energy concentration on feed intake of laying hens. Rather there are more consistent reports that laying hens can respond more effectively to dietary energy concentration on feed intake, unlike genetically improved broiler chickens. On the other hand, there are several reports that dietary energy intake did not affect feed intake especially in genetically modified broilers chickens. For instance, Araújo et al. [96] reported that there was no significant difference observed in feed intake among broilers fed high- and low-energy diets. A similar result was observed by Richards [80], who concluded that there was no effect on feed intake when varying concentration of dietary energy was administered on genetically improved broilers. Rosa et al. [97] also reported that feed intake was not affected by two different genetic broiler chicken groups. Richards and Proszkowiec-Weglarz [85] reported that modern commercial broiler breeders do not adequately control voluntary feed intake to meet their energy requirements and maintain energy balance. These authors thus advised that feeding must be limited in these birds using other feed intake regulatory strategies to avoid overconsumption, ascites and excessive fattening during production since dietary energy concentration does not influence feed intake in these breeds of birds.

From the aforementioned, reports on regulating feed intake through dietary energy intake have been inconsistent. These contradictions could be attributed to the influences of several factors as mentioned in this chapter. Factors such as genotype, environment, variability in stocking density, and so on must be kept uniform with dietary energy concentration being a major source of variation for future variation. More research needs to be geared towards confirming or considering the effects of other nutrients and ANF on energy concentration as regards its efficacy on feed intake regulation needs to be considered. The effect of size with regard to the response of heavy or light breeds of birds to dietary energy concentration and its effects on the amount of feed these birds consume. Thus, a better understanding of the interaction of dietary energy concentration with other factors will go a long way to understand the mechanism of how dietary energy intake affects feed intake and to what degree/level feed intake can be influenced in poultry birds. However, more reports favour the fact that dietary energy regulates feed intake more in laying hens and to some extent in broilers. The differences that have occurred between broilers and laying hens in terms of the response of these birds to feed intake according to dietary energy intake was explained by Denbow [98]. The author stated that due to years of genetic selection for improved growth in broiler chickens, the various mechanisms that control feed intake in broiler chickens have altered compared to laying chickens that have not been selected for growth. Invariably, the author recommended the need for comparative studies to investigate the mechanisms involved in feed intake regulation for broiler chickens that have been selected for growth against laying chickens that have not been selected for growth.

7. Effect and implication of imbalance in energy intake in poultry

Broiler chickens have been genetically bred for increased weight gain, feed efficiency, growth rate, and breast muscle weight to meet the requirements of consumers [99]. This process has produced modern commercial chicken lines with a faster growth rate, better breast meat yield and feed conversion, as well as higher body fat compared with unselected lines [100]. Dietary energy is essential for maintenance of the chicken's normal metabolism and meat yield. However, when the amount of energy consumed by the bird exceeds that required for the purpose of maintenance and growth, the remainder is deposited as fat [101]. This situation may be further aided by the imbalance in nutrients in the diets, especially the energy to protein ratio [102, 103]. After hatching, birds are expected to increase their body weights over time and the amount and ratios of body protein and fat augment at various rates [104]; however, there is potential to deposit fat faster at later phases [102]. More so, the excessive fat in modern chicken strains is one of the most important challenges facing the poultry industry [105]. For example, Choct et al. [106] found that modern broilers contain 15–20% fat, and >85% of this fat is not required for physiological body processes. In general, disproportionate fat laydown is an undesirable trait for producers and consumers alike because it is considered a waste of dietary energy and a product with little economic value, which reduces carcass yield, and quality, and affects consumer acceptance [107]. In the modern broiler industry, carcass fat is always considered to be an unfavourable characteristic [108], as it decreases feed efficiency and carcass yield; moreover, it leads to rejection of the broiler meat by the consumers [109, 110]. However, fatty acids and overall fat, both in muscle or adipose tissue, impact vitally on many different areas of meat quality and are necessary to the nutritional value of meat [111]. Additionally, the development of flavour in meat is significantly affected by the lipids of fatty tissue. Lipids impact flavour through their influence on flavour generation, flavour perception (mouth-feel, aroma and taste) and flavour stability. Tumova and Teimouri [110] and Lawrence and Fowler [112] reported that high densities of linoleic acid in the fatty tissue could have a remarkable impact on flavour. Apart from the problem of fat deposition, there is a tendency for high mortality as well as development of metabolic diseases and skeletal disorders [110].

8. Various strategies employed to manage dietary energy intake

As discussed earlier in this chapter, high or low dietary energy content can lower or increase feed intake [69]. Low feed intake as a result of high energy content (leading to inadequate intake of other vital nutrients) has been reported to result in poor performance. In most cases, high dietary energy intake causes high fat deposition with a resultant poor quality end-product and increased mortality rate. On the other hand, low dietary energy intake has been reported to result in low energy storage, inability to achieve homeostasis and reduced body weight of poultry birds [101, 110]. Therefore, practices aimed at managing dietary energy will aid in ensuring adequate feed intake with a resultant improvement in performance, product quality as well as reduced cost of poultry production. For many decades, meat type broiler and broiler breeder farmers have knowingly and unknowingly used different methods individually or collectively to manage dietary energy intake. Examples of these practices include nutritional strategies (use of high or low energy and fibre diets, pelleting as well as the use of microbial enzymes); use of genetically improved breeds; feeding practices (panned restriction feeding system or *ad libitum* feeding practice); type of rearing system used (intensive housing system, free ranging system or semi-intensive system), and disease prevention practices [1, 81]. These practices will be briefly discussed in this section. The positive or negative effect of these practices as reported by various researchers will be concisely discussed. The application of these practices to manage dietary energy intake to improve productivity and reduce the cost of production for broiler farmers and hatcheries will also be discussed.

8.1. Nutritional strategies used to manage dietary energy intake

Reduction in abdominal fat is a current goal in poultry industry so as to improve the efficiency of diets and to provide a less fat-laden meat product for consumers. Different nutritional strategies provide an opportunity to reduce production costs and at the same time, improve carcass quality in broiler chickens. Lowering the dietary energy level has been used to achieve the reduction in abdominal fat deposition. A study by Rosa et al. [97] evaluated the effect of energy intake and broiler genotype on performance, carcass yield, and fat deposition in two different genetic groups of broilers and reported that genetic improvement had a significant effect on broiler energy metabolism, and that abdominal fat decreased with low energy intake

(2950 kcal/kg) compared to the other diets. In another study, Choct et al. [106] examined the influence of different fat sources at two dietary levels on lean growth in broilers and concluded that the addition of fish oil to broiler diets reduced the abdominal fat pad weights. Fish oil contains long-chain polyunsaturated fatty acids, which enhance low-density lipoprotein and triglyceride levels while increasing glucose uptake into the muscle tissue in blood and lessening the negative effects of the immune system on protein breakdown. However, one consideration with the use of fish oil is its development of off-flavour in bird diets and the reduced shelf life of the chicken meat, which can be improved with the use of preserving agents and antioxidants [113]. According to Leeson [114], the success of the use of lower-energy diets is in the ability to predict change in feed intake and corresponding modification to all other nutrients in the diet, hence, a reduced dietary energy intake may be triggered by excess or imbalance of other nutrients in broiler diet. Leeson [114] further proposed that when all nutrients are tied to dietary energy, broilers are able to remarkably maintain energy intake when confronted with a major reduction in dietary energy concentration. More so, a recent study at the University of New England tested the effect of dietary fibre and energy levels on energy intake. It was observed that low while an optimum energy level in diet in combination with high dietary fibre inclusion reduced abdominal fat and cost in broilers as shown in **Table 3** [115]. Another nutritional strategy that has been used to manage dietary energy intake in broiler chickens is supplementation with exogenous that target energy-yielding substrates. **Table 4** shows examples of various carbohydrate- and lipid-targeting enzymes as well as their targeted substrates and energy sources. Such exogenous enzymes aid in the release of trapped dietary energy, especially energy sources such as wheat, rye, barley and oat that are high in NSP [116]. Exogenous carbohydrase enzymes have been reported to reduce or eliminate the effect of NSP, thereby furnishing more nutrients. Increased feed consumption in broilers leads to increased dietary energy intake. In the same vein, increased dietary intake leads to increased fat deposition and poor product quality. Based on this fact, most poultry farmers have imbibed the practice of reducing the quantity of feed offered to their birds and simultaneously adding exogenous enzymes to help release nutrients bound by antinutritional factors. This practice has been reported to result in broilers that grow faster and also have leaner meat [117].

8.2. Managing dietary energy intake in broilers through selective genetic improvement

High carcass fat is considered unfavourable by consumers in most parts of the world. Based on this fact, breeding programs have been developed with the aim of selecting against high fat deposition in broiler carcass in order to improve the quality of the product [118]. Modern broilers have been genetically selected to have significantly reduced fat deposition and also have better weight gain and FCR as a result of significantly masking the effect of dietary energy content in the diet [119]. Because of the tremendous success achieved through artificial selection of broiler chickens, there has been a reduction in total feed and energy required to raise broiler chickens to slaughter or market weight. Genetically, lean birds have better energy use efficiency [120]. This achievement has also resulted to a reduction in cost of production [121]. It is worthy to note, however, that genetic improvement of broilers with the aim of controlling the effect of high or low dietary energy intake could be influenced by several factors such as: nutrition, health of the

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Feed consumption and utilisation (0–35 d)

Dietary fibre content	Energy content	Feed intake (g/b)	Body weight (g/b)	Body weight gain (g/b)	FCR
Low	Optimum	3432.0	2250.9	2209.6	1.55
Low	Low	3248.0	2177.2	2136.1	1.52
Medium	Optimum	3332.9	2143.6	2102.2	1.59
Medium	Low	3337.7	2026.3	1984.7	1.68
High	Optimum	3510.5	2142.9	2101.7	1.67
High	Low	3324.7	2103.8	2062.8	1.61

Meat yield (g/kg live weight) (35 d)

Dietary fibre content	Energy content	Live weight	Carcass weight	Thigh	Drumstick	Breast (skin-less)	Abdominal fat pad
Low	Optimum	2248.4	1678.3	263.9	216.4	416.5	30.6
Low	Low	2201.0	1630.0	250.1	215.5	392.2	23.0
Medium	Optimum	2179.2	1629.3	250.9	213.5	395.0	25.1
Medium	Low	2093.2	1562.3	240.4	199.9	391.8	22.6
High	Optimum	2201.2	1621.2	244.2	207.5	413.4	22.2
High	Low	2250.6	1684.0	278.3	211.2	410.9	24.6

Economic analysis

Dietary fibre content	Energy content	Feed cost ($/bird)	Feed cost ($/kg gain)
Low	Optimum	1.25	0.57
Low	Low	1.16	0.54
Medium	Optimum	1.23	0.58
-Medium	Low	1.19	0.60
High	Optimum	1.30	0.62
High	Low	1.21	0.59

Source: Chen [115].

Table 3. Feed intake, feed utilisation, meat yield and economic analysis of broiler chickens fed finisher diets differing in fibre and energy contents.

bird, environment, and so on. The authors of Refs. [1, 97, 122] reported that the genetic make-up of a broiler bird is not the sole reason for the success achieved in managing dietary energy intake by some broiler producers. The authors suggested that the success achieved in this area may be as a result of the combination of genetics and other factors such as environmental influence, nutrition, management practices, age, sex of the birds and disease prevention strategies.

Enzyme	Substrate targeted	Mode of action	Feed ingredient of interest
β-Glucanase	β-Glucans		Oats, rye and barley
Xylanases	Arabinoxylans		Wheat, triticale, barley and rye
Amylase	Starch		Cereal grains, roots and tubers
Lipase	Lipid		Lipid in feed ingredient
Adopted from Ravindran [116].			

Table 4. Different types of commercially available energy-targeting enzymes used to manage dietary energy.

8.3. Feeding practices used to manage dietary energy intake

Various practices such as restricted feeding and *ad libitum* feeding have been reported to influence dietary energy intake in meat broilers, laying hens as well as in broiler breeders [123]. These practices could have negative or positive effect on broiler performance and cost of production. Several researchers have reported the advantages and disadvantages of these feeding strategies [124–129]. For instance, Acar et al. [125] and Butzen et al. [128] both agreed that excessive fat deposition, ascites, sudden death syndrome as well as various metabolic disorders and disease in broiler can be reduced through planned feed restriction practice. To achieve success in managing dietary energy intake using these practices, adequate knowledge and skills in administering these strategies become key factors towards using them to achieve the right dietary energy intake in meat broilers, laying hens as well as in rearing broiler breeders.

8.3.1. Ad libitum feeding as a tool in controlling energy intake

Ad libitum feeding is defined as an animal husbandry practice in which animals are allowed unlimited access to feed on free choice basis [128, 130]. Feeding meat and breeder broilers *ad libitum* lead to increased feed and dietary energy intake and fat deposition compared to birds on restricted feeding [131]. According to Heck et al. [132], energy conversion (kJ/g egg) from 32 to 40 weeks of age was much higher in the broiler breeders on *ad libitum* feeding group than in broiler breeders that were on restricted feeding plan. The authors further explained that sexual maturity was delayed by 6 weeks in restricted breeders compared to *ad libitum* fed broiler breeders that started to lay at 20 weeks. On the contrary, the authors also reported that broiler breeder hens fed *ad libitum*, had low egg production and a high proportion of defective eggs, which was largely rectified by feed restriction.

8.3.2. Using feed restriction to manage energy intake

Feed restriction involves a calculated or planned practice of decreasing the amount of feed being offered to broiler birds with the aim of decreasing feed intake over a certain time interval in an attempt to slow the rate of weight gain, fat deposition and various metabolic disorders associated to excessive feeding. Contemporary commercial broilers are the product of intensive genetic selection for rapid growth. An unpremeditated result of these genetic selection programs has been the loss of ability by broilers to control feed intake to adequately meet up with maintenance, growth, and reproductive function [133]. Based on this fact, broilers tend to overfeed, and this uncontrollable feeding habit has been reported to cause nutritional, metabolic and health problems related to obesity. To manage this problem, most farmers have resorted to the subjecting of their meat or breeder broilers to planned feed restriction. Early age planned feeding restriction practice in meat or breeder broilers is geared towards ensuring that appropriate body composition and weight are achieved at important phases of the production cycle [133]. The success of a planned feed restriction in managing dietary energy intake depends on quantity of feed and timing of the feed restriction. This statement is in agreement with the report of Chenxi et al. [134] who concluded that feed restriction done by dilution of dietary energy and protein by 10% from 8 to 14 (early age planned feed restriction) is a suitable feeding program. The authors further explained that compared to the control group, there was no significant difference in body weight FCR and feed intake at 42 days. Chen et al. [135] also observed that 30% dietary energy restriction resulted in a decrease in fat deposition and an improvement in body weight and FCR at later phase of life. Bruggenan et al. [136] suggested that restriction applied at 7–15 weeks of age followed by either *ad libitum* feeding or continued feed restriction controlled feed and nutrient intake which was the best for improving reproductive performance in broiler breeder females.

8.4. Feed processing strategies aimed at managing dietary energy intake in poultry

Birds try to make adjustments geared towards controlling the amount of energy they consume. Feed processing is an important strategy used by poultry producers to manage dietary energy intake. The form in which feed is presented to broiler birds can affect the energy and nutrient (energy, protein, vitamins and mineral) intake. Feeding broilers with mash leads to ingredient selection, which results in poor performance [137]. According to Davis et al. [138] cited by Amerah et al. [139], poultry tends to select maize particles while ignoring soybean (protein source needed for growth and tissue build up), which would affect the intake of amino acids, vitamins and minerals, when fed with mash diets. The selection of maize feed particles tends to increase the dietary energy intake, with a resultant increase in fat deposition. This condition leads to poor growth and poor product quality in broilers. To solve this problem, broiler producers now use crumbles at the starter phase, and pellets at grower and finisher phases. This strategy tends to eliminate the issue of feed ingredient particle selection noticed when mash diets are fed to broilers. In laying hens, excessive fat deposition hinders egg production and thus feeding of mash to layers is a common practice, especially if the mash diet is properly/uniformly mixed.

8.5. Rearing system as a means of managing dietary energy intake

The increasing global demand by broiler meat and egg consumers for high-quality poultry products has necessitated the drive of breeders and producers towards meeting this demand at the least possible cost. In an effort to meet this demand, farmers are adopting different housing and rearing strategies (a deviation from the normal intensive system) such as free range and semi-intensive [140, 141]. It is well documented that the environment under which a poultry are reared plays a pivotal role in the quality of the product. Environment and housing system influence feed intake with a corresponding effect on dietary energy intake. Two types of rearing system are mostly employed in poultry production and they include intensive housing system and free range system. However, in order to reduce the shortcomings of these two rearing systems, a rearing strategy known as semi-intensive system is gradually gaining popularity [140]. Although free range and semi-intensive rearing systems are mostly used for egg laying hens, the increasing demand by consumers for meat produced from organically reared broilers is driving the introduction of these rearing systems in meat-type broiler production [141].

8.6. Managing dietary energy intake by controlling lightening regime

Light is a critical factor used to manipulate feed intake in broilers. By artificially increasing the length of time, the bird is subjected to light, its feed or dietary energy intake can be increased. On the other hand, lowered or total light-out tends to reduce feed intake in broilers. This fact is true because broilers tend to stop feeding once the light is off but resume feeding once the light is on. This technique has been employed in modern poultry systems to achieve optimum growth rates [142]. Intermittent lighting programs are routinely used by broiler producers. Buryse et al. [143] concluded that intermittent lighting program had a favourable effect on feed conversion and weight gain, with a decrease in fat deposition. Apeldoorn et al. [144] reported that the improvement in feed conversion with intermittent lighting programs was related to reduction in feed intake. This reduces the cost of production while growth rate and meat quality are unaltered. The author also showed that reduced feed efficiency was related to higher ME/GE utilisation.

8.7. Disease prevention practices as a tool in controlling dietary energy intake

Broilers in optimum health condition up to finisher phase have been reported to yield quality meat. Diseased birds tend to have reduced feed and dietary energy intake with a resultant decrease in meat, egg quality and mortality of poultry birds. The ability of a producer to effectively prevent disease or infections will go a long way to maintain feed and dietary energy intake and prevent unnecessary expenditure associated with purchase of drugs. Disease conditions tend to reduce feed intake and lead to malnutrition, which is a predisposing factor to various metabolic diseases [1]. Several disease prevention strategies such as the use of disease-free poultry birds, adherence to biosecurity, adequate and prompt vaccination when and if needed, isolation of sick birds, prevention of predators and potential disease-carrying vectors could go a long way to enable the birds to consume the right dietary energy content, leading to quality at least cost.

9. Conclusion

Improving poultry meat quality as well as cutting down on the cost of broiler production has been some of the major objectives of most farmers, processors and researchers. To achieve these objectives, several strategies have been adopted, one of which is dietary energy management.

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Increasing or decreasing dietary energy intake has been reported to influence feed intake with a corresponding effect on performance and cost of production. Results on the use of this method have been inconsistent. These inconsistencies are due to several factors, including genotype, diet composition, digestible nutrient contents, energy to protein ratio, feed form, feed processing, dietary energy sources, physical environment and disease. However, the progress achieved is also very encouraging. It is therefore necessary to explore the effect of the abovementioned factors on dietary energy intake and seek for innovative ways to mask the effect of these factors so as to have a more consistent outcome when dietary energy intake strategy is used to influence the cost of production and product quality of broiler chickens. Various strategies aimed at reducing dietary energy intake through the use of high fibre diet combined with enzyme is very promising in improving carcass quality and reduce cost.

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