ABSTRACT

QUINTANA OSPINA, GUSTAVO ADOLFO. Data Analytics in Broiler Production. (Under the direction of Dr. Edgar Oviedo-Rondón).

Broiler live performance is affected by different factors such as environment, management, and nutrition. However, data about the impact of these variables under commercial operations is still scarce. The second chapter evaluated growth dynamics, feed intake (FI), feed conversion ratio (FCR), and mortality of broilers raised under commercial conditions with control feeding to determine differences to improve these parameters. Performance records of 1,347 male and 1,353 female Ross 308 AP broiler flocks were obtained from an integrated poultry company located in Colombia. Decision trees determined high (HE) and low (LE) feed efficiency groups using FCR at 35 d. Three non-linear models were fit with week BW data for each flock within performance groups. Live performance parameters and model estimates were subject to one-way ANOVA with efficiency as the main effect and mean separation with the t-student test. HE males and females had a feed restriction above 22% from the genetic line recommendations with greater subsequent feed allowance, reached the inflection point (IP) later, and presented a lower exponential growth rate.

Using environmental monitoring data, chapter three described the effects of hours of exposure to non-recommended temperature (T), RH, and a thermal-humidity index (THI) on BW and FCR. Correlation analyses and linear regressions were fitted between live performance parameters and hours of exposure to non-recommended values. Broiler BW and FCR were worsened by temperatures 2.5 °C below recommended conditions during the first three wk. Additionally, farm-associated factors were compiled using a survey. Continuous variables were clustered with FCR at 35d, and all factors were assessed in a one-way ANOVA with factor level or cluster as the main effect and BW and FCR at 35d as responses. Machine learning (ML) models

were fit with performance records up to 21d and farm-associated factors as predictors, while BW and FCR at 35d were used as responses. A multiple linear regression (MLR), a random forest (RF), and an artificial neural network (ANN) was constructed using the R's *caret* package with five-fold cross-validation. All farm-associated factors affected live performance in chickens. RF had the highest (R^2=0.78) predictive capabilities compared to ANN and MLR. Variable importance indicated that BW, BW gain, FI, and FCR at 14 and 21d, and distance from the hatchery to the farm, farm altitude and sex were important for predicting BW at 35d.

In the fourth chapter, the nutrient intake was estimated for pre-starter, starter, and grower phases based on the dietary nutrient composition and feed amount offered to chickens for each feeding phase. Correlation analyses, simple and MLR were fitted to determine the relationship between cumulative intake (CI) of metabolizable energy (ME), crude protein (CP), digestible lysine (dLys), Calcium (Ca), Phosphorus (P), and fat with BW and FCR at 35d. Positive correlations were observed with all nutrients during the grower phase. MLR indicated that BW increased as ME increased while accounting for the negative linear effects of CP. FCR at 35d resulted in low goodness-of-fit. Also, decision trees indicated that CI of ME, P, dig Lys, and fat, farm altitude, distance from hatchery to farm were important factors to model BW (R^2=0.55-0.71) and FCR (R^2= 0.40–0.48). In conclusion, feed restriction of 23% on average compared to 18% improved FCR. Temperatures 2.5 °C below from recommendations during the first three weeks worsen FCR 0.011 g:g at 14d, and 0.004 g:g at 21 and 35d. Management factors like distance from the hatchery to the farm and farm altitude, and energy and intake during the grower phase affected broiler live performance. Moreover, data analytics tools helped determine management factors that combined with nutrient intake, affected the BW and FCR of broilers at 35d.

Data Analytics in Broiler Production

by
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DEDICATION

I would like to dedicate the work of this thesis to my dad in heaven, who has given me the strength to continue with each step that I take. To my mom for the tireless task of giving me the best of herself to see me become a professional. To my beloved wife, who has held my hand and supported me throughout this journey. To my sisters for encouraging and motivating me. Lastly, to my grandparents, who have given me their unconditional love.

BIOGRAPHY

Gustavo Quintana was born to Sandra Ospina and Gustavo Quintana in Ibague, Colombia. There, he attended the school of Veterinary Medicine and Animal Science at the University of Tolima. While in college, Gustavo gained skills to develop research projects by participating in research related to poultry science and molecular biology technics. In early 2018, Gustavo was selected to conduct an international internship at NC State University. After championing the internship, he graduated as a Doctor of Veterinary Medicine (DVM). Gustavo was later hired as a nutritionist at the largest commercial feed company in Colombia, where he gained experience in diet formulation and nutrition for multiple species. In 2020, Gustavo was hand selected to pursue his master's degree at the Prestage Department of Poultry Science at NC State University where he graduated. Under the direction of Dr. Edgar Oviedo, he became versed in animal nutrition, statistical analysis, and machine learning techniques. While studying he also participated in the development of an online course in data analytics for the poultry and swine industries which he instructed to industry professionals across many countries. Gustavo's interest in research is centered on integrating the use of big data analytics to poultry farming, considering nutritional and management factors affecting broiler and broiler breeder productions. Currently, Gustavo lives in Envigado, Colombia and awaits to start his new challenge as a head of poultry nutrition in a business group.

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CHAPTER I

LITERATURE REVIEW

Introduction

In the last five decades, genetic selection and research in different areas of poultry science such as nutrition and management have allowed improving broiler growth rates by 400% with a reduction in the feed conversion ratio (FCR) of 50% (Zuidhof *et al.*, 2014). Consequently, the worldwide poultry meat industry produced 9 million tons per year in 1961 to 132 million tons per year forecasted for 2021, representing 39% of the global meat production (FAO, 2021). Still, poultry meat production is expected to increase 17.8% by 2030 (OECD/FAO, 2021), which makes it necessary to understand the current challenges in the poultry production sector to optimize the growth and efficiency of birds.

Within those aspects, it has been demonstrated that broiler live performance parameters are affected by environmental conditions (Goo *et al.,* 2019; Zhou *et al.,* 2019 Awad *et al.,* 2020; Liu *et al.,* 2020), management (Bergough *et al.*, 2013; Toledo *et al.*, 2019; Yerpes *et al.,* 2020) and nutrition (Fallah *et al.,* 2019; Chrystal *et al.,* 2020; Maharjan *et al.*, 2021; Barekatain *et al.*, 2021; Kidd *et al.*, 2021). Additionally, some reports may indicate that modern broilers exhibit different growth curves and efficiencies of energy and nutrient utilization altered by strain and sex (Zuidhof *et al*., 2014; Maharjan *et al*., 2021). These factors added up the increasing competitiveness for land, water, and energy to produce food (Godfray *et al.,* 2010), impacting the profitability and sustainability of the poultry operations worldwide.

Broiler companies around the world also produce lots of data in the whole production system for planning, control, and benchmarking (Taube-Netto, 1996; Manning *et al*., 2008; Agri

Stats, 2021). However, the data available is seldom used for optimization in decision making analysis, especially when it is related to live production. This data is currently produced in large volumes at high speed due to electronic sensors and informational technologies, it is highly variable, does not have structure (Neethirajan, 2020). Then, the use of mathematical models and machine learning (ML)-based techniques to analyze data product of the day-to-day operations (Pitesky *et al.*, 2020; Neethirajan, 2020) become an efficient and less expensive method to unveil and quantify the effect of those factors that reduce the live performance of broilers.

Traditionally, the growth of broilers has been depicted by non-linear models (Demuner *et al.*, 2017; Narinç *et al.*, 2017; Nogueira *et al.*, 2019). These growth curves, exhibit an exponential growth rate followed by a reduction and subsequent decrease of the rate that represent the inflection point and exponential growth decay observed in different species including broilers (Tjorve *et al.*, 2017). Within those non-linear models, different mathematical equations have been proposed to characterize the growth of chickens. Some of them include the traditional Gompertz form (Gompertz, 1825) and its variations (Laird *et al.*, 1965; Kathleen *et al.*, 2017), Logistics (Robertson, 1923), von Bertalanffy (von Bertalanffy, 1957), Richards (Richards, 1959; Aggrey, 2002), Weibull (Topal and Bolukbasi, 2008) and some others (Al-Samarai *et al.,* 2015; Demuner *et al.*, 2017), which vary in the number of parameters and data fit. Even, complex algorithms of prediction such as artificial neural networks (ANN) that could account for better fit have been reported as tools utilized in poultry production (Ahmad, 2009; Demmers *et al.,* 2010; Johansen *et al.,* 2017).

On the other hand, the environmental conditions within poultry houses are key in the live performance of chickens (Astill *et al.,* 2020). Studies conducted within environmental-controlled chambers have demonstrated that high or low temperature and RH reduce broilers' BW, BW gain, and feed intake while increasing FCR and mortality (Yahav, 2000; Ipek and Sahan, 2006; Mohammadalipour *et al.,* 2017; Liu *et al.*, 2020; Zhou *et al.*, 2019). Although indoor environmental data under commercial operations are often collected, it tends to be not analyzed. Consequently, the impact of these variables in facilities with cycling variability due to environmental day and night temperatures are still scarce. In addition, some other factors related to chick transportation (Oviedo-Rondón *et al.,* 2009; Bergough *et al.*, 2013), farm location (Rachmawati *et al.* 2016), and equipment (Yerpes *et al.,* 2020) could contribute to observing suboptimal performance in broilers.

Economically, the feed in commercial poultry production can represent about 70% of the total production cost (Mallick *et al.,* 2020). Thus, appropriate nutrient levels must be formulated to obtain the best performance while optimizing the operation cost. Different genetic companies (Cobb, 2018; Aviagen, 2019) have developed dietary nutrient recommendations for broilers. Still, some authors (Rostagno *et al.,* 2017; Maharjan *et al.,* 2021) have indicated that the dietary nutrient composition should be adjusted according to strains, environmental conditions, or market needs. Metabolizable energy (ME), crude protein (CP), digestible amino acids (AA), minerals, and fat at different dietary levels, have been demonstrated to alter responses at slaughter age (Rosa *et al.*, 2007; Poorghasemi *et al.,* 2013; Kriseldi *et al.*, 2018; Fallah *et al.,* 2019; Barekatain *et al.*, 2021; Kidd *et al.*, 2021). However, the feed ingredient composition (Moss *et al.,* 2021) and feed formulation may alter the dietary nutrient composition and consequently the nutrient intake and the performance of broilers.

This literature review will discuss different non-linear and machine learning models utilized to represent and predict the growth of broilers. Additionally, it will detail the effect of temperature and RH in BW, BW gain, feed intake, FCR, and mortality in broilers exposed to different environmental conditions, considering the interactions of these two variables through thermal-humidity indices proposed for poultry. Lastly, it will be shown how the effects of dietary levels of ME, CP, digestible AA, minerals, and fat, as well as the cumulative nutrient intake, may affect the live performance of broilers at different ages.

MODELS TO EVALUATE AND PREDICT BROILER BODYWEIGHT AND FEED CONVERSION RATIO

Non-linear models

Non-linear models have been widely used to represent the relationship between growth and time of plants, birds, and even tumor and bacterial cells (Tjorve and Tjorve, 2017). The Gompertz equation described for the first time in 1825 by Benjamin Gompertz (Gompertz, 1825) has been demonstrated to be the mathematical model that better describe broilers' growth (Al-Nasrawi, 2013; Mouffok *et al.,* 2018). However, some other models (Table 1.1) have been developed and tested in the growth of broilers (Robertson, 1923; von Bertalanffy, 1957; Richards, 1959; Laird *et al.,* 1965; Topal and Bolukbasi, 2008). Non-linear functions are characterized by presenting an initial exponential growth rate that reaches a maximum growth point known as inflection point. Then, the shape of the curve changes and the growth starts to present a daily decrease in the rate or deacceleration (Tjorve and Tjorve, 2017). The output of non-linear models are the parameters described on them. The determination of these parameters is crucial to predict the BW and nutrient deposition at any age (Marcato *et al.,* 2008). Additionally, it has been described that by knowing the growth pattern of birds in a production system, growth models help in determine the best slaughter age and weight to avoid raising animals after the inflection point has been reached (Marcato *et al.*, 2008) which could be economically unfavorable.

Different studies have demonstrated that growth patterns may change in broilers due to target BW, strain and sex. In an experiment conducted by Nogueira *et al.* (2019), four commercial broiler strains (Cobb500, Ross AP95, Hubbard Flex, and new French) were raised to 42 d under the same conditions. In that study, the Ross AP95 males demonstrated to reach the highest maximum growth with 119 g/d at 31 d compared to Cobb 500 (31 d, 111 g/d), Hubbard Flex (29 d, 110 g/d), and new French (32 d, 116 g/d). Although the Hubbard Flex was the first to reach the maximum growth, chickens from that strain resulted in a lower rate of decay that indicates that the maximum growth was maintained for a longer period (4 d). In the model predictability performance, Mouffok *et al.* (2019) raised chickens to 49 d in three BW groups, light (<= 2,500 g), moderate (2,500 – 3,000 g), and heavy (> 3,000 g) and compared six equations, Gompertz, logistic, weighted least squares, von Bertalanffy, Richards, and Weibull. Residual analyses demonstrated that the Gompertz model for all BW categories resulted in the most suitable and lowest error (<10 g) up to four wk. After that period, logistic and von Bertalanffy models could better represent the shape of the curve. In that study, goodness-of-fit metrics determined that all models presented high fit ($R^2 > 0.95$).

Another report by Moharrery and Mirzaei (2014) evaluating the growth of two broiler strains (Ross 308 and Iranian native chickens) raised to 56 d with four energy levels (3,200, 3,008, 2,828, and 2,658 kcal/kg), concluded that the Richards model fitted better all data based on the residual sum of squares. The same report showed that adjusted R^2 was greater than 0.98. Therefore, it has been recommended (Zhao *et al*., 2015) that R^2 should be taken with caution since non-linear models tend to be high and close in this parameter, making difficult the differentiation of the best model. Also, because non-linear models present high goodness-of-fit, an appropriate growth model will depend on the accuracy of the data (Moharrey and Mirzaei, 2014). Duan-yai *et al.* (1999)

compared two forms of Gompertz with growth data from three broiler strains (C, R, I) raised at two ages, 35 and 105 d. In that experiment, the authors proved that the two forms of Gompertz should produce the same parameter estimates. Still, the amount of data used to predict responses at 35 or 105 d affected the ability of models to perform. Models fit with data up to 35 d produced higher error when predicting BW at 105 d. It seems that growth data at early phases are not enough to determine the inflection point (Duan-yai *et al.,* 1999). Despite some authors have evaluated growth patterns in commercial broiler strains, to the best of the authors' knowledge, no reports were observed in commercial operations where chickens have been raised under variable conditions such as different farms, regions or management practices.

Decision trees and random forests

Under commercial operations, the lack of structured data for analysis is a concern (Jackman *et al.*, 2020; Pitesky *et al.*, 2020). Thus, to discover patterns not commonly observed in data through traditional statistical tools, data mining techniques have been proposed to analyze large datasets (Aggarwal, 2015; Bramer, 2016). One of those techniques is the classification and regression tree algorithm, also known as decision trees. The algorithm creates subgroups considering the relationship among categorical or continuous predictors to split the data based on the Pearson's Chi-square (Aggarwal, 2015; Bramer, 2016). Then, different split points generate the nodes or subgroups (Figure 1.1.). Decision trees can be further classified into two major groups, regression trees in which the response is continuous such as broiler BW or FCR or classification trees where the response is categorical (Olden *et al.*, 2008). For each case, the node will provide the mean and standard deviation of the response for regression trees, while nodes in classification trees are expressed as a probability of the response to occur (Olden *et al.*, 2008).

In a study conducted by Mendes and Akkartal (2009) aiming to relate physical measurements of chickens in relationship with their BW, it was determined in a decision tree analysis that chicken BW at slaughter age was influenced by the BW, breastbone length, shank width, and breast circumference at 2 wk of age. Thus, 2-wk-old chickens with breast circumference greater than 14.18 cm, breastbone longer than 55.82 mm and chickens heavier than 295.95 g will result in a BW at slaughter age of 2,314.5 g compared to those with shank width smaller than 8.32 mm, breastbone greater than 60.26 mm and less than 295.95 g of BW which could result in 1,880.9 g. Some other studies have focused on using decision tree analysis to determine critical points in the development of health issues (Cordeiro *et al.,* 2012; Carroll *et al.,* 2014; Nääs *et al.*, 2021) and food safety (Pitesky *et al.,* 2020). Still, most of the variables included in models previously reported are not commonly captured in commercial operations. Tovar (2019) suggested that decision trees may be used to determine different groups in broiler breeders reared under commercial settings, based on a performance trait (hen-housed egg production) to analyze the impact of growth dynamics. This methodology, which has not been previously reported in broilers could probably be employed to provide some structure to commercial data of broilers in such a way that it can be analyzed.

On the other hand, the optimization of several decision trees with the random combination of independent variables simultaneously is known as random forest (Breiman, 2001). This tree-based technique uses bootstrap sampling or bootstrapping to fit multiple decision trees and average the response. It indicates that for each decision tree, data will be randomly subsampled with the replacement of *n* size to run a decision tree. Thus, each subsample will have the same *n* number (Hastie *et al.,* 2009). The model is then trained to determine the best number of variables to be included within each decision tree. At the same time, each subsample is evaluated in decision trees with all possible combinations of variables. Because of the randomization of variables to include decision trees, it is expected to have a model with unbiased and non-correlated variables (Olden *et al.,* 2008; Hastie *et al.*, 2009).

Artificial neural networks (ANN)

This technique combines regression and classification models through mathematical functions in a neuron-like transmission system to predict responses (Hastie *et al.,* 2009; Thessen, 2016). This concept was first presented by McCulloch and Pitts (1943), but its use in poultry was limited until 1996, when Roush *et al.* (1996) described the application of ANN in the prediction of ascites in broilers. In less complex structures, ANN is composed by a layer of input variables, a hidden layer, where all mathematical processes are carried out, and an output layer (Aggarwal, 2015). Due to the ability of ANN to use the combination of different mathematical functions, the hidden layer may be composed of different nodes. In that case, it will be referred to as a multilayer perceptron (Figure 1.2). Since ANN tries to mimic the human learning process, it takes a series of input variables normalized to randomly assign different weights for each variable and then compute a sum of all weights. That process is then repeated several times by changing the importance of each variable as human neurons change the strength of the sign in the learning process (Aggarwal, 2015). For simplicity, the algorithm uses the sum of weights to compute a non-linear function, known as activation functions, to generate the prediction. These functions can be sigmoidal, hyperbolic tangent, and rectified linear units, among others (Kubat, 2017). Additionally, ANN may combine different activation functions in the hidden layer and assign a weight to produce the output.

In predicting broiler BW, Ahmad (2009) compared the performance of three ANN models and a generalized ANN by using simulated growth data. The author determined that all models resulted in R^2 greater than 0.97 and proposed ANN as an alternative to predict BW. Demmers *et al.* (2010) indicated that models for predictive control of BW could be constructed considering variable environmental and management conditions. In that study, by setting feed allocation at 90 or 110% from normal rates, light intensity at 10 or 100 lux, and RH at 56 or 70%, the model predicted broiler BW at 50 d with a maximum deviation of 5.2% and a difference in feed intake of 0.07 kg (4.66 predicted *vs.* 4.59 kg actual). Another study (Johansen *et al.,* 2017) including data of approximately 40,000 broilers from 12 flocks along 19 months, showed that temperature, humidity, CO_2, light intensity, ventilation rates and heating levels could estimate the BW at 34 d with a difference of 47 g (2,138 g predicted *vs.* 2,091 g actual observed) in a 7 hidden neurons model. However, the authors indicated a low variability in temperature, high correlation with CO_2, and several spikes in light intensity. Thus, the model was only valid for tightly temperature-controlled broiler houses. Still, that study employed data from a typical poultry house for all flocks, which could not represent the variability observed in commercial operations where factors can drastically change from one farm to another.

Variable importance analysis

In addition to the predictive capabilities that have been described for random forests and neural networks, some methodologies have been proposed to determine the importance of variables included in the models (Nicodemus *et al*., 2010). For random forests, the method that accounts for the contribution of features in models is called the permutation importance (Breiman, 2001). For ANN the Olden's method (Olden *et al.,* 2004) or Connection weights are the most used.

In the permutation importance for random forests, the importance of variables is estimated as a loss in the accuracy of the model when a variable is permuted (Breiman, 2001). Therefore, the importance is expressed as the increase in mean square error (MSE). Once the model is fitted, and the MSE of the baseline model is calculated, each variable is then permuted, and the model run again. The new MSE will work as a permuted value, and the percentage of change in MSE can be computed.

The method to calculate the variable importance from ANN is presented in Figure 1.3. As observed in the ANN description in Figure 1.2., each variable will be assigned a weight towards each node. Similarly, in the response estimation, the output from each node will have a weight that contributes to the response layer. According to Olden *et al.* (2004), the weight between each input and the nodes should be multiplied by the hidden node and the response. For instance, in the graph, the connection weight from the input 1 with the node A is -0.93 and the connection weight of the node A with the output layer is -1.75. Thus, the product of these two values will be 1.63. The procedure will be repeated for all inputs and nodes. Finally, all the connection weight products by input are added, and the variables are ranked based on the sum of connection weights.

ENVIRONMENTAL AND FARM-ASSOCIATED FACTORS AFFECTING BROILER BODYWEIGHT AND FEED CONVERSION RATIO

Feed restriction programs

Broilers are typically raised in *ad libitum* feeding systems under commercial conditions. However, it has been reported that high altitudes may produce high mortality in broilers due to metabolic issues linked to ascites and sudden death syndrome (Özkan *et al.,* 2010; Mohammadalipour *et al.* 2017; van der Klein *et al.,* 2017; Xu *et al.,* 2017). Consequently, different restriction programs have been developed to control the growth rate and ameliorate the effects of low temperature and oxygen availability (van der Klein *et al.,* 2017; Xu *et al.,* 2017). Previous research focused on feeding restriction programs in broilers is described in Table 1.2. One of the approaches used to reduce the growth rate has been implementing a feed restriction program only during the second week of life (Butzen *et al.,* 2013; Mohammadalipour *et al.,* 2017; Xu *et al.,* 2017), also defined as early feeding restriction. In a study conducted by Butzen *et al.* (2013), both males and females subjected to a feeding restriction of 20% from the *ad libitum* intake between 8 and 16 d presented lower BW at 21 d than their counterparts fed *ad libitum*. Still, chickens after 28 d and up to 42 d, resulted in similar BW, regardless of the feed restriction program established at 2 wk of age. Mohammadalipour *et al.* (2017) proved that a greater feed restriction (40% from *ad libitum*) during the second wk produced more efficient chickens in the second and third wk of age, with no significant differences in further ages. Another report with a feed restriction during the whole growing period (1 to 36 d) indicated that after a reduced feed allowance (10 – 20% from *ad libitum*), chickens were lighter compared to chickens from the control treatment (Khurshid *et al.*, 2019) with no effects on FCR. According to those studies, feed restriction programs have achieved the purpose of reducing the growth rate while accounting for beneficial effects on improved feed efficiency. The latter seems to be preserved one more week after feeding restriction programs are removed resulting in animals returning to normal levels of efficiency. In contrast, it was described (Dissanayake *et al.,* 2017; Bordin *et al.,* 2021) that continuous programs of feeding control could also improve BW. Dissanayake *et al.* (2017) evaluated three levels (10, 20 and 30% from *ad libitum*) of control feeding against the *ad libitum* program. Those authors observed that in all phases under evaluation (0 to 21, 22 to 42 and 0 to 42) the FCR was improved as the feed restriction increased, but at 10% restriction, broilers also improved BW. The findings reported by Dissanayake *et al.* (2017) were then supported by Bordin *et al.* (2021), who indicated that chickens offered 80% of the feed allowance from 10 d of age resulted in the best FCR (1.515 g:g) and additionally, obtained similar BW gain and uniformity than chickens either offered 90% (1.667

g:g) or fed *ad libitum* (1.767 g:g). Similarly, broilers raised in the U.S. to reach 1,814 g of BW at 35 d exhibited on average 1.604 g:g of FCR (Agri Stats, 2021). Still, data about growth models on feed restricted chickens is scarce. None of these reports detailed the effects of feed restrictions under commercial operations nor in tropical conditions where additional environmental and management factors may play an important role in the BW or FCR at slaughter age. Thus, the development of growth models from commercial data that consider the FCR as a factor may help determine appropriate management strategies in poultry companies that follow a feed restriction program.

Temperature and relative humidity

The improved feed efficiency and BW of modern broilers product of the intensive genetic selection (Zuidhof *et al.*, 2014) has altered the energetic metabolism of broilers (Chen *et al.,* 2014; Yang *et al.*, 2014; Tallentire *et al.,* 2016; Mohammadalipour *et al.,* 2017; Zhou *et al.,* 2021) and the way chickens interact with the environment (Yousaf *et al.,* 2019; Kang and Shim, 2021). Thus, diverse reports (Ipek and Sahan 2006; Awad *et al.* 2020) evidence the effects on BW or FCR when chickens are raised under challenging conditions, either in hot or cold environments. Previous research detailing the effects of high or low temperatures on broiler live performance is presented in Table 1.3. Recent reports (Goo *et al.,* 2019; Awad *et al.*, 2020) indicate that chickens exposed to long (6 h/d) periods or continuously to high temperatures (27.8 – 34 °C) and consequently to heat stress between 21 and 35 d resulted in decreased BW (171 g less) and poor efficiency (0.06 g:g higher) compared to chicken raised in an environment with optimum temperature according to the age (20 °C). Likewise, Zhou *et al.* (2021) reported that chickens subjected to 72 h at 16 °C between 14 and 17 d presented 18.84 g less average BW gain (95.41 *vs.* 114.25 g) and 0.23 g:g worse FCR (1.57 *vs.* 1.34). Another report from Mohammadalipour *et al.* (2017) demonstrated that chickens between 21 and 42 d raised in environments 6 °C cooler were 0.09 g:g less efficient between 28 and 42 d (2.12 *vs.* 2.03 g:g) and presented 5% more cumulative mortality from 21 d compared to those housed in normal temperature conditions (15 *vs.* 22 °C). It has been suggested that the lower BW gain and worse FCR result from an increased basal metabolic rate due to a higher requirement of energy for heat production (Chen *et al.,* 2014; Yang *et al.*, 2014; Zhou *et al.,* 2021). Although these reports indicate that lower temperature may reduce the live performance of broilers, other authors (Candido *et al.,* 2016; Su *et al.*, 2020) have suggested that chickens can still adapt to environments up to 3 °C lower than recommended in the early stages without further effects in BW nor FCR. However, housing and environmental conditions to carry out these experiments may not reflect the commercial conditions, where great variability among house structures, ventilation systems, local environment, and some other factors influence the conditions within the broiler house. Consequently, chickens might not adapt since temperatures under these conditions are not held constant, which is necessary to modify the way chickens react to the environment offered. Instead, studies based on data analytics using environmental sensors (Neethirajan, 2020) could reveal the actual impact of fluctuating temperatures on broiler live performance.

On the other hand, some reports indicate that relative humidity (RH) could affect broiler BW and FCR. However, the response may depend on the environmental temperature (Weaver and Meijerhof, 1991; Yahav, 2000; Zhou *et al.,* 2019). Chickens exposed to constant RH of 45% were heavier at 42 d than those subject to either weekly increments of 8% from 40 to 80% RH or maintained steady at 75% RH (2,277 *vs.* 2,245 g). In contrast, Zhou *et al.* (2019) did not report differences in average daily feed intake, FCR, or mortality at three levels of RH, 35, 60, or 85%. Still, Yahav (2000) described different responses in BW when chickens were exposed to four RH treatments (40-45, 50-55, 60-65, and 70-75% RH) but at two different temperatures (28 or 30 °C). Overall, heavier chickens were observed across treatments within 28 °C than those placed at 30 °C. At both temperatures, the highest BW was detected in the treatment of 60-65% RH, but at 28 °C no differences were observed among the other treatments while chickens housed at 30 °C and 40-45% RH resulted in decreased BW in comparison to their counterparts at higher RH. Other authors (Zulovich and DeShazer, 1990; Xin *et al.,* 1992; Brown-Brandl *et al.,* 1997; Tao and Xin, 2003; Chepete *et al.,* 2005) have consequently developed equations for poultry based on temperature, RH, and ventilation to depict the interaction among environmental factors that can alter the performance of broilers. Still, some equations have been limited for practical application since they account for minimum or maximum temperatures along the day, include measurements that are not often collected or have been designed for the specific type of production, environment, or facilities (Chepete *et al.*, 2005; Purswell *et al.*, 2012).

With the development of sensor technology to monitor and control the inhouse environmental conditions, temperature and RH are one of the most common data available from all farms, but seldom or never analyzed to optimum conditions for better broiler live performance (Neethirajan, 2020; Martinez *et al*., 2021).

Farm-associated factors

Some studies focusing on different aspects of the farms have been conducted to determine the relationship between these factors and the performance of broilers. Those studies included the transport of day-old chicks (Bergoug *et al.,* 2013), litter material (Angelo *et al.,* 1997; Araújo *et al.,* 2007; Ramadan *et al.,* 2013; Brito *et al.,* 2016; Garcês *et al.,* 2017; Toledo *et al.,* 2019), litter reuse (Garcés-Gudino *et al.*, 2017; Abougabal, 2019), geographical altitude (Rachmawati *et al.,* 2016) among others.

Under commercial operations, it is known that day-old chicks need to be transported from the hatcheries to the farms, which can represent long trips within suboptimal conditions of feed and water deprival, heat stress, and dehydration (Decuypere *et al.,* 2001; Oviedo-Rondón *et al.,* 2009; Abreu *et al.,* 2017; Yerpes *et al.,* 2021). Yerpes *et al.* (2021) found significant positive correlations between the journey duration and the weight loss of chicks at placement. Also, Bergoug *et al.* (2013) evaluated three transportation durations, 0h that represented chicks traveling up to 200 m or less than 5 min to the placement site, and 4h and 10h meaning the time chicks were transported by truck from the hatchery until the farm. Results indicated that chicks subject to less than 5 min trip were heavier during the first three wk of age. After that, no differences were detected among treatments. No effects of transportation were observed on FCR at all ages (Bergoug *et al.*, 2013). Although chicks being transported were different in BW from those placed near the hatchery, transportation conditions included a truck with air conditioning (28 to 29 °C) and controlled RH (34 to 36%), which can greatly differ from traditional transportation conditions that can reach 34 °C (Oviedo-Rondón *et al.*, 2009). Still, under more challenging transport conditions of commercial operations, chick transportation from hatchery to farm is not often considered a cause that may reduce broiler live performance at the end of the production cycle.

Once the chickens reach the farm, the first contact is with the litter material. Wood shaving and rice hulls are the most common material employed for placing birds, but other by-products such as wheat straw, grass, paper, sand, or sawdust have been widely evaluated (Angelo *et al.,* 1997; Araújo *et al.,* 2007; Ramadan *et al.,* 2013; Brito *et al.,* 2016; Garcês *et al.,* 2017; Toledo *et al.*, 2019) on the performance of broilers. Usually, those experiments have not reported significant differences among litter materials on live performance. It was observed that many studies accounted for a low number of replicates (Garcês *et al.,* 2017; Ramadan and El-Khloya, 2017) per treatment which could not represent enough sample error to determine significant differences among treatments. In contrast, a comprehensive meta-analysis conducted by Toledo *et al.* (2019) indicated that heavier and more efficient chickens resulted from systems where wood shaving had been used as a litter compared to rice hulls or alternative litters, respectively. Increasing the number of replicates or analyzing commercial data where several flocks are placed in different litter materials that depend on local availability could probably provide some input on the actual effect of litter type on the BW and FCR. Additionally, the litter may be either new or reused. A few studies have been conducted to determine the impact of litter recycling (Garcés-Gudino *et al.,* 2017; Abougabal, 2019) on live performance of broilers. In a report from Abougabal (2019) was concluded that litter recycling did not represent a hazard for the performance of broilers since different treatments (new litter, 50% new litter – 50% reused litter, 100% reused litter, and 100% reused treated litter) showed no differences in broilers BW along the production cycle nor FCR at the end of the experiment. Other variables analyzed, such as mortality, livability, European production efficiency index, or carcass traits, did not exhibit differences among treatments (Abougabal, 2019).

Conversely, Garcés-Gudino *et al.* (2017) suggested that litterrecycling may have benefits by improving BW, FCR, and reducing coccidia oocyst counts. In that experiment, the litter was treated to reduce the bacterial load prior to placing the subsequent broiler flocks. Results indicated that broilers placed in litters reused once or twice were significantly heavier (1,922 *vs.* 1,753 g), had better BW gain (53.7 *vs.* 48.8 g/d), were more efficient (1.588 *vs.* 1.633 g:g), and presented less mortality (1.61 *vs.* 3.2%) than those chickens placed over new litter. The authors suggested (Garcés-Gudino *et al.,* 2017) that the probiotic effect of the reused litter may enhance the immune response in chickens leading to better performance (Chapman, 1999; Cressman *et al.,* 2010; Garcés-Gudino *et al.,* 2017).

On the other hand, the geographic altitude of the farms has demonstrated to alter the response of chickens at slaughter age. Rachmawati *et al.* (2016) experimented with chickens allocated in three altitudes measured in meters above sea level and labeled as lowlands (< 400 m.a.s.l.), middle lands (400-700 m.a.s.l.), and highlands (> 700 m.a.s.l.). The authors indicated that heavier chickens (184 g) at 35 d were observed above 700 m.a.s.l. than those chicks placed in low or middle lands. However, these differences may be attributed to the differential temperature between locations. It was described in the report that lowlands accounted for temperatures between 28.89 and 32.34°C, middle lands between 25.80 and 28.37 °C and highlands between 23.69 and 25.60 °C. Thus, the effects of farm altitude on broiler performance may be highly related to environmental temperature, which at higher altitudes would reduce the effects of heat stress resulting in better performance.

Although these factors have been demonstrated to influence broiler BW and FCR, no reports detail the possible effects in commercial operations. Often, these variables are not analyzed because the data collection and the development of appropriate analysis methods are still a challenge. In this case, ML models that account for the high number of variables and allow to rank them in importance could reveal a better understanding of the role of farm-associated variables in live performance and how to design ideal plans that minimize or compensate for harmful effects of factors on the growth and efficiency of broilers.

IMPACT OF NUTRIENTS ON BROILER BODYWEIGHT AND FEED CONVERSION RATIO

Generally, the effects of energy and nutrient levels on broiler performance have been studied with one and up to three nutritional factors changing. However, in commercial production, the flocks produced in a period of time could be exposed to variations in the real final concentration, intake, digestibility and bioavailability of several nutrients simultaneously. The following discussion will address the effects of energy or specific nutrient levels in modern broiler chickens. However, the objective of research in the present thesis is to detect the multiple and variable effects of nutrient consumption simultaneously on the variability of final BW and FCR. The traditional method to evaluate nutrient levels relates responses to the energy or nutrient concentration, but not to the final amounts of nutrient ingested. In contrast, for optimization and planning nutrient intake is the only way to compare among flocks and companies (Agri Stats, 2021). Conflicting results or variations in response to energy or nutrient levels may not depend only on dietary concentration, but on the feed intake variability that could be affected by the previous growth rate, feed intake, environmental conditions, health status, level of stress and competition within the flock, among other factors. Some literature will be reviewed to observe the multiple variations in the responses that could be observed in nutrient levels.

Energy

Dietary energy has been described as of great importance in poultry since it represents around 60% of the total diet cost (Ahiwe *et al.,* 2018) and is highly related to the growth rate and carcass quality (Rosa *et al.,* 2007; Ahiwe *et al.,* 2018; Maharjan *et al.,* 2021). Additionally, some reports may indicate that unbalanced or excessive energy in broiler diets could reduce the FI (Leeson *et al.,* 1996; Rosa *et al.* 2007; Maharjan *et al.,* 2021) and consequently the intake of other nutrients. Nevertheless, reports usually indicate the dietary nutrient density offered to chickens while actual metabolizable energy (ME) intake across the production cycle is not commonly presented. Several studies have been conducted (Vieira *et al.*, 2006; Infante-Rodriguez *et al.,* 2016; Cerrate *et al.,* 2019; Massuquetto *et al.,* 2020; Maharjan *et al.,* 2021) to determine ideal levels of ME for broilers in different growth phases. Viera *et al.* (2006) evaluated three levels of ME (2,870, 3,000, and 3,100 kcal/kg) between 0 and 7 d of age. The authors indicated that no differences in BW were observed while chickens fed 3,000 or 3,100 kcal/kg were more efficient (1.054 *vs.* 1.106 g:g) than their counterparts from the 2,870 kcal/kg treatment. The estimated ME intake was 419, 426, and 440 kcal for each treatment. Similarly, Infante-Rodriguez (2016) mentioned that chickens fed ME levels from 2,960 to 3,080 kcal/kg, which represented an intake of ranging from 3,461 and 3,572 kcal did not exhibit differences on BW gain at 21 d while chickens from the treatment with 3,040 kcal/kg were the most efficient compared to diets with less dietary energy. Thus, variation in the cumulative ME intake or dietary energy level does not affect the BW at early stages of growth. Still, they do alter the efficiency of broilers. In a report by Maharjan *et al.* (2021) two broiler strains (A and B) fed with five levels of ME (2,800, 2,925, 3,050, 3,175, and 3,300 kcal/kg) were evaluated under two environments (hot and cool) between 22 and 42 d of age. The authors from that study indicated that the ME intake estimated from 10,600 to 11,656 kcal resulted in positive linear effects with BW, improvements in the FCR but a negative linear effect with the FI regardless of the strain or environment. In contrast, Massuquetto *et al.* (2020) observed that after 3,121 kcal/kg in broiler diets between 35 and 47 d did not affect BW, suggesting that the maximum response is reached at 8,193 kcal of energy intake between that period.

Crude protein and digestible lysine

CP and dLys play an important role in the broiler metabolism and growth as major constituents of body tissues and protein accretion for lean mass (Alagawany *et al.,* 2020). Consequently, it has been described that dietary CP intake affects protein turnover in broilers (Qaid and Al-Garadi, 2021). Kamely *et al.* (2020) reported that chickens fed standard (23.78%) or reduced (21.23%) CP diets during starter (1-14 d) resulted in no differences on BW or FCR at 14 or 35 d. Ghahri *et al.* (2010) evaluated three levels of dietary CP (18, 20, and 22%) and four levels of dLys (0.8, 0.9, 1.0, 1.1%) in chickens between 21 and 42 d. In that experiment, it was reported that the BW gain increased with the CP level while dLys exhibited a quadratic effect. An intake between 21.72 g and 30.67 g was calculated for dLys. In another experiment conducted by Hirai *et al.* (2020), chickens fed three levels of dLys (1.00, 1.08, and 1.18%) resulted in heavier broilers (1,461 *vs.* 1,424 g) at 1.18% dLys or 19.1 g of intake compared to other treatments that received on average 17.6 g. Other authors (Cemin *et al.*, 2017; Lee *et al.*, 2018) have evaluated different levels of dLys to describe optimum levels of dLys. Cemin *et al.* (2017) determined by using dLys levels ranging from 0.97 to 1.37, 0.77 to 1.17, and 0.68 to 1.07% during starter, grower, and finisher, respectively, that chickens presented the maximum performance at 1.16, 1.04, and 1.00 for the same phases. Still, Lee *et al.* (2018) indicated that dLys can be included as high as 1.33% in the starter phase for optimal performance according to broken-line regression, .

Calcium and phosphorus

These two nutrients account for important functions in the growth and development of broilers due to their contribution to bone formation, muscle functionality, and metabolism (Underwood and Suttle, 1999; Imari *et al.*, 2020). Han *et al.* (2016) indicated that increasing the Ca:P ratio from 1.14 to 2.86 from 1 to 42 d of age resulted in a linear increase of BW. Similarly, Jiang *et al.* (2016) showed that diets containing high non-phytate P in growers (0.45%) and finisher (0.35%) produced heavier chickens without differences in FCR. However, Imari *et al.* (2020) demonstrated that chickens restricted up to 30% in Ca and P levels between 11 and 24 d did not exhibit differences in BW at the end of the grower and finisher phases. Calcium is considered one of the most variable nutrients in feed and excess has been related to gut health issues and lower utilization of other nutrients including P (Walk *et al*., 2021).

CONCLUSIONS

In conclusion, the broiler BW and FCR are affected by several farm-associated, management, environmental, and nutritional factors. However, these factors' combination or contribution to the live performance of broilers has not been described in experimental conditions nor under commercial operations where high variability can be observed due to different conditions proper of integrated companies. Statistical and data analytics tools may help determine how these factors can alter the performance of broilers while implementing strategic solutions to address issues observed in commercial settings.

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Table 1.1. Growth models used in poultry and parameters description.

Model Name	Equation	Parameters	Authors
Gompertz	$W_t = W_A * exp(-exp(-B\ (t - t^*)))$	W_t Body weight (g) at time t W_A Asymptotic response B Growth rate constant (g/d) t^* Time (d) when broilers reach the maximum growth rate	Gompertz, 1825
Gompertz-Laird	$y = W_0 * exp[(L/K)(1 - exp - Kt)]$	W_0 Initial BW K Rate of exponential decay L Initial growth rate t Age (wk or days)	Laird *et al.,* 1965
Logistic	$y = W_A\ /\ [1 + exp - K(t - ti)]$	W_A Asymptotic response K Exponential growth rate ti Age at inflection point	Robertson, 1923
von Bertalanffy	$y = W_A * (1 - B * exp(-K * t))^3$	W_A Asymptotic response K Maximum relative growth B Integration constant	von Bertalanffy, 1957
Richards	$W_t = W_A[1 - (1 - m)\ exp\left[-\frac{K(t - t_i)}{m^{\frac{m}{1-m}}}\right]]^{1/(1-m)}$	W_t Body weight (g) at time t W_A Asymptotic response K Maximum relative growth ti Age at maximum rate of growth m Shape parameter. $m^{1/(1-m)}$ is relative weight at *ti*	Richards, 1959
Weibull	$W_t = W_A - m * exp -k * t^d$	W_t Body weight (g) at time t W_A Asymptotic response m Shape parameter k Coefficient of relative growth t^d Time	Weibull, 1951

Table 1.2. Previous research of the effects of feed restriction in broilers.

Authors	Objective	Variable of interest	Treatments	Main results
Zhan *et al.,* 2007	To detect the effects of early feed restriction on metabolic programming and compensatory growth	BW, average daily gain, average daily feed intake, FCR, carcass composition, breast muscle and crude protein or ether extract	2 treatments: ad libitum and restricted (deprived of feed 4h/d, from 1-24 d)	Broilers raised under feed restriction resulted in a reduction on avg daily gain, avg feed intake, breast muscle, carcass yield and abdominal fat at 21 d. At 63 d the abdominal fat yield increased. No other differences were detected on growth parameters at 63 d between treatments
Özkan *et al.,* 2010	To evaluate the combined effects of feed restriction programs, high and low altitude and cold vs. normal ambient temperatures on the development of ascites	BW, feed intake, FCR, ascites, mortality	*Ad libitum*, restriction from 7 to 14 d and from 7 to 21 d. High and low altitude and cold and normal temperatures	*Ad libitum* broilers raised in high altitude under normal temperature had 38.6 g of feed intake more compared to broilers restricted from 7 to 21 d raised under the same conditions from 28 to 35 d (175.4 *vs.* 132 g). The condition, feeding and sex affected BW gain at all periods.
Jalal and Zakaria 2012	To evaluate the effect of quantitative early feed restriction programs on growth and carcass traits	BW, BW gain, feed intake, FCR, mortality, carcass traits	4 treatments: control (100% *ad libitum)*, diets that provided 50%, 65% and 80% of *ad libitum* feed intake	Significant differences indicated that broilers from 65% had higher BW gain at 21 d. This parameter decreased at 35 d on broiler fed 50%, 65% and 80%. The control group resulted in the best FCR at 21, 28, 35 and 42 d.
Butzen *et al.,* 2013	To evaluate the effect of early feed restriction by quantity, time, quality, weight of body fractions and changes in breast meat quality.	BW, BW gain, feed intake, FCR, breast fillet quality	2 separate experiments with 4 treatments each: a*d libitum*, 80% of *ad libitum* feed intake, time restriction (*ad libitum* offered 8 h/d), quality restriction (*ad libitum* with 80% of limiting nutrients, diluted with 10% kaolin and 10% rice hulls)	Male broilers on time restriction were lighter at 28 and 35 d compared to other treatments. But females in the same treatment were lighter at 16, 21 and 28 d compared to female broilers from *ad libitum*, and quality restriction. Mal broilers under *ad libitum* and 80% treatments had the best FCR from 8 to 16 d. from 1 to 42 d 80% and time restriction broilers obtained the best FCR.
Dissanayake *et al.,* 2017	To study the effects of quantitative feed restriction on the performance and cost of production	BW, feed intake, FCR, carcass weight, organs weight, feed cost, profit	Control, 90, 80, and 70% of the control diet	Broilers in the 90% resulted in a higher BW gain from 22 to 42 d and from 0 to 42 d, compared to the 70% treatments. This last group had the best FCR from 0 to 42 d.

Table 1.2. (Continued)

Authors	Objective	Variable of interest	Treatments	Main results
Mohammadalipour *et al.,* 2017	To determine the effect of a 40% quantitative early feed restriction on hematological and metabolic alterations, internal organs, growth performance and incidence of ascites under cold and normal temperatures	BW, BW gain, feed intake, FCR, ascites mortality, internal organs, biochemical parameters, blood enzymatic activity	2 dietary treatments: ad libitum and restricted (40% feed restriction from 7 to 14 d) subject to 2 temperature treatments, either cold or normal	Restricted broilers within the normal temperature group had a lower average daily feed intake from 7 to 21 wk than broilers that ate *ad libitum.* The worst FCR was observed in ad libitum broilers from 7 to 21 wk.
van der Klein *et al.,* 2017	To detect the effects of graded levels of feed restriction during the second and third wk on mixed sex broilers	BW, fed intake, uniformity, average daily gain, FCR	Treatments second wk: *ad libitum*, 90, 80, 70% of *ad libitum.* Treatments third wk: *ad libitum*, 95, 90, 85, 80% of *ad libitum*	Broilers restricted 70% at second wk and 80% at third wk had a reduction in the average daily gain during the restriction period. Levels of restriction did not affect BW, FCR, fat deposition, and organs weight at 35 d.
Khurshid *et al.,* 2019	To find the appropriate level of quantitative feed restriction without affecting the broilers performance	BW, feed intake, BW gain, FCR, mortality and the Broiler Farm Economy Index (BFEI) was calculated	*Ad libitum*, and 5, 10, 15, and 20% restricted from *ad libitum*	Broilers under any of the feed restriction treatments had a lighter final BW, and lower BW gain at 36 d, but no significant differences were detected on FCR.
Bordin *et al.,* 2021	To evaluate the performance of broilers subjected to a quantitative feed restriction	BW gain, FCR, uniformity, mortality	3 treatments: *Ad libitum,* 10% restriction, 20% restriction	The best FCR was found on broiler restricted 20%. No significant effects were detected on BW gain, uniformity, and mortality.

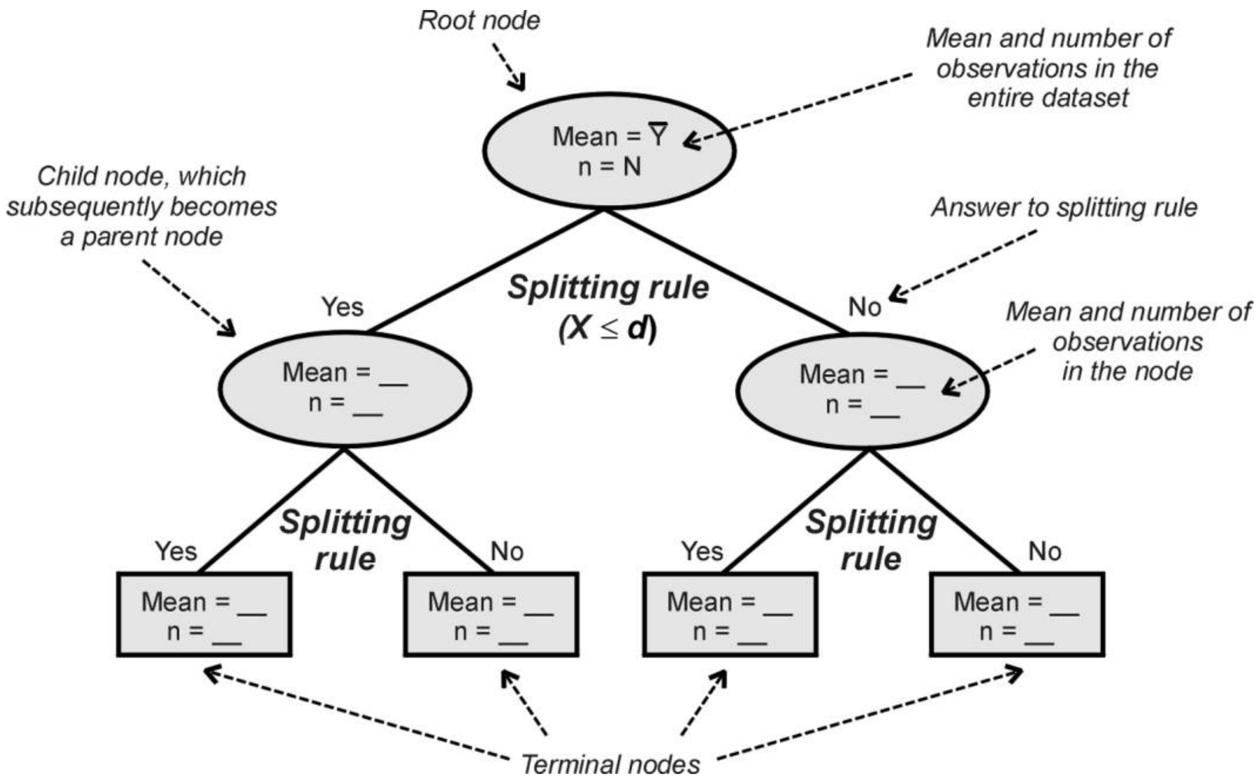
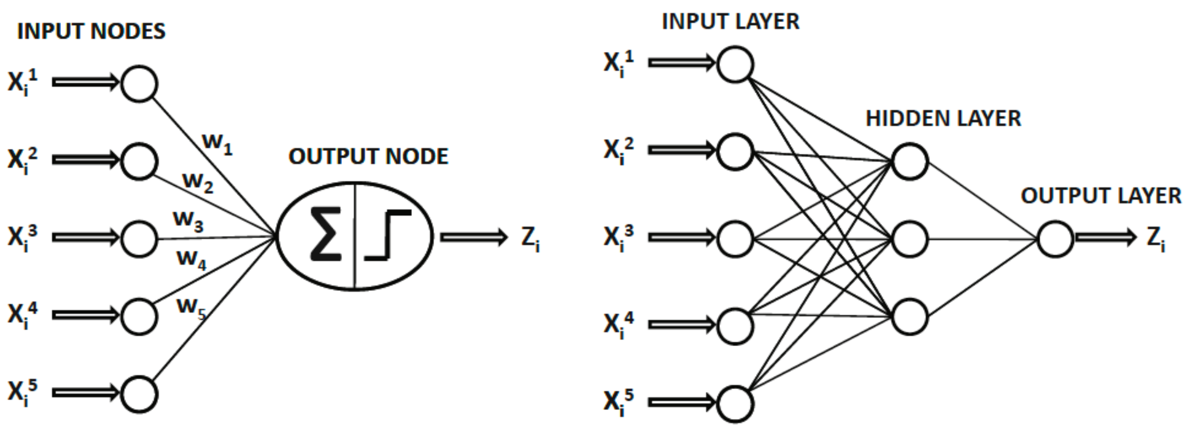


Figure 1.1. Anatomical structure of a decision tree (Olden *et al.*, 2008)



(a) Perceptron (b) Multilayer

Figure 1.2. Basic architecture of (a) perceptron and (b) multilayer perceptron (Aggrawal *et al.*, 2015).

Input-Hidden Connection Weights

X \ Y	Hidden A	Hidden B	Hidden C	Hidden D	Hidden E
Input 1	-0.93	-1.49	0.37	-0.91	0.37
Input 2	-0.57	-1.96	-0.14	1.18	1.26
Input 3	-0.85	1.74	-1.86	-0.05	0.10
Input 4	0.25	-3.01	-0.99	-1.34	-1.65
Input 5	-0.82	0.09	0.86	-0.41	-0.05

X

Hidden-Output Connection Weights

	Hidden A	Hidden B	Hidden C	Hidden D	Hidden E
Output	-1.75	-1.08	-1.13	-2.90	3.37

Connection Weight Products

X \ Y	Hidden A	Hidden B	Hidden C	Hidden D	Hidden E
Input 1	1.63	1.62	-0.42	2.64	1.24
Input 2	1.00	2.12	0.16	-3.43	4.25
Input 3	1.48	-1.89	2.10	0.14	0.34
Input 4	-0.43	3.26	1.12	3.90	-5.57
Input 5	1.43	-0.09	-0.97	1.18	-0.16

$$\boldsymbol{Input_X = \sum_{Y=A}^{E} Hidden_{XY}}$$

	Importance	Rank
Input 1	6.71	1
Input 2	4.10	2
Input 3	2.18	3
Input 4	2.28	4
Input 5	1.38	5

Connection Weight Approach

Figure 1.3. Determination of variable importance by Connection Weight Approach. Adapted from Olden *et al.* (2004)

CHAPTER II

Effect of broiler growth dynamics on the bodyweight and feed conversion ratio of broilers raised to 35 d under commercial tropical conditions

ABSTRACT

Data collection is common in commercial broiler production; however, growth modeling is still a challenge since this data many times lacks an inflection point (IP). This study evaluated BW dynamics, feed intake (FI), BW gain, FCR, and mortality of broiler flocks reared under commercial tropical conditions with control feeding to optimize FCR. The data analyzed included performance records of 1,347 male and 1,353 female Ross 308 AP broiler flocks with a total of 95.4 million chickens placed from 2018 to 2020. Decision trees determined high (HE) and low (LE) feed efficiency groups using FCR at 35d. Logistic, Gompertz-Laird, and von Bertalanffy growth models were fitted with week BW data for each flock within performance groups in R Software. All models resulted in similar R^2, AIC, BIC, and RMSE. The logistic model indicated more accurate estimates. Live performance parameters and model estimates were analyzed using a one-way ANOVA with efficiency as the main effect and mean separation with the t-students test. Fifty-one HE male flocks had 1.371 g:g FCR and 105 LE flocks had 1.527 g:g, while 31 HE female flocks had 1.426 g:g and 128 LE flocks had 1.526 g:g FCR. Males from the HE group were heavier ($P < 0.001$) at hatch and 35 d but lighter ($P < 0.001$) at 14, 21, and 28 d. In contrast, efficiency groups in the females were only significantly different ($P < 0.05$) at 14 and 35 d. The LE females had higher BW at 14 but lower at 35 d. The HE males and females ($P < 0.001$) were offered on average 8.52% and 4.64% less feed than the LE group and were consistently more efficient ($P < 0.001$) from 7 d until slaughter age. No differences in mortality ($P > 0.05$) were observed. LE

males had an IP at 30 d ($P < 0.001$) with exponential growth rate (K) of 0.122 ($P < 0.001$) and BW at IP (Wi) ($P < 0.001$) of 1,467 g. IP in HE males was 4 d later, with a K of 0.114 and Wi of 1,828 g. The maximum daily increment (MI) in HE males was 14 g higher ($P < 0.001$) than the LE rate. On females, despite no differences were observed on the K ($P > 0.05$), the HE group had an IP 2 d later (32 *vs*. 30d), with greater Wi (1,510 *vs*. 1,329 g), and MI. In conclusion, greater feeding control between the second and the fourth week of age, followed by higher feed allowance during the last week, was associated with a better feed efficiency at 35 d in males and females. Also, models demonstrated that a reduced growth rate resulted in heavier chickens at 35 d with better feed efficiency and greater BW gain.

INTRODUCTION

Broiler feed conversion ratio (FCR) is affected by growth dynamics (Buntzen *et al.,* 2013; Bordin *et al.,* 2021), which is expressed as a relationship between BW or feed intake (FI) with age. Growth curves are non-linear models traditionally used to depict the relationship between growth parameters and age (Aggrey, 2002; Al-Nasrawi *et al.,* 2013; Demuner *et al*., 2017; Narinç *et al.*, 2017; Nogueira *et al*., 2019). These models may include the Gompertz function (Gompertz, 1825), the Gompertz-Laird form (Laird *et al.*, 1965) and some other Gompertz variations (Kathleen *et al.*, 2017), the Logistic (Robertson, 1923), and von Bertalanffy functions (von Bertalanffy, 1957), among others (Aggrey, 2002; Narinç *et al.*, 2017; Tjorve *et al*., 2017).

Under commercial settings, broilers are typically raised with *ad libitum* feed allowance. However, controlled feeding programs have been employed for several years in regions with high altitudes as a strategy to reduce the growth rate of broilers and decrease high mortality rates derived from metabolic issues such as ascites and sudden death syndrome (Ozkan *et al.,* 2010; Mohammadalipour *et al.* 2017; van der Klein *et al.,* 2017; Xu *et al.,* 2017). On the other hand, Zuidhof *et al.* (2014) indicated that BW gain had increased about 400% while the FCR has been reduced 50% in the last 50 years, thus changing the growth dynamics of broilers. The constant genetic selection for the improvement of broilers' feed efficiency added up to the strategies employed in commercial operations to raise broilers has led many authors to compare the chickens' growth curves from genetically selected fast-growing (Marcato *et al*., 2008; Demuner *et al*., 2017) and native (Ibiapina-Neto *et al.*, 2020; Mata-Estrada *et al*., 2020; Oliveira Brito *et al.*, 2021) broiler strains, in sexed and unsexed systems (Duan-yai *et al.,* 1999; Al-Nasrawi., 2013; Al-Samarai, 2015). Nevertheless, reports about the growth of broiler chickens subject to feeding control and raised under commercial tropical conditions are still scarce.

Conflicting results have described how different feeding programs may affect the FCR and BW at slaughter age (Buntzen *et al.,* 2013; Dissanayake *et al.*, 2017; Mohammadalipour *et al.,* 2017; Khurshid *et al.,* 2019). Some authors have informed that applying for feeding restriction programs with up to 20% of the *ad libitum* intake during the second week of age (Buntzen *et al.,* 2013; Mohammadalipour *et al.,* 2017) or during the entire cycle (Khurshid *et al.,* 2019), resulted in better FCR early in life with no significant differences in BW at slaughter age (36 d), due to compensatory growth (Zhan *et al*., 2007; Jalal *et al*., 2012). Contrarily, Dissanayake and David (2017) showed that chickens with feeding controlled 10, 20, and 30% from the *ad libitum* intake did reduce both the FCR and the BW, except for the treatment with 10% restriction that increased the BW at 42 d. In this scenario, growth curves play an important role by predicting live performance responses based on the growth dynamics and providing estimates with biological meaning that allow the comparison between flocks of different sex and feed efficiency. These properties could be very useful to be used under commercial conditions to design strategies to predict performance or evaluate the effects of nutritional and management factors (Knížetová *et al*., 1991; Aggrey, 2002; Narinc *et al*., 2017).

On the other hand, the lack of predefined groups or treatments as independent variables for unstructured data analysis is limiting and concern under commercial operations (Jackman *et al*., 2020; Pitesky *et al*., 2020). Therefore, data mining tools are needed to unveil patterns when large amounts of data are presented. Within the available tools, the classification and regression tree algorithm, also known as decision trees, allows creating subgroups based on categorical or continuous predictors (Aggarwal, 2015; Bramer, 2016). Partition trees analyze the independent variable to determine the ideal split point of the dataset by examining the relationship between the variables with Pearson's Chi-square. However, because this statistical test relies on the sample size, P-values tend to be extremely low or significant and need to be corrected by the inverse of P-value or LogWorth (Klimberg and McCullough, 2016). It indicates that the subgroups produced in a decision tree differ statistically. This partition technique could determine groups of low (LE) and high (HE) efficiency of feed utilization in a dataset of a commercial broiler integration to determine root causes. The objective of this study was to estimate and compare the growth pattern of males and females Ross 308 AP broilers according to two categories of FCR at 35 d, HE and LE, and reared under commercial tropical conditions with control feeding to determine conditions that optimize FCR.

MATERIALS AND METHODS

Database and statistical software

One database was obtained from a broiler integration located in Colombia. The database contained BW, FI, FCR, and mortality records of 1,649 male and 1,406 female Ross 308 AP broiler flocks subject to feed restriction from the Aviagen (2017) recommendations. However, data was cleaned and flock records containing missing data were removed. Thus, a total of 1,349 male and 1,353 female flocks presented complete data collected weekly from flock placement until 35 d. The database was organized in such way that each column represented a performance variable and each row a broiler flock. BW corresponds to averages of samples of 1% of the population per broiler house. Cumulative mortality for each week was calculated. The data analyzed represented 95 million chickens raised between 2018 and 2020 in 86 farms under commercial tropical conditions with control feeding across three major poultry production regions of Colombia. In this operation, eggs were incubated using multistage machines in two company-owned hatcheries. At hatch, chicks were sexed, boxed, and transported to farms located up to 531 km away from the hatcheries and a mean altitude of 1,381± 449 meters above sea level. Subsequently, hatchlings were placed in litter-based open-sided broiler houses with rice hulls or wood shavings and fed pre-starter (150 g), starter (900 g), and grower (1,643 ± 145 g) diets up to 35 d. Stocking density was 12.74 ± 1.12 chickens or 28.5 kg/m^2.

The database was organized in Excel® and saved as a comma-separated value file to be imported into the statistical software. Data were analyzed using R (R Core Team, 2021) in RStudio (RStudio Team, Boston, MA, USA) and JMP Pro 15 (SAS Institute, Cary, NC, USA).

Statistical analysis

Data partition. Decision trees (Aggarwal, 2015; Bramer, 2016) were fitted to determine two efficiency groups based upon sex and FCR at 35 d. Partition trees included flock ID as a predictor and FCR at 35 d as the response.

Additional parameters of live performance. Percentage data for week, and cumulative mortality were transformed into the arcsine square-root percentage for analysis. Weekly BW, FI, FCR, week mortality, and cumulative mortality were also subject to a one-way ANOVA with efficiency group as the main effect and mean separation with the t-student test.

Growth models. Three growth models, Logistic (Robertson, 1923), Gompertz-Laird (Laird *et al.*, 1965), and von Bertalanffy (von Bertalanffy, 1957), were fitted both to each flock and all data within the efficiency groups with week data to estimate the relationship between age and BW. The following equations described the models:

- Logistic:

$$y = W_A \,/\, [1 + exp - K(t - ti)]$$

Where,

W_A = Asymptotic response

$K =$ Exponential growth rate

$ti =$ Age at inflection point

- Gompertz-Laird:

$$y = W_0 * exp[(L/K)(1 - exp - Kt)]$$

Where,

W_0 = Initial response

K = Rate of exponential decay

L = Initial growth rate

- von Bertalanffy:

$$y = W_A * (1 - B * exp(-K * t))^3$$

Where,

$W_A =$ Asymptotic response

$K =$ Maximum relative growth

$B =$ Integration constant

The response in which the maximum growth rate is observed, also known as Wi and maximum increment (*MI*), were estimated using the parameters of the logistic model as reported by Al-Nasrawi (2013) with the equations listed below:

$$Wi = W_A / 2$$

$$MI = K * Wi / 2$$

Likewise, the Wi and age at the inflection point (*ti*) from the von Bertalanffy model were calculated (Goshu and Koya, 2013) as follows:

$$ti = ln(3B)/K$$

$$W_i = W_A * 8/27$$

From the Gompertz-Laird model estimates, ti and asymptotic response (W_A) were determined (Aggrey, 2002) with the following equations:

$$ti = (1/K) * \log(L/K)$$

$$W_A = W_0 \exp(L/K)$$

All growth models were fitted using the R stats package's nonlinear least squares (*nls*) function. Coefficient of determination (R^2), Akaike's information criterion (AIC), Bayesian information criterion (BIC), number of iterations, and root mean square error (RMSE) were calculated using the *broom* R package (Robinson, 2014) and utilized as goodness-of-fit metrics to evaluate model performance. The best model criteria included the highest R^2 and the lowest AIC, BIC, RMSE, and lowest iterations.

Parameter estimates from the model of each flock were analyzed as dependent variables using a one-way ANOVA with efficiency as an independent variable and mean separation with the t-student test. Correlation and regression analyses were conducted to determine relationships among parameter estimates.

RESULTS

Data partition

Results of the decision tree for males are presented in Figure 1 and for females in Figure 2. The decision tree for males included seven splits and classified (R^2 = 0.93, RASE = 0.157) the flocks into the HE group containing 51 flocks with an average FCR of 1.371 at 35 d, while the LE group had 105 flocks with an average FCR of 1.527. For females, the decision tree contained eight splits and determined ($R^2 = 0.95$, RASE = 0.011) one HE group comprising 31 flocks with an average FCR of 1.426 and the LE group with 128 flocks and FCR of 1.526 at 35 d.

Live performance

A summary of live performance results for males and females is presented in Table 2.2. Male BW was different ($P < 0.001$) between efficiency groups at all ages except for 7 d. Males from the HE group were heavier ($P < 0.001$) at hatch and 35 d but lighter ($P < 0.001$) at 14, 21, and 28 d. In contrast, efficiency groups in the females were only significantly different ($P < 0.05$) at 14 and 35 d. The LE females resulted in higher BW at 14 but lower at 35 d. Although FI was controlled in the integration with a pre-planned table, there was variation in the amount of feed offered between farms and flocks. However, differences ($P < 0.001$) in FI were observed during the whole production cycle. The HE males and females ($P < 0.001$) were offered on average 8.52% and 4.64% less feed than the LE group. Similarly, LE chickens from both sexes were consistently ($P < 0.001$) less efficient than their counterpart from 7 to 35 d. On week mortality, significant differences ($P = 0.001$) were observed only on males from 8 to 14 d. Chickens from LE group presented ($P = 0.001$) a mortality 0.22% higher than HE chickens (0.81 *vs.* 0.59%). Consequently, male cumulative mortality up to the second ($P < 0.001$) and the third ($P = 0.001$) week of age were significantly different between efficiency groups. LE males resulted in cumulative mortalities 0.31 and 0.38% higher than the HE chickens at 14 and 21 d. No other differences were detected in males from the third week onwards or between female efficiency groups on the week and cumulative mortality.

Growth models

Parameter estimates for all models are presented in Table 2.3 for males and Table 2.4 for females. Significant differences ($P < 0.001$) were detected between parameter estimates from male efficiency groups in the Logistic, Gompertz-Laird, and von Bertalanffy models. All parameter estimates from the Logistic model were higher ($P < 0.001$) in HE male chickens except for *K* ($P < 0.001$) that was 0.008 lower (0.122 *vs.* 0.114). It indicated that the LE males reached the *Wi* 4 days earlier ($P < 0.001$) and 361 g lighter ($P < 0.001$) than the HE group. Additionally, males from this group presented an average *MI* of 14 g/d higher than their counterparts (103 *vs.* 89 g/d). The Gompertz-Laird models predicted heavier HE chickens ($P < 0.001$) at hatch and asymptotic age ($P < 0.001$) with a longer *ti* ($P < 0.001$). Significant differences on *L* and *K* indicated LE males presented faster initial growth rates and rates of exponential decay ($P < 0.001$). Similarly, the von Bertalanffy model for males indicated higher ($P < 0.001$) parameters for HE males compared to LE chickens except for *K* that was greater ($P < 0.001$) in the LE group.

On female BW, estimates from the Logistic model resulted in HE chickens being 363 g heavier at asymptotic age ($P < 0.001$) compared to the LE group. HE female chickens reached the *ti* at 32 d while LE chickens exhibited the maximum daily growth at 30 d. However, the difference in the *Wi* between HE and LE was estimated ($P < 0.001$) in 181 g (1,510 *vs.* 1,329 g) with 9 g/d more ($P < 0.001$) of *MI*, respectively. No significant differences ($P > 0.05$) were observed on *K*. Similarly, Gompertz-Laird model estimates showed no significant differences ($P > 0.05$) between efficiency groups on W_0 and *L* means. Significant effects of efficiency were detected on *K, ti,* and W_A from the Gompertz-Laird model. LE females presented a higher rate of exponential decay ($P < 0.001$) but lower ($P < 0.001$) *ti* and W_A. Significant effects of efficiency were also observed in all parameters from the von Bertalanffy models. All estimates from LE chickens were lower ($P < 0.001$) except for *K* that showed a higher estimate ($P < 0.001$) compared to the LE group.Strong ($P < 0.001$) negative correlations ($r = -0.86$) were detected between model parameters associated with growth rates and age at *Wi* regardless of model, sex, or efficiency group.

Predicted BW and BW gain from all three models (Fig. 2.3) indicated that LE males presented a daily BW gain higher than HE chickens up to 24 d. However, HE male chickens exhibited a lower decay rate, resulting in superior daily BW gain after 24 d and heavier chickens from 32 d onwards. In contrast, LE females were slightly over its counterpart up to 18 d, but as observed in the males, the difference in growth rate was enough to produce heavier female chickens from 25 d.

Goodness-of-fit metrics (Table 2.3) from models that fit all data by efficiency and sex resulted in similar R^2, AIC, and BIC values. However, the von Bertalanffy model presented the greatest number of iterations for both efficiency groups and sexes compared to the Logistic and Gompertz-Laird models. The RMSE from the Logistic models were on average 3.39 higher than the other two models. In contrast, residual analyses for HE male chickens' data (Figure 2.4) indicated that all three models overfit the response at 0 and 28 d. The von Bertalanffy model presented the least error compared to the Logistic and Gompertz-Laird models at both ages. At 7 and 21 d, all models underfit the BW, except for the Logistic model that was 2.94 g above the mean BW compared to the Gompertz-Laird and von Bertalanffy models that were 7.7 and 9.0 g below for that week, respectively. On females, all models overestimated the bodyweight at hatch at 28 and 35 d in the HE group. From these results, the von Bertalanffy model presented the lowest residuals at hatch and at 28 d but the highest at 35 d.

Similarly, at 14 and 21 d, all models underfit the response. The von Bertalanffy model demonstrated to be only -1 and -5 g far from the response while the Gompertz-Laird was -8 g at both ages and the Logistic -19 and -22 g at 14 and 21 g, respectively. In contrast, all models for the LE female group underfit the response. The von Bertalanffy model resulted in the lowest error at hatch and 7 d, while the Logistic model was more accurate from 14 to 28 d but presented the highest error at 35 d.

DISCUSSION

Live performance

In the present study, HE male chickens had a BW at hatch 2 g lower than LE chickens but resulted in heavier broilers at 35 d and more efficient throughout the whole production cycle. Several authors have described the BW at hatch as a trait highly related to egg weight (Ramaphala and Mbajiorgu, 2013; Iqbal *et al.*, 2014; Duman and Şekeroğlu, 2017), breeder age (Yalçin *et al.,* 2013; Ipek and Sozcu, 2014; Machado *et al*., 2020), and incubation conditions (Deeming, 2005; Barbosa *et al.,* 2008; Willemsen *et al.*, 2010). Thus, significant differences in BW might be observed at hatch. However, Duman and Şekeroğlu (2017) reported that differences in BW at hatch disappeared after the first week of age and affected neither BW nor FCR at 35 or 39 d in Ross 308 broilers. In contrast, Nazligül *et al.* (2005) indicated that with intensive care, birds coming from smaller or bigger eggs could reach normal development due to compensatory growth. Duan-yai *et al.* (1999) evaluated three available commercial strains of broilers in Australia (C, R, and I). They determined that the male chickens from the I strain, which were the lightest at hatch, had an average of 141 g more at 35 d than the other two strains (1,922 *vs.* 1,781 g) but 379 g less at 105 d (5,239 *vs.* 5,618 g).

Some poultry producing companies utilize quantitative control feeding in broilers to mitigate the effect of lower oxygen availability and cool environmental temperature as elevation increases in the mountains and consequently avoid high mortality due to ascites (Puyana and Betancourt, 2015; Mohammadalipour *et al.* 2017). Also, this approach has been employed as a strategy to reduce metabolic disorders and bone developmental issues related to the rapid growth of modern chickens (van der Klein *et al.,* 2017; Xu *et al.,* 2017). Although all animals in the present study were feed-controlled throughout the cycle compared to the Ross 308 AP recommendations (Aviagen, 2017), the level of feed-restriction observed was greater in both males and females from the HE groups than the LE chickens.

Some studies have described the early feeding restriction (Buntzen *et al.,* 2013; Mohammadalipour *et al.,* 2017; Xu *et al.,* 2017) as a method that limits the amount of feed allowance only during the second week of life. Mohammadalipour *et al.* (2017) indicated that Ross 308 male chickens were significantly more efficient during the second and third week of age when subjected to a 40% feed restriction from 7 to 14 d was carried out. Birds were under normal environmental conditions (33°C, 30°C, and 27°C for weeks 1, 2, and 3, respectively). Afterward, no significant effects were observed in that study. Similarly, Buntzen *et al.* (2013) demonstrated that Cobb 500 male and female broilers offered with 80% of the *ad libitum* intake from 8 to 16 d were significantly lighter from 16 to 21 d. Still, chickens could recover a BW similar to the control treatment from 28 d onwards. In that study, no significant differences among treatments were reported either in BW for both sexes at 42 d or in FCR from 1 to 42 d between these two treatments. Khurshid *et al.* (2019) showed that reducing the amount of feed offered between 10 and 20% of the *ad libitum* intake from 1 to 36 d resulted in lighter broilers at 36 d compared to those chickens without restriction. Still, there was no difference in FCR among restriction treatments (5, 10, 15, and 20%). In contrast, Dissanayake *et al.* (2017) reported that using a feed allowance reduced 10, 20, and 30% from the *ad libitum* group, the FCR was improved as the feed restriction was increased in all periods evaluated (0 to 21, 22 to 42 and 0 to 42). However, the best performance was observed at a 10% restriction that lowered the FCR but increased the BW. Bordin *et al.* (2021) also reported that chickens subject to feed restriction of 20% from 10 d presented the lowest FCR while the daily BW gain and uniformity did not vary among chickens restricted at 10% or fed *ad libitum*. According to these studies, chickens could preserve a greater feed efficiency one week more after the established control feeding. Still, longer periods of restriction could condition chickens to be more efficient. It has also been described that feed restriction in broilers could improve ileal digestibility of dry matter, crude protein, and energy (Massuquetto *et al.*, 2019) as well as produce morphological changes in epithelial cells from the small and large intestines that could modify the transport of nutrients (Da Silva *et al.*, 2007; Gilbert *et al.*, 2008; Bordin *et al.*, 2021).

The results from this study showed that while LE males had a consistent feeding control of 17.25% on average compared to the Ross 308 AP recommendations from the second week onwards, the HE males were subject to a feed restriction of 25.45% on average from the second week of age up to four weeks and then a reduction in the restriction of 1.62% in the last week (25.45 *vs.* 23.83%). It seems that after chickens were conditioned to feeding control, a greater feed allowance during the previous week could result in heavier chickens at 35 d and still be more efficient. Similarly, LE females resulted in a feed restriction of 18.1% from the second week onwards. HE females demonstrated a feed restriction of 22.5% between two and four weeks of age to be later offered with 3.38% more feed during the last week.

Growth models

Significant differences between efficiency groups were observed in both male and female model estimates from the present study. Parameters from all models were higher in HE groups compared to LE groups except for estimates associated with growth rates (K for all three models) that were lower. However, W_A widely differed among models, resulting in the Logistic model with acceptable values since values up to 7,000 g have been previously reported for commercial strains of broilers raised to maturity (Goliomytis *et al.,* 2003). Similarly, Atil *et al.* (2007) demonstrated that the Logistic model provided better biological estimates than Gompertz and von Bertalanffy models when fitting growth curves for two commercial broiler genetic lines and both sexes. Another study (Mouffok *et al.,* 2019) determined that Gompertz and von Bertalanffy models presented higher asymptotic values than the Logistic model in Cobb 500 broilers raised to 49 d. As explained by Duan-yai *et al.* (1999), it could be that data up to 35 d of age is not sufficient to describe the inflection point of chickens.

In the present study, hatching BW was overestimated in all models. Some authors (Magothe *et al.*, 2010; Mata-Estrada *et al.*, 2020) have indicated that the Gompertz model usually overfits this parameter to improve the fit in the following weeks, while other studies (Al-Samarai *et al.*, 2015) resulted in underfit responses. Since hatching and asymptotic BW parameters have usually been over or underfitted, it has been proposed that these parameters should not be considered (Magothe *et al.*, 2010; Mata-Estrada *et al.*, 2020) for practical meaning and relevance should be focused on the ability to predict responses in the subsequent weeks (Yee *et al.*, 1993; Roush *et al.*, 2006).

As expected, strong negative correlations were observed between *K* and *ti* estimates. Correlation coefficients for both males and females regardless of model, sex, and efficiency group indicated that as chickens grew faster, the *Wi* was reached earlier. Previous reports (Al-Nasrawi *et al.*, 2013; Al-Samarai *et al.*, 2015) described similar findings in Ross 308 broilers when using Gompertz, Logistic, von Bertalanffy, and Weighted Least Square models. According to Marcato *et al.* (2008), the maximum BW gain in broilers depends on the protein deposition, driven by genetics, and consequently has a daily limit. A recent report from Dukha *et al.* (2018) showed in a mechanistic model based on Gompertz for body protein mass that the value of protein deposition drastically alters the potential mature BW at any step of the growth.

Moreover, the maturity rate or precocity parameter at low-rate values may result in late “maturity”. In contrast, higher values of precocity could result in early maturing or reaching the *Wi* (Dukha *et al.* 2018), as observed in the present study. Thus, it has been proposed (Kessler *et al.*, 2000; Marcato *et al.*, 2008; Nogueira *et al.*, 2019) that the longer the chicken takes to reach the *Wi* in protein deposition, which could be directly related to the growth rate, the more efficient will be the chicken to produce lean tissue.

In this study, all models, regardless of sex or efficiency group, resulted in R^2 greater than 0.99. Several authors have reported similar results when evaluating growth curves under different conditions (Roush *et al*., 2006; Al-Nasrawi, 2013; Al-Samarai, 2015; Demuner *et al*., 2017). Thus, some reports indicate that the model evaluation should be conducted with caution when using R^2 as a differentiator since this parameter tend to be high and close among models, which could make difficult the identification of a significantly better model (Drumond *et al.,* 2013; Al-Samarai, 2015; Demuner *et al.,* 2017). Traditionally, the model that has provided better interpretability and goodness-of-fit in broilers has been the Gompertz model in the traditional form when the dataset contains data for more than six weeks, which includes the *Wi* (Freitas, 2005; Mazucheli *et al.*, 2011; Drumond *et al*., 2013; Mohammed, 2015; Mota *et al*., 2015). However, in this study, despite the Gompertz-Laird model obtaining the best goodness-of-fit metrics and the lowest residuals, the Logistic model provided estimates with better biological meaning. It indicated that in the evaluation of the growth of broilers up to 35 d, the Gompertz-Laird model shows better predictability capabilities while the Logistic model produces better parameter estimates.

Therefore, the purpose of the model and the amount of data should be considered when deciding based on growth curves under commercial conditions.

Conclusions

In conclusion, both male and female Ross 308 AP broilers presented a better feed efficiency at 35 d when a feed restriction of 25.45 and 22.50% from the genetic line FI recommendation was established between the second and the fourth week of age with a subsequent increase in the feed allowance during the last week. Also, models demonstrated a reduced growth rate, resulting in heavier chickens at 35 d with better feed efficiency and greater BW gain after 24 d for males and 22 d for females.

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Table 2.1. Observed weekly BW, FI, FCR, mortality, and cumulative mortality of male and female LE and HE groups[1] of Ross 308 AP chickens under commercial conditions and feed control.

Age (d)	Males					Females				
	LE (*n*=51)	HE (*n*=105)	SEM	CV	*P*-value	LE (*n*=31)	HE (*n*=128)	SEM	CV	*P*-value
BW	--------------(g)------------			(%)		--------------(g)------------			(%)	
0	39^{b}	41^{a}	0.3	6.1	<0.001	40	41	0.3	6.5	0.103
7	164	165	1.3	6.5	0.885	161	162	1.6	7.4	0.847
14	381^{a}	359^{b}	2.6	5.9	<0.001	362^{a}	352^{b}	3.3	6.8	0.038
21	748^{a}	716^{b}	4.9	5.5	<0.001	700	692	5.2	5.6	0.310
28	1,267^{a}	1,224^{b}	7.0	4.7	<0.001	1,160	1,176	7.5	4.8	0.161
35	1,891^{b}	1,937^{a}	7.7	3.4	<0.001	1,716^{b}	1,795^{a}	9.1	3.9	<0.001
FI	--------------(g)------------					--------------(g)------------				
7	145^{a}	138^{b}	1.4	7.9	0.001	142^{a}	137^{b}	1.4	7.6	0.014
14	450^{a}	406^{b}	3.1	5.9	<0.001	424^{a}	396^{b}	3.8	6.8	<0.001
21	991^{a}	895^{b}	5.5	4.8	<0.001	921^{a}	875^{b}	5.7	4.7	<0.001
28	1,804^{a}	1,616^{b}	8.8	4.2	<0.001	1,646^{a}	1,587^{b}	9.1	4.1	<0.001
35	2,881^{a}	2,655^{b}	11.7	3.5	<0.001	2,620^{a}	2,560^{b}	13.7	3.9	0.004
FCR	------------(g:g)------------					------------(g:g)------------				
7	0.882^{a}	0.841^{b}	0.007	6.4	<0.001	0.883^{a}	0.846^{b}	0.009	7.3	0.004
14	1.179^{a}	1.131^{b}	0.006	4.0	<0.001	1.172^{a}	1.126^{b}	0.005	3.4	<0.001
21	1.327^{a}	1.251^{b}	0.006	3.9	<0.001	1.317^{a}	1.265^{b}	0.005	3.1	<0.001
28	1.424^{a}	1.322^{b}	0.005	2.7	<0.001	1.419^{a}	1.350^{b}	0.004	2.3	<0.001
35	1.527^{a}	1.371^{b}	0.002	1.0	<0.001	1.526^{a}	1.426^{b}	0.001	0.4	<0.001
Week mortality	-------------(%)------------					-------------(%)------------				
0 - 7	0.45	0.35	0.03	30.2	0.055	0.49	0.71	0.06	36.3	0.084
8 - 14	0.81^{a}	0.59^{b}	0.05	23.9	0.001	0.75	0.98	0.07	29.2	0.071
15 - 12	0.59	0.51	0.04	26.6	0.072	0.49	0.54	0.05	32.9	0.846
22 - 28	0.51	0.46	0.04	30.6	0.269	0.37	0.42	0.05	35.2	0.551
29 - 35	0.51	0.47	0.03	27.9	0.521	0.38	0.40	0.05	39.6	0.869
Cum. mortality	-------------(%)------------					-------------(%)------------				
0 - 14	1.22^{a}	0.91^{b}	0.08	23.1	<0.001	1.20	1.55	0.11	26.1	0.136
0 - 21	1.77^{a}	1.39^{b}	0.11	22.8	0.001	1.78	1.93	0.17	30.1	0.975
0 - 28	2.34	2.01	0.15	25.2	0.061	2.15	2.72	0.22	30.5	0.223
0 - 35	3.03	2.93	0.23	28.6	0.415	2.59	3.09	0.27	31.5	0.351

[1]Feed efficiency groups were determined by decision trees using FCR at 35 d as the response.

Table 2.2. Logistic, Gompertz-Laird and von Bertalanffy parameter estimates of male and female LE and HE groups[1] of Ross 308 AP chickens under commercial conditions and feed control.

Model estimate	Males					Females				
	LE (*n*=51)	HE (*n*=105)	SEM	CV	*P*-value	LE (*n*=31)	HE (*n*=128)	SEM	CV	*P*-value
Logistic				--(%)--					--(%)--	
Asymptotic response (W_A), g	2,934[b]	3,655[a]	41	10.9	< 0.001	2,657[b]	3,020[a]	38	10.3	< 0.001
Exponential growth rate (K)	0.122[a]	0.114[b]	0.001	5.2	< 0.001	0.119	0.117	0.001	5.3	0.062
Age at inflection point (ti), d	30[b]	34[a]	0.2	6.3	< 0.001	30[b]	32[a]	0.3	6.2	< 0.001
Response at inflection point (Wi), g	1,467[b]	1,828[a]	20	10.9	< 0.001	1,329[b]	1,510[a]	19	10.3	< 0.001
Maximum increment (MI), g/d	89[b]	103[a]	1	6.7	< 0.001	79[b]	88[a]	1	7	< 0.001
Gompertz-Laird										
Initial response (W_0), g	50[b]	57[a]	1	14.8	< 0.001	51	52	1	14.7	0.221
Initial growth rate (L)	0.188[a]	0.163[b]	0.002	10.9	< 0.001	0.182[a]	0.172[b]	0.003	10.8	0.011
Rate of exponential decay (K)	0.038[a]	0.029[b]	0.001	14.4	< 0.001	0.038[a]	0.033[b]	0.001	13.9	< 0.001
Age at inflection point (ti), d	43[b]	62[a]	1	20.5	< 0.001	43[b]	51[a]	1	17.9	< 0.001
Asymptotic response (W_A), g	7,717[b]	18,730[a]	832	62.7	< 0.001	6,884[b]	10,167[a]	423	41.9	< 0.001
von Bertalanffy										
Asymptotic response (W_A), g	143,570[b]	678,172[a]	80,956	220.5	< 0.001	92,429[b]	370,448[a]	49,854	243.2	< 0.001
Integration constant (B)	0.911b	0.940a	0.004	2.6	< 0.001	0.899[b]	0.930[a]	0.004	3.1	< 0.001
Maximum relative growth (K)	0.010[a]	0.006[b]	0.001	42.9	< 0.001	0.010[a]	0.006[b]	0.001	44.7	< 0.001
Age at inflection point (ti), d	133[b]	251[a]	17	68.9	< 0.001	122[b]	205[a]	13	63.9	< 0.001
Response at inflection point (Wi), g	42,539[b]	200,940[a]	23,987	220.5	< 0.001	27,386[b]	109,762[a]	14,771	243.2	< 0.001

[1]Feed efficiency groups were determined by decision trees using FCR at 35 d as the response.
[a-b] Means in columns followed by different superscript letters are statistically different by student's t-test ($P < 0.05$).

Table 2.3. Goodness-of-fit metrics from Logistic, Gompertz-Laird and von Bertalanffy fit all data of male and female LE and HE groups[1] of Ross 308 AP chickens raised under commercial conditions and feed control.

Model	Males		Females	
	LE (n = 51)	HE (n = 105)	LE (n = 31)	HE (n = 128)
Logistic				
R^2	0.995	0.996	0.994	0.996
RMSE	44.7	43.0	44.9	41.4
AIC	6,834.7	3,116.1	7,968.6	1,920.7
BIC	6,852.6	3,131.0	7,987.2	1,933.6
Number of iterations	6	4	5	4
Gompertz-Laird				
R^2	0.996	0.997	0.995	0.996
RMSE	41.2	39.2	41.6	38.5
AIC	6,729.0	3,061.0	7,853.1	1,893.5
BIC	6,746.9	3,075.8	7,871.7	1,906.4
Number of iterations	5	6	5	5
von Bertalanffy				
R^2	0.996	0.997	0.995	0.996
RMSE	41.5	38.7	41.7	38.5
AIC	6,737.4	3,052.5	7,854.2	1,893.9
BIC	6,755.4	3,067.3	7,872.7	1,906.8
Number of iterations	22	197	22	44

[1]Feed efficiency groups were determined by decision trees using FCR at 35 d as the response.

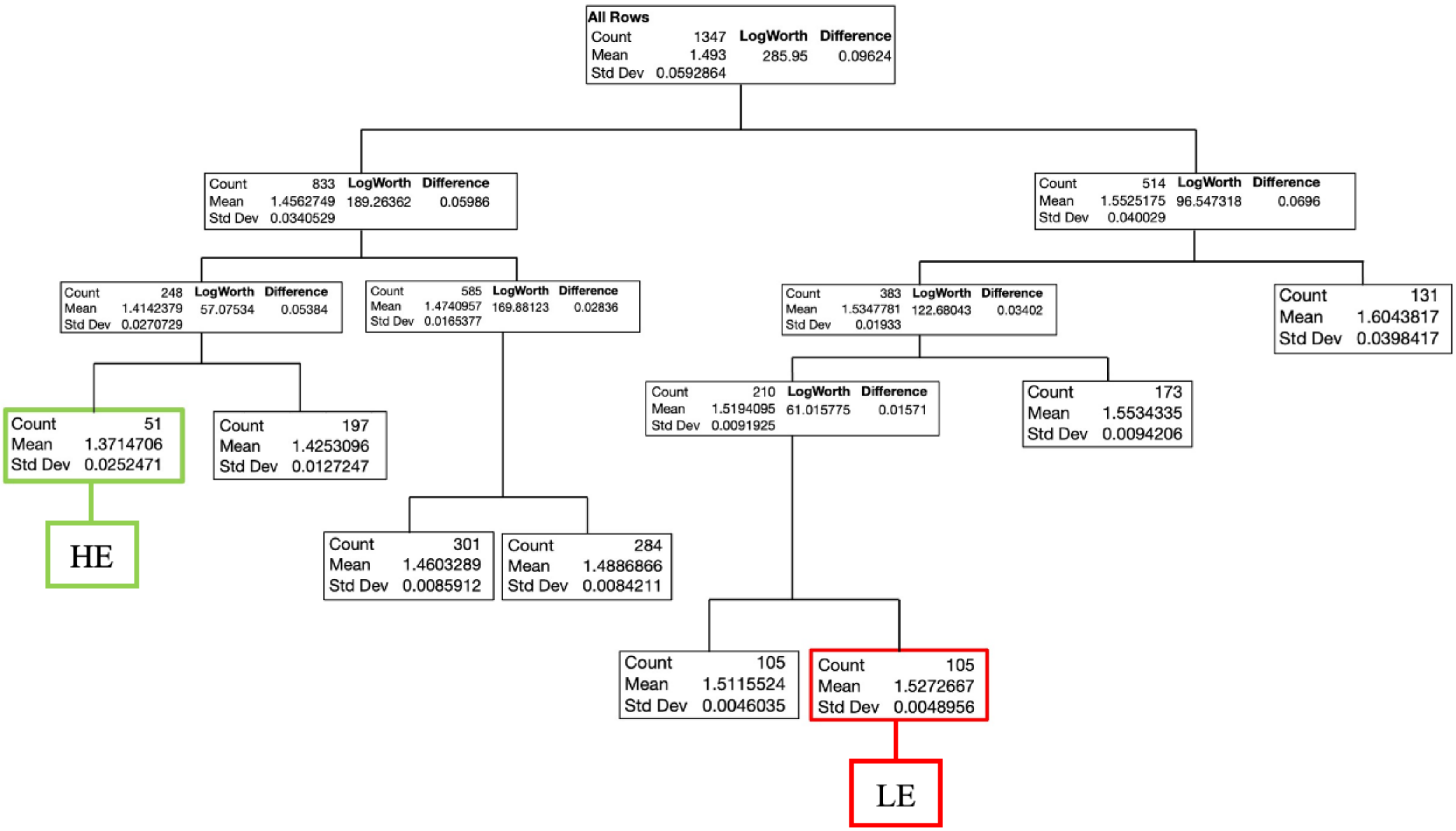

Figure 2.1. Decision tree for Ross 308 AP male chicken flocks with FCR at 35 d as the response. ($R^2 = 0.93$; RASE = 0.016; AICc = -7,349.9)

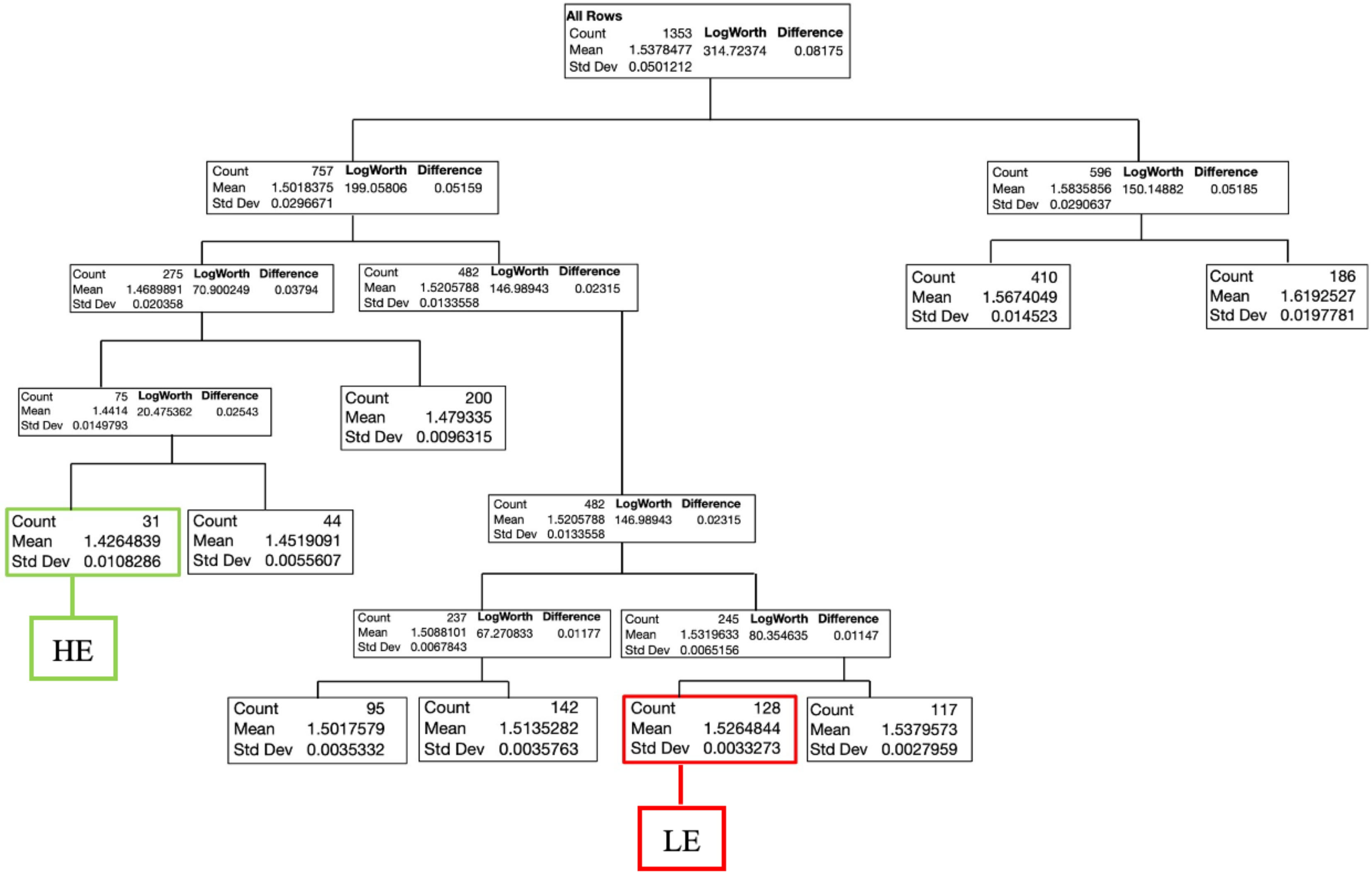

Figure 2.2. Decision tree for Ross 308 AP female chicken flocks with FCR at 35 d as the response. ($R^2 = 0.95$; RASE = 0.012; AICc = -8,162.3)

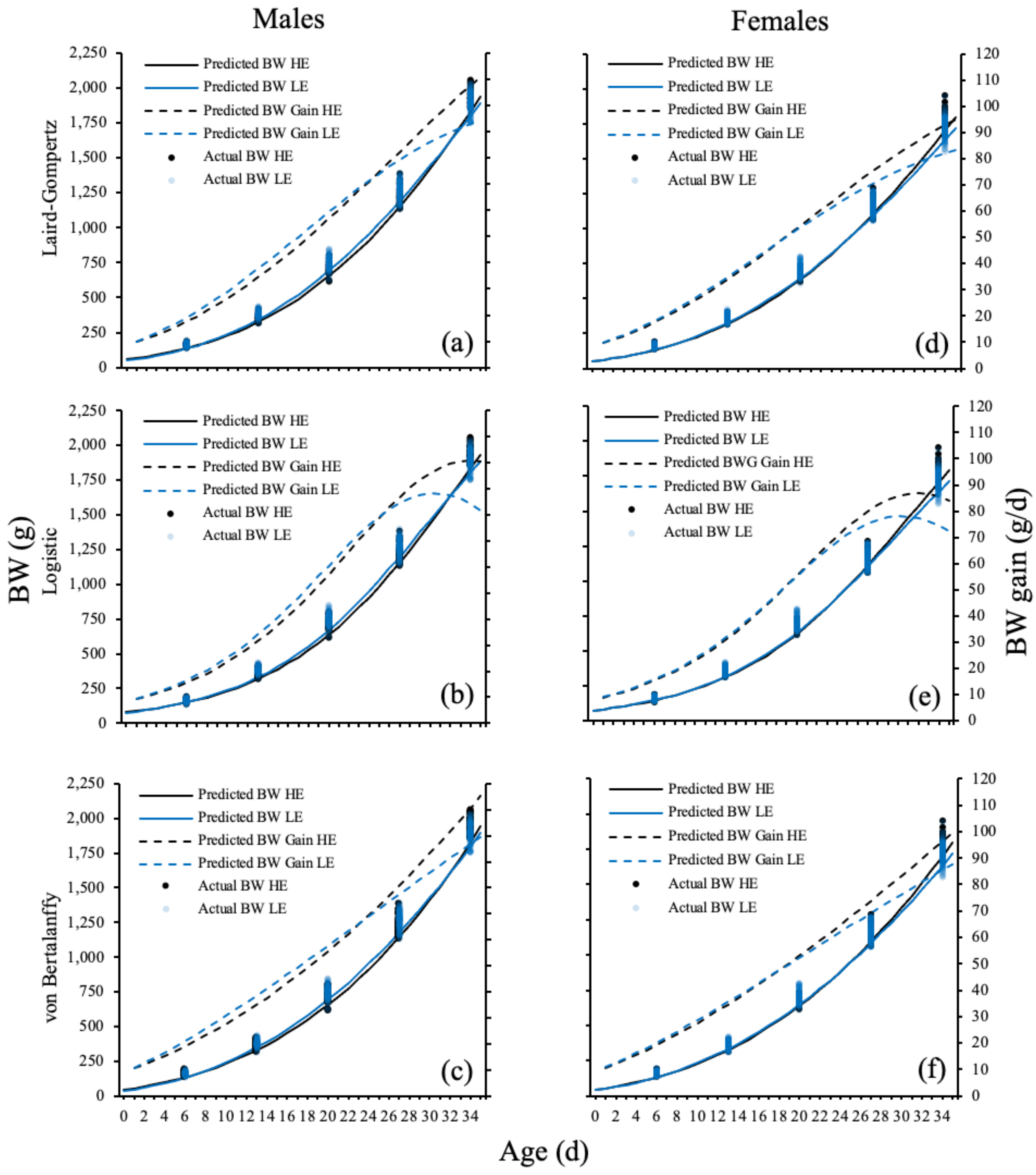

Figure 2.3 Actual and predicted BW from Laird-Gompertz, Logistic, and von Bertalanffy models fit all data by efficiency group[1] of Ross 308 AP male (a,b,c) and female (d,e,f) chickens up to 35 d.

[1]Feed efficiency groups were determined by decision trees using FCR at 35 d as the response.

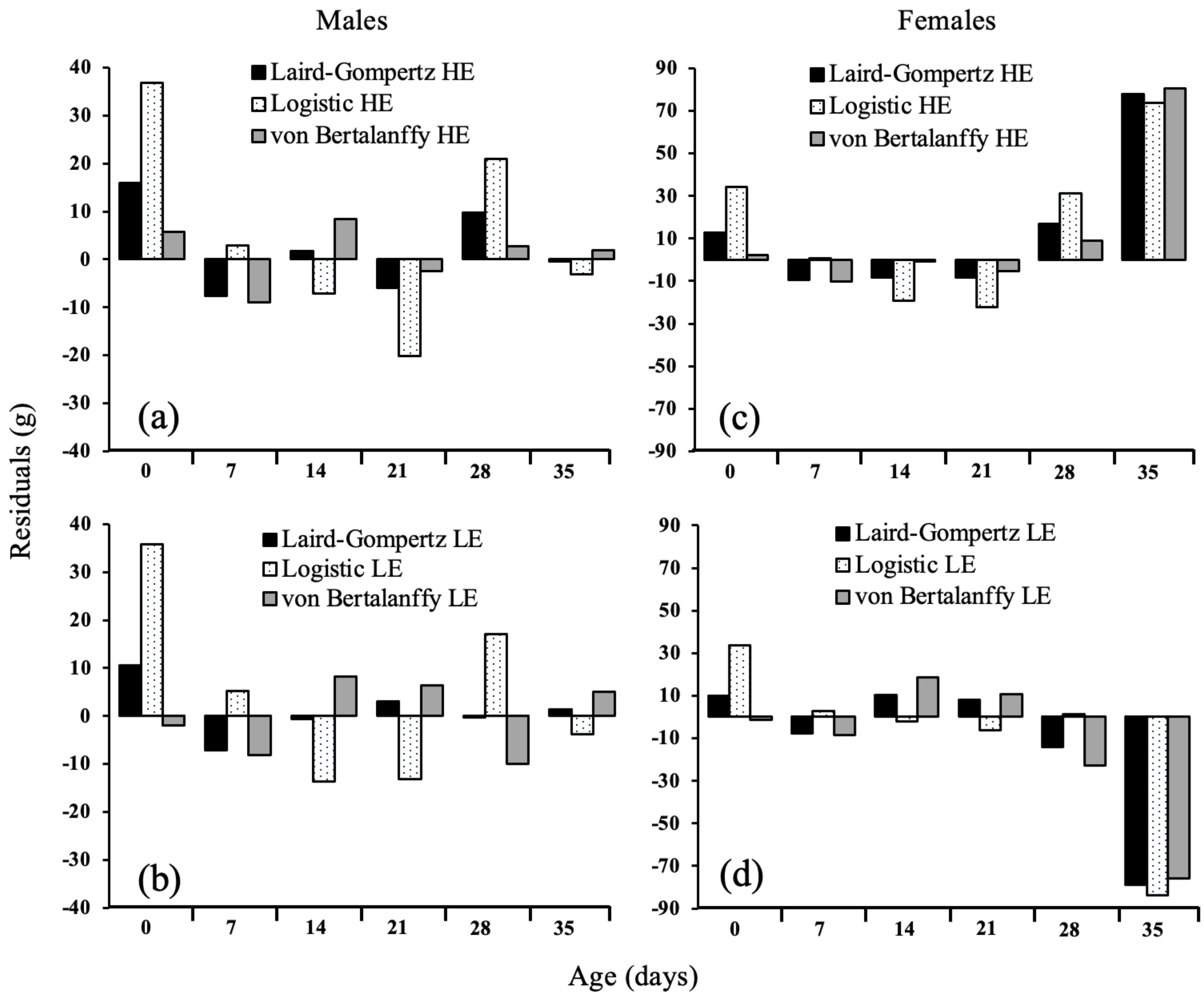

Figure 2.4. Residuals of Laird-Gompertz, Logistic, and von Bertalanffy models fit all data by efficiency group[1] of Ross 308 AP male (a,b) and female (c,d) chickens up to 35 d.

[1]Feed efficiency groups were determined by decision trees using FCR at 35 d as the response.

CHAPTER III

Effect of environmental and farm-associated factors on live performance parameters of broilers raised under commercial tropical conditions

ABSTRACT

Although temperature (T), relative humidity (RH), and farm-associated factors are known to affect broiler live performance, data about the impact of these variables under commercial operations are still scarce. This study aimed to evaluate the effect of T, RH, a thermal humidity index (THI), and farm-associated factors on BW, BW gain, feed conversion ratio (FCR), and mortality of broilers raised to 35 d under commercial tropical conditions. The data analyzed included performance records of 1,347 male and 1,353 female Ross 308 AP broiler flocks placed between 2018 and 2020. Environmental monitoring data were obtained in ten datasets containing T and RH hourly collected from 29 farms. Farm-associated factors were gathered using a survey. Three data analyses were conducted in parallel. A table based on the Aviagen chick management recommendations (Aviagen, 2018) for T and RH was used as a reference to calculate the amount of time in hours chickens were exposed to T out of ± 1.5, 2.5, 5, and 7 °C and below 50 or above 70% RH from the recommendations. Correlation analyses and linear regressions were conducted among live performance variables and hours of exposure to non-recommended environmental conditions. In the second analysis, continuous variables from the management survey were clustered with FCR at 35 d using a *k*-means cluster procedure. BW, FCR, and mortality at 35 d were analyzed using a one-way ANOVA with categorical variables or clusters as main effects and mean separation with Tukey's or student t-test. The third analysis used data from performance

variables up to 21 d and farm-associated factors to model BW and FCR at 35 with three supervised machine learning (ML) methods. A multiple linear regression (MLR), a random forest (RF), and artificial neural networks were fit using the R's *caret* package. Variable importance analyses were conducted for all models. Results indicated that BW and BW gain were reduced, and FCR worsened (P<0.001) up to 21 d when chickens were exposed to T lower than 2.5 °C while mortality at 28 and 35 d increased.

Additionally, all farm-associated factors affected live performance in chickens. RF demonstrated to be the best model to predict the BW (R^2 = 0.78) and FCR (R^2 = 0.48) compared to the ANN and MLR. Variable importance indicated that BW, BW gain, feed intake, and FCR results at 14 and 21 d were important to predict BW at 35. At the same time, sex, distance between hatchery and farm and farm altitude accounted for the greatest contribution from the farm-associated factors.

INTRODUCTION

During the last five decades, broiler chickens have been subject to continuous genetic selection (Zuidhof *et al.,* 2014) to improve BW and feed conversion ratio (FCR). However, these changes have resulted in alterations of the energy metabolism and energy expenditure (Chen *et al.,* 2014; Yang *et al.,* 2014; Tallentire *et al.,* 2016; Mohammadalipour *et al.,* 2017; Zhou *et al.,* 2021) which make them very sensitive to environmental conditions (Yousaf *et al.,* 2019; Kang and Shim, 2021). Extensive research (Siegel and van Kampen, 1984; Faria Filho *et al.,* 2005; Smith and Vale, 2006; Cassuce *et al.,* 2013; Candido *et al.,* 2016; Naga Raja Kumari and Narendra Nath, 2019) has demonstrated the optimum T (thermoneutral zone) for ideal performance at all ages and the physiological consequences of keeping birds under higher (heat stress) or lower (cold stress) than recommended T.

Under heat stress, Goo *et al.* (2019) indicated that chickens subject to 27.8 °C from 21 to 35 d of age resulted in a final BW with 171 g less than their counterparts raised at 20 °C (1,676 *vs.* 1,847 g). Similarly, Awad *et al.* (2020) reported a significant increase in the FCR of 0.06 g:g when chickens were exposed to 34 °C, 6 hours daily from 22 to 35 d. A recent meta-analysis (Liu *et al.,* 2020), including seven trials for BW gain and 11 experiments for FCR, demonstrated that heat-stressed chickens gained on average 151.4 g less while feed efficiency increased 0.17 g:g. On the other hand, different authors (Ipek and Sahan, 2006; Mohammadalipour *et al.,* 2017; Zhou *et al.,* 2021) have shown the effects of low T on broiler performance. Ipek and Sahan (2006) indicated that broilers subject to cold stress were significantly 111 g lighter on average from 1 to 5 wk of age while FCR was higher 0.36 g:g on average from 1 to 3 wk. Zhou *et al.* (2021) demonstrated that chickens exposed to 16 °C between 14 and 17 d of age presented 18.84 g of BW less and 0.23 g:g more FCR at the end of the trial. Similarly, Mohammadalipour *et al.,* 2017 reported FCR 0.09

g:g poorer between 28 and 42 d (2.12 *vs.* 2.03 g:g) in chickens raised under cold T from 21 to 42 d. In the same study, higher mortality due to ascites was detected in chickens raised in cold T compared to normal conditions.

Studies evaluating the effects of relative humidity (RH) on broiler live performance have shown conflicting results across the years depending on the ambient T (Weaver and Meijerhof, 1990; Yahav, 2000; Zhou *et al.,* 2019). Thus, different T-humidity indices (THI) have been developed to account for the variation of both environmental parameters (Zulovich and DeShazer, 1990; Xin *et al.,* 1992; Brown-Brandl *et al.,* 1997; Tao and Xin, 2003; Chepete *et al.,* 2005). Purswell *et al.* (2012) observed that chickens raised between 49 to 63 d of age under a THI (THI = 0.85 x T_{db} + 0.15 x T_{wb}) value of 15.3 °C resulted in the best BW compared to chickens subjected to a THI of 26.2 °C (4,547 vs. 3,873 g), while FCR was substantially increased during this period (6.00 *vs.* 3.09 g:g) at this level compared to treatments from 14.8 to 25.8 °C.

In addition to farm environmental conditions, some other factors like transportation of day-old chicks from hatchery to farm, farm location, and equipment, among others, have been related to suboptimal live performance and high mortality in broilers (Bergoug *et al.,* 2013; Rachmawati *et al.,* 2016; Toledo *et al.,* 2019; Yerpes *et al.,* 2020). In a study conducted by Bergoug *et al.* (2013), broilers on average 1.6 (38.4 *vs.* 40.0 g), 7.2 (153.3 *vs.* 158.8 g), 18.9 (409.5 *vs.* 423.0 g), and 26.5 g (872.7 vs. 890.8 g) lighter were observed at placement, 7, 14, and 21 d, respectively, when d-old-chick transportation time from hatchery to farm increased from 0 to 4, and even 10h. In other reports, Rachmawati *et al.* (2016) showed that when farm altitude was greater than 700 meters above the sea level, BW at slaughter age was reduced 184.1 g (1,697 *vs.* 1881 g). On the other hand, Garces *et al.* (2017) and Toledo *et al.* (2019) have indicated that litter type may affect survival rate, BW, BW gain, and FCR in broilers. In commercial operations, only a few reports

(Yerpes *et al.,* 2020; van Limbergen *et al.,* 2020) have described the effects of house, season, equipment, and factors that are not conventionally evaluated in broiler production. Despite the T and RH are usually monitored daily or hourly in broiler farms, and that management factors are highly related to flock performance, data about the impact of these variables under commercial operations are still scarce. The use of commercial data is always challenging (Pitesky *et al.,* 2020), but using modern data analytics and machine learning (ML) tools is possible to explore environmental sensor data, data without structure, greatly variable, and produced in big amounts (Neethirajan, 2020). This study aimed to evaluate the effect of T, RH, a THI, growth, management, and farm-associated factors on BW, BW gain, FCR, and mortality of chickens raised to 35 d under commercial tropical conditions.

MATERIALS AND METHODS

Database and statistical software

Ten datasets were obtained from a broiler integration located in Colombia. One dataset contained live performance parameters from 1,347 male and 1,353 female Ross 308 AP broiler flocks collected weekly from placement up to slaughter age in 86 farms related to one poultry integrator company. However, since not all flocks were processed at the same age, the cutoff point on the data was 35 d. Performance records included BW, BW gain, FCR, and mortality of all flocks placed between 2018 and 2020. The weekly performance was obtained from averages of random samples of individual BW of 1% of the flocks and feed intake from records per house. From these, 38 male and 42 female Ross 308 AP broiler flocks were identified to be continuously subject to environmental monitoring between January and July 2020 in 29 farms under commercial conditions with control feeding across three major poultry production regions of the country. The regions were labeled as Northwest, Midwest, and East. Groups of farms were fed diets of similar composition since feed formulation details are common to the whole company. The other nine datasets contained broiler house T and RH records collected hourly over the entire growing cycle of the flocks previously mentioned. Farm-associated conditions were collected using a survey and are detailed in Table 3.1 and Table 3.2. Data were cleaned, organized, and analyzed using R (R Core Team, 2021) in RStudio (RStudio Team, Boston, MA, USA) and JMP Pro 15 (SAS Institute, Cary, NC, USA). Three parallel analyses were carried out with the data collected.

Data analysis 1: Performance and environment

Environmental records from electronic sensors that captured the environmental data hourly during the whole five weeks of each flock were imported to statistical software and merged by farm, date and time. Then, the placement date and the date at 35 d were added to the environmental dataset to estimate the age of chickens within each flock. This data was highly variable, and other authors have reported that traditional statistical procedures did not find good relationships with performance (Wen *et al*., 2021). Consequently, a table based on the Aviagen chick management recommendations (Aviagen, 2018) for T and RH was used as a reference to calculate the amount of time in hours chickens were exposed to non-recommended environmental conditions from hatch up to 35 d. The ideal range of T was allowed between ±1.5 °C away from the recommended value. For each flock, exposure time to be lower or greater than 1.5, 2.5, 5.0, and 7.0 °C from the recommendations and RH below 50 and above 75% was calculated. Additionally, a THI was computed for each hour based on the equation described by Berman *et al.* (2016) as follows:

$$THI = 3.43 + 1.058 \times T - 0.293 \times RH + 0.0164 \times T \times RH + 35.7$$

Where,

T = Temperature,

RH = Relative humidity

Index boundaries for each day of age were calculated based on the combination of recommended T and RH. Time of exposure to THI levels out of limits was also considered for analysis. Since feed allowance was controlled during the growth of chickens, this variable was not included for analysis.

Correlation analyses were conducted between live performance parameters and time of exposure in hours to non-recommended T, RH, and THI levels. Correlations were fit using either week or cumulative periods of exposure from placement to each week of age up to 35 d. Linear regressions were carried out on correlated variables with live performance parameters as response and environmental exposure time as a predictor.

Data analysis 2: Farm management factors and performance

Farm-associated and management factors were joined to the broiler performance records based on the farm name. Continuous variables from the farm management survey, including all 86 farms, were clustered with FCR at 35 d using a *k*-means cluster procedure in JMP 15 (SAS Institute, Cary NC). Several clusters were developed based on an iterative fitting process. The k-means procedure algorithm randomly took many starting points as cluster seeds or centers and computed the distance between each pair of datapoints. Then, it iteratively moved the centers to minimize the total within-cluster variance (Hastie *et al.,* 2009). The k-means cluster with the lowest AIC and BIC was chosen for further analysis.

After clustering all possible variables, data were analyzed in a one-way ANOVA with variable cluster (continuous variables) or factors (categorical variables) as main effects and BW, FCR, or cumulative mortality at 35 d as responses. Mean separation was performed using the LS means method using Tukey's or student's *t*-test at a significance level of alpha = 0.05.

Management survey indicated that the company was divided into three major poultry production regions labeled as Northwest, Midwest, and East, which received chicks coming from two company-owned hatcheries (Hatchery 1 and Hatchery 2). Farms also had two technification levels, high level that accounted for farms with greater capacity, more number of houses and more retrofitted houses, and low technification level or farms with less capacity and few houses with open-sided structure. Farms were located up to 531 km or 11 h away from the hatchery. These two variables were clustered in three groups, near (73 ± 71 km), intermediate (356 ± 169 km), and far (454 ± 64 km) for distance in km and three groups accounted for the distance measured in hours, near (2.1 ± 1.6 h), intermediate (7.0 ± 2.9 h), and far (8.2 ± 1.8 h). Also, farms had an average altitude of 1,381 ± 449 m.a.s.l. which were grouped in low (1,041 ± 349 m.a.s.l), middle (1,446 ± 498 m.a.s.l.), and high (1,670 ± 434 m.a.s.l.) altitude. Poultry houses were equipped with rice hulls or wood shavings as litter material, and the number of flocks the farm recycled the litter was clustered into 0.8 ± 0.7, 1.3 ± 1.2, 5.8 ± 2.2 and 12.0 ± 0.01 times. Downtime between flocks resulted in three ranks, 12.7 ± 1.0, 13.5 ± 1.2 and 15.0 ± 1.6 d. Other characteristics linked to house infrastructure were also detailed. It was observed that some farms had poultry houses with 1 or 2 stories, which allowed them to place chicks on both floors, and the house floor was composed of two materials soil or concrete. Additionally, different systems of water storage were reported by farm managers. Water tanks that had any protection against sun and rain (covered), tanks outside the house with no environmental protection (uncovered), and water tanks located underground.

Data analysis 3: Prediction of performance with ML

Three supervised ML methods were evaluated in this analysis (Rahimi *et al.,* 2012; Neethirajan, 2020). Farm-associated factors were joined to the performance records from all flocks to model chickens' BW and FCR at 35 d. Data was automatically divided into random training and testing datasets to fit the models using a five-fold cross-validation procedure. Models were then trained using four-folds, and the predictability performance was assessed with the hold-out fold, repeating this step for each of the five folds (Kuhn, 2008; Rahimi *et al.,* 2012). This k-fold cross-validation inevitably results in lower R^2 but more confidence for predictability (Bischl *et al.,* 2016). Categorical predictors such as farm region or litter type were transformed to dummy or indicator variables which denotes the absence or presence of a factor with 0 and 1, respectively, and data were normalized in a range from 0 to 1 (Kuhn, 2008; Kuhn and Johnson, 2013) A multiple linear regression (MLR) model was fit using the *lm* function from the R stats package while a random forest (RF) and artificial neural network (ANN) were trained and validated using the *caret* package (Kuhn, 2008). BW and FCR at 35 d were used as responses and performance records and farm-associated conditions as predictors to fit these models. Broiler performance records up to 21 d of age only were included to obtain a prediction two wk before slaughter age.

R^2 and RMSE were calculated and averaged across five folds for each model for model evaluation. In the MLR, collinearity was evaluated with the variance inflation factor (VIF). Variable selection was carried out based on *P*-value, thus, collinear, and non-significant predictors were manually removed to obtain the final model. A variable importance analysis (Wei *et al.,* 2015; Kazemitabar *et al.,* 2017) was conducted in all models. In the MLR, the variable contribution was estimated as the predictor percentage sum of squares over the sum of squares of the model. For RF, the permutation importance (Breiman, 2001) was employed, which is expressed as the increase in MSE, while the ANN utilized the connection weights approach described by Olden *et al.* (2004).

RESULTS

Data analysis 1: Performance and environment

Correlation coefficients of live performance parameters and time of exposure to T below or above recommended values are shown in Figure 3.1 and Figure 3.2.Overall, live performance results were mainly correlated ($P < 0.05$) to exposure to non-recommended T up to 21 d, except for cumulative mortality that included cumulative values of exposure up to 28 d. Negative correlations of BW ($P < 0.05$) were detected when chickens were exposed to T 5 ºC below the recommended values at 7, 14, and 21 d. Linear regression estimates from the same wk of age indicated ($P < 0.05$) that chickens lost 1.51, 3.50, and 4.91 g, respectively, each hour they were exposed to these conditions. Also, cooler environmental T affected FCR at the second and third wk of age ($P < 0.05$). Chickens exposed to T 2.5 ºC lower than recommended from 7 to 14 d or from 14 to 21 were less efficient 0.011 and 0.004 g:g each additional hour under these conditions at 14 at 21 d, respectively. No significant correlations ($P > 0.05$) were observed in mortality during the first three wk of age. However, non-recommended T up to four wk of age affected cumulative mortality at four and five wk of age. As time under a T below 2.5 ºC from 0 to 28 d increased ($P < 0.05$), mortality augmented on average 0.018% at 28 and 35 d per each additional hour of exposure. No significant correlations ($P > 0.05$) between BW or BW gain with environmental T were observed at 28 and 35 d. FCR significant correlations ($P < 0.05$) with time exposed to T below the recommended values during the last wk. Positive correlations ($P < 0.05$) and regression analyses indicated that each hour exposed to T below 2.5ºC up to the fourth wk of age reduced the feed efficiency 0.004 g:g at 35 d.

Results from correlations and regression analyses between live performance parameters and time of exposure to non-recommended values of RH are detailed in Table 3.3. Significant correlations ($P < 0.05$) between FCR or mortality and time exposed to non-recommended RH values were detected at 7, 21, and 28 d of age. However, correlation coefficients were between 0.41 and 0.51, and regression analyses showed poor goodness-of-fit with R^2 lower than 0.26. Similarly, correlation coefficients between live performance parameters and THI levels indicated that only FCR at 21 d was positively associated ($r = 0.69$; $P = 0.025$) to exposure at lower levels of THI. Linear regression demonstrated (FCR at 21 d = 1.284 + 0.007 * Hours of exposure; $P = 0.025$; $R^2 = 0.49$) that each hour chickens were exposed to THI levels lower than recommended from 14 to 21 d, feed efficiency was increased 0.007 g.

Data analysis 2: Farm management and infrastructure factors and performance

Significant effects of farm-associated factors ($P < 0.05$) were detected in male and female BW, FCR, and cumulative mortality at 35 d (Table 3.4). Male chickens from the Northwest region of the country resulted in the lowest BW ($P < 0.001$) but, at the same time, the best FCR ($P < 0.001$). In contrast, females from the East region were observed to show the worst live performance with the lightest chickens and the highest ($P < 0.001$) FCR. Cumulative mortality at 35 d in farms from the East region was on average 0.39% higher in both males and females ($P < 0.001$) than farms located in the Midwest (2.78 *vs.* 2.39%). On the technification level, farms with high levels produced heavier male chickens ($P < 0.001$) but less efficient ($P < 0.001$) than their counterparts in the low category. Contrarily, low-level farms produced female chickens 18 g heavier ($P < 0.001$) and 0.017 g:g more efficiency ($P < 0.001$) than those raised in high technification farms.

Live performance of chickens raised at different geographic altitudes also varied ($P < 0.001$). Chickens raised at higher elevation (1,670 ± 434 m.a.s.l.) resulted in the best performance with males and females 106 and 114 g ($P < 0.001$) heavier, 0.120 and 0.098 g:g ($P < 0.001$) more efficient, and 1.11 and 0.63% ($P < 0.001$) less mortality at 35 d compared to chickens placed on middle altitude farms (1,446 ± 498 m.a.s.l.). Flocks raised in lower altitudes (1,041 ± 349 m.a.s.l.) resulted in intermediate responses.

Conflicting results were observed in chickens coming from different hatcheries (Table 3.5). Male chickens from Hatchery 1 displayed less FCR (P < 0.001) and the lowest BW than chickens from Hatchery 2. Different from males, females exhibited the highest BW (*P* < 0.001) and lowest FCR (*P* < 0.001) when chicks were obtained from Hatchery 1. At the same time, females from Hatchery 2 resulted in 42 g lighter and 0.038 g:g less efficient than their counterparts from Hatchery 1. No significant effects of chick source (*P* > 0.05) were identified in cumulative mortality at 35 d for males or females. Similar results were observed on chick transportation measured either in the physical distance between the hatchery and the farm in km or time (h) needed to reach the farm. Male chicks subject to long trips (454 ± 64 km) were 97 g heavier (*P* < 0.001) at 35 d (1,909 *vs.* 1,812 g) than chickens subject to intermediate trips (356 ± 169 km). Still, male and female chickens raised in farms near (73 ± 71 km) to the hatcheries were significantly (*P* < 0.001) 0.098 and 0.025 g:g more efficient than those chickens traveling 356 ± 169 km (1.473 *vs.* 1.571 g:g) or 454 ± 64 km (1.473 vs. 1.498 g:g), respectively, to reach the farm. Chickens traveling intermediate distances (356 ± 169 km) presented on average 0.86% and 0.74% more (*P* < 0.001) male and female mortality, respectively, (*P* < 0.001) than chickens from the short (73 ± 71 km) and long 454 ± 64 km clusters.

Differences due to litter type (*P* < 0.05) indicated that male chickens raised in rice hulls were heavier (*P* < 0.001) and had the worst FCR (*P* < 0.001) compared to those raised in wood shavings, whereas females accounted for lower BW (*P* < 0.001) and worse FCR (*P* < 0.001) than their counterparts placed in wood shavings. Additionally, the number of times the litter was recycled affected (*P* < 0.05) BW, FCR, and mortality at 35 d. Flocks subject to non-recycled litters or with the minimal number of times (0.8 ± 0.7) resulted in males and females on average 80 g and 65 g lighter ($P < 0.001$), respectively than flocks from all other clusters. Flocks in this cluster of low litter recycling were also ($P < 0.001$) the least efficient (1.556 g:g) and demonstrated ($P < 0.001$) the highest mortality for both males (0.63% more) and females (0.74 % more) compared to flocks raised in litter recycled all other groups. Finally, flocks with an average downtime of 13.5 d resulted ($P < 0.001$) in the heaviest (1,906 g males, and 1,778 females) and most efficient (1.457 males, and 1.466 females) flocks at 35 d with the lowest mortality (2.51%) compared to flocks which downtime was shorter (12.7 ± 1.0) or longer (15.0 ± 1.6).

Data analysis 3: Prediction of performance with ML

BW Prediction. The results of the five-fold cross-validation process presented in Table 3.6 indicated that RF had the better fit ($R^2 = 0.78$), followed by the ANN ($R^2 = 0.73$) and MLR ($R^2 = 0.59$). Hyperparameter tunning (Kuhn, 2008; Kuhn and Johnson, 2013; Bischl *et al.,* 2016; Probst *et al.,* 2019) indicated that the best fit of RF was achieved with 37 parameters while the best fit of ANN included three nodes. On fitting the FCR, goodness-of-fit metrics for five-fold cross-validation resulted in an R^2 of 0.18, 0.48, and 0.45 for MLR, RF, and ANN, respectively. Variable importance analyses (Breiman, 2001; Olden *et al.,* 2004; Wei *et al.,* 2015; Kazemitabar *et al.,* 2017) demonstrated that the MLR for BW included only eight non-collinear and significant predictors from which sex accounted for 89% of the total response, feed intake at 14 d 4.41%, and BW gain at 7 d 1.82% (Table 3.6). The RF model obtained for BW indicated that BW at 21 d, sex, and distance from hatchery to farm in km was ranked as the first three most important to predict the final response at 35 d (Figure 3.3a). Other farm factors were also ranked as key factors for prediction. This included farm altitude (21.98%) and the region where the farm was located (14.05%). Among farm-associated factors, the downtime between flocks presented a 14.72% of the increase in MSE, becoming the most important factor. Similarly, the ANN showed that mortality at 14 d, BW at 21 d, and BW gain at 21 d were key in the model (Figure 3.3b). However, this model detected predictors related to farm infrastructure like water tank location, type of house, and farm area within the top 20 factors to predict BW at 35 d.

FCR prediction. In MLR, FCR at 21 d was the most important variable with 42.41% of the total response, followed by downtime between flocks with 18.67%, feed intake at 14 d with 17.63%, and percentage of retrofitted houses (infrastructure) with 7.34%. The other predictors in the model contributed less than 4% each. A total of 10 variables were included in this model. In the variable importance analysis from the RF of FCR at 35 d, the FCR at 21 d was the most important variable (63.26%) compared to other predictors, followed by sex (24.07%) and farm elevation (18.59%) (Figure 3.3c). Similar to the BW models, BW, BW gain, and FCR at 14 and 21 d were within the 20 most important factors, and distance between farm and hatchery (16.86%) was listed within the ten first ones. The ANN demonstrated that the response strongly depended on the feed intake, FCR and BW results at 21 d, followed by the percentage of retrofitted and open-sided houses present in the farm (Figure 3.3d). Again, the BW and BW gain at 14 d and the downtime between flocks are displayed as essential factors for predicting FCR at 35 d.

DISCUSSION

Broiler performance and environment

During the first three weeks of age, cumulative exposure to 2.5 ºC below recommended T was correlated to poorer BW, BW gain and FCR, and high mortality during the whole production cycle. In a recent study, Su *et al.* (2020) demonstrated that chickens exposed to 3 ºC lower than the control group from 8 d onwards resulted in similar FCR and BW up to three and six wk, respectively, compared to chickens kept under thermoneutral conditions. In contrast, chickens exposed to 12 ºC lower than the control group from 8 d onwards were significantly lighter and less efficient than their counterparts from two up to six wk of age.

In another report, Candido *et al.* (2016) indicated that mild cold T during early stages (27 ºC first wk, 24 ºC in the second wk) did not affect BW and FCR from 0 to 21 d, while the greatest BW gain was observed in chickens subject to these T. According to those studies, 3 ºC below the ideal T was still within the versatile T range for chicks, preventing a reduction in the live performance. Although in the current study no significant correlations of T lower than 1.5 nor 2.5 ºC with live performance parameters were detected within the first wk of age, the sensitivity of chickens to lower T seemed to increase with age since more exposure to mild cold T reduced FCR at 14 d and BW and FCR at 21 d. Other authors that have reported similar results (Chen *et al.,* 2014; Yang *et al.,* 2014; Mohammadalipour *et al.,* 2017; Zhou *et al.,* 2021) have indicated that an increase in the basal metabolic rate and energy metabolism due to cold stress led to the rise in chicken energy requirements which explained the diminished BW or increased FCR observed here. Zhou *et al.* (2021) also suggested that these effects were related to a redistribution of nutrients during the growth toward thermoregulatory responses.

On the other hand, chickens mainly exposed to intermittently T below 2.5 ºC from recommendations up to four wk of age were correlated with high mortality and worsened FCR at 28 and 35 d. Similarly, Bruzual *et al.* (2000) demonstrated that chicks raised to 12 d under cooler brooding T (26 ± 4 ºC first wk, 24 ± 4 ºC second wk) presented 1.71% more mortality compared to chicks subject to warmer T (32 ± 4 ºC first wk, 29 ± 4 ºC second wk). Another report indicated that the highest mortality at 42 d resulted from chicks exposed to 26.7 ºC at first wk, compared to other treatments (4.79 *vs.* 2.36%) that ranged between 29.4 and 35 ºC (Deaton *et al.,* 1996). The information obtained from the dataset analyzed suggested that low T in commercial operations might be an issue leading to mortality at the end of the production cycle. It is also necessary to consider that previous studies from the literature described in the present thesis have been conducted under experimental conditions, achieving desired environmental T and RH through environmentally controlled chambers, which greatly differed with environmental conditions under commercial operations.

Additionally, environmental conditions in the tropics may greatly influencing the poultry house environment due to the open-sided structure, which in this company represented 90.14% of all houses evaluated. Thus, cycling T between day and night or hourly, precipitations, region, geographic altitude, cold wind drafts from mountains, ventilation and heating systems, and other variables could drive the environment response observed in this poultry company. It is assumed that mainly highly variable indoor environmental conditions (Figure 3.4) that resulted in more cumulative hours of exposure to house T and RH below recommendations, affected broiler flocks during the first two weeks, since it is more difficult for chickens to adapt to variable environments (Yahav *et al.,* 1996) and consequently live performance at slaughter age is negatively affected.

On fitting the RH data range from 30.32 to 92 %, only a few mild correlations were observed up to 28 d while linear models among correlated variables had low R^2 (0.17 – 0.26). Similarly, Zhou *et al.* (2019) reported that average daily feed intake, FCR, or mortality were not affected when chickens were exposed to RH of 35, 60, or 85%. In contrast, Weaver and Meijerhof (1990) detected broilers on average 32 g lighter at 42 d when they were either subject to weekly increments of 8% of RH from 40 to 80% or raised at a constant 75% RH. Yahav (2000) indicated that BW at 35 d was reduced when chickens were reared in environments with RH less or greater than 60-65% compared to other treatments (40-45, 50-55, and 70-75%) while no differences among treatments were observed on FCR or BW at 28 d. However, it was described (Yahav, 2000) that the response varied at different ambient T (28 or 30 ºC). Then, RH could rely on ambient T to affect live performance. At 28 ºC, Yahav (2000) determined that the heaviest broilers were observed between 60 and 65% of RH compared to other treatments. Chickens within RH treatments of 50-55% and 70-75% but at 30 ºC improved their BW (3.74%), while the 40-45% RH treatment obtained the lightest chickens in both scenarios at 28 (1,438 g) and 30 ºC (1,398 g). Zhou *et al.* (2019) also indicated that although average daily feed intake was not affected by RH treatments at 26 ºC, this parameter was reduced by 35 and 85% RH at 31 ºC.

THI analyses indicated that as hours of exposure from 14 and 21 d under THI levels below the combined Aviagen recommended T and RH increased, the FCR at 21 d worsened 0.007. In contrast, Purswell *et al.* (2012) did not determine effects on live performance parameters between 49 and 63 d when chickens were exposed to THI between 14.8 and 20.7 ºC. In that study, the BW, BW gain, feed intake, and FCR were diminished with higher THI levels. It is assumed that the well-developed feather cover that those animals could have at 49 d helped to resist lower THI levels and resulted in similar responses at slaughter age. Contrarily, chickens at 21 d from the current study may not have a good development of feather, which causes that exposure to slightly lower THI to increase mortality. According to the results presented herein, BW, BW gain, and FCR of chickens were more affected by low T during the first three wk of age. At the same time, mortality was associated with an increase of up to 125 hours between 0 and 28 d in the exposure to T 2.5 ºC lower than recommended. The RH between 30.32 and 92% seemed to be a parameter that did not significantly affect the live performance of chickens possible to detect in this data analysis. The THI employed here (Berman *et al.,* 2016) did not show a significant relationship with performance variables. Finally, the methodology described herein based on hours of exposure to different environmental conditions can provide a better understanding of the effects of T and RH since mean environmental values, maximum and minimum T per day could not reflect the actual fluctuation within the poultry house.

In conclusion, lower T than recommended affected the live performance of broilers during the whole production cycle. On the contrary, only a few correlations were observed with RH, while the THI did not depict the effects observed with lower T.

Farm management and infrastructure factors and performance

On farm-associated factors, chickens that were raised at the highest altitude (1,670 ± 434 m.a.s.l) were the heaviest (1,836 g) and the most efficient (1.466 g:g) in both males and females compared to those chickens raised at a medium elevation (1,446 ± 498 m.a.s.l.). Rachmawati *et al.* (2016) indicated that the heaviest chickens at 35 d were observed when farms were located above 700 m.a.s.l. while no differences were detected between chickens raised either in lowlands (< 400 m.) or middle lands (400 – 700 m.). In that study, the authors suggested that a higher BW could result from a greater feed intake associated with an increment in the maintenance requirements due to cooler ambient T (Rachmawati *et al.* 2016). In contrast, it is assumed that higher altitudes may represent lower environmental T, reducing the effects of heat stress observed in low-altitude regions.

In the present study, the rice hulls as litter type also worsened FCR of both males and females compared to wood shaving. The litter material like wood shavings, sawdust, sand, rice hulls, wheat straw, and grass in which chickens are raised is a factor that has been widely evaluated in poultry (Angelo *et al.,* 1997; Araújo *et al.,* 2007; Ramadan *et al.,* 2013; Brito *et al.,* 2016; Garcês *et al.,* 2017;). Garcês *et al.* (2017) reported that chickens raised to 35 d in rice hulls did not significantly differ in BW, FI, or FCR to those raised in wood shavings. Nevertheless, the survival rate in chickens reared in rice hulls was 4.8% lower than their counterparts reared in wood shavings (Garcês *et al.,* 2017). Still, the number of replicates in that study was limited to only three pens per treatment which could not be enough to reproduce the results, while the current data analysis utilized on average 601 flocks for each litter type.

Similarly, using two replicates per treatment, Ramadan and El-Khloya (2017) showed that live performance parameters or carcass traits were not affected by the litter type when using five different types of litter, including wood shavings and rice hulls. Toledo *et al.* (2019) conducted a comprehensive meta-analysis indicating that broilers raised in wood shavings presented higher BW and better FCR than those reared on rice hulls or alternative litters, respectively. It has been suggested that rice hulls account for the greater proliferation of fungi and consequently mycotoxins (Llewellyn, 1988) which are known to worsen live performance in broilers.

In addition, the results presented herein indicated that BW in males and females improved when the litter was recycled more than once. Abougabal (2019) observed no significant differences in the BW from 1 to 6 wk of age nor in the FCR at the end of the experiment when evaluating four litter treatments (new litter, 50% new litter – 50% reused litter, 100% reused litter, and 100% reused treated litter). Still, the author suggested that recycled litter was not a hazard for broiler production performance. In contrast, an experiment conducted by Garcés-Gudino *et al.* (2017) in tropical conditions indicated that BW (1,922 *vs.* 1,753 g), BW gain (53.7 *vs.* 48.8 g/d), FCR (1.588 *vs.* 1.633 g:g), and mortality (1.61 *vs.* 3.2%) at 35 d were improved when the same litter was used for two or three production cycles. It has been mentioned that the recycling process may have beneficial impacts on the performance of broilers since the litter bacterial environment could work as a probiotic or a direct-fed microbial supplementation in chickens that contribute to improving the immunity and the response against coccidia challenges which usually affect the live performance of broilers (Chapman, 1999; Cressman *et al.,* 2010; Garcés-Gudino *et al.* 2017; Smith, 2019).

The distance from the hatchery to the farm measured in both kilometers and time spent to reach the farm showed that chicks traveling the longest distances were heavier at 35 d. In contrast, Bergoug *et al.* (2013) indicated that chicks traveling 4 and 10 h had less BW from the placement up to 21 d where the effect of transportation time disappeared, compared to chicks that traveled less than 5 minutes to the farm (0h, control). However, it was further investigated with hatchery shipping reports that the results presented herein could vary because chicks intended to travel long distances are usually scheduled to start the journey at night, which could reduce stress generated by heat, dehydration, and feed and water deprival, in comparison to chicks delivered during the day. Those aspects related to stress during transportation could be more detrimental to chick development and health than the duration of the trip *per se* (Decuypere *et al.,* 2001; Oviedo-Rondón *et al.,* 2009; Abreu *et al.,* 2017; Yerpes *et al.,* 2021). Still, males and females were more efficient when post-hatch transportation was the shortest.

When evaluating these factors together with the growth parameters, variable importance analyses from the supervised ML models demonstrated that the BW and FCR at 35 d are highly dependent on the live performance that chickens may exhibit during the second and third wk of age. Other parameters like sex, the distance between the hatchery and the farm, and farm elevation were important to predict BW.

Prediction of performance with ML

The MLR presented the lowest predictability for BW and FCR at 35 d. In contrast, the RF had the best model fit and the best method to predict both the BW and FCR at 35 d. However, the variation of the FCR was explained in less than 50% by these ML techniques under five-fold cross-validation. Based on the present data, it was concluded that the contribution of management, environment and infrastructe to the FCR at 35 d is less than 50%. Most likely, its variability is associated with other factors like nutrition, which was not included in those models.

Finally, BW at 21 d, sex, distance from hatchery to farm, feed intake, and farm altitude were the five most important variables to predict the BW at 35 d. In comparison, FCR at 21 d, sex, farm altitude, feed intake at 21, and FCR at 14 d accounted for the most important factors in the prediction of FCR at 35.

Conclusions

In conclusion, temperatures lower than 2.5 ºC added up to the variable environmental conditions reduced the BW, and BW gain at 7, 14 and 21 d, while the FCR was worsened at 14 (0.011 g:g), 21 (0.004 g:g), and 35 (0.004 g:g) d of age. In addition, mortality increased 0.018% on average at 28 and 35 d when chickens were exposed to temperatures lower than 2.5 ºC. All farm-associated and chick source factors affected the performance of broilers and sex, distance from the hatchery to the farm and farm altitude were within the five most important variables to determine broiler BW at 35 d.

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Table 3.1. Descriptive statistics for farm-associated categorical variables.

Variable	Category	Northwest		Midwest		East	
		n	%	*n*	%	*n*	%
		(farms[1])					
Farms		42	48.84	17	19.77	27	31.40
Technification level	High	7	8.14	9	10.47	10	11.63
	Low	35	40.70	8	9.30	17	19.77
Chick source	Hatchery 1	42	48.84	0	0.00	0	0.00
	Hatchery 2	0	0.00	17	19.77	27	31.40
Litter type	Rice hulls	0	0.00	1	1.16	27	31.40
	Wood shavings	42	48.84	16	18.60	0	0.00
		(houses[2])					
Houses		367	49.80	153	20.76	217	29.44
Type of house	Open-sided	358	48.31	118	15.92	194	26.18
	Retrofitted	15	2.02	21	2.83	23	3.10
	Controlled	0	0.00	12	1.62	0	0.00
House stories[3]	1	262	35.74	143	19.51	217	29.60
	2	101	13.78	10	1.36	0	0.00
House floor type	Soil	273	37.24	61	8.32	96	13.10
	Concrete	90	12.28	92	12.55	121	16.51
Water storage system	Covered	202	27.41	118	16.01	148	20.08
	Uncovered	157	21.30	41	5.56	69	9.36
	Underground	2	0.27	0	0.00	0	0.00

[1]Variable percentage based on the number of farms by factor level over the total number of farms (n = 86)

[2] Variable percentage based on the number of houses by factor level over the total number of houses (n = 737)

[3] Number of houses with one or two stories enabled to place chicks.

Table 3.2. Descriptive statistics for farm-associated continuous variables.

Variable	Northwest				Midwest				East			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
Altitude (m.a.s.l.)	1,588	398	1,050	2,353	1,184	300	915	1,955	1,184	466	99	2,253
Litter reuse cycles (# times)	1.9	1.85	0	12	5.58	4.15	0	12	0.44	0.57	0	2
Distance from hatchery (km)	39.1	18.6	5	80	188.8	29.4	132	245	444.6	40	358	531
Distance from hatchery (h)	1.5	0.6	0.1	3	5.4	0.7	4	6.5	8.3	1.1	6	11
Downtime between flocks (d)	14.1	0.4	14	16	16.3	1.4	14	21	13.0	1.6	11	20
Farm area (m^2)	6,435	4,607	1,620	24,992	12,655	8,761	1,440	31,680	7,795	9,238	1,240	48,956

Table 3.3. Correlation coefficients and regression estimates of live performance parameters from 28 to 35 d and time of exposure to a relative humidity below and above-recommended values of Ross 308 AP broilers raised to 35 d.

Age	Live Performance	Relative humidity (%)	Age of exposure (d)	*r*	*P*-value correlation	*n*	Intercept	Estimate	R^2	R^2 adj	RMSE	*P*-value linear regression
7	FCR	< 50	0 to 7	-0.51	<0.001	46	0.936	-0.002	0.26	0.24	0.06	<0.001
21	Week mortality	< 50	14 to 21	-0.46	0.015	28	0.155	-0.004	0.21	0.18	0.07	0.015
21	Cumulative mortality	< 50	14 to 21	-0.45	0.015	29	0.209	-0.003	0.20	0.17	0.06	0.015
21	FCR	< 50 or > 75	14 to 21	0.41	<0.001	69	1.277	0.001	0.17	0.16	0.06	<0.001
28	FCR	< 50	21 to 28	0.41	0.035	27	1.360	0.003	0.17	0.13	0.06	0.035
28	FCR	> 75	0 to 28	0.41	0.001	68	1.384	0.0002	0.17	0.16	0.06	0.001
28	FCR	< 50 or > 75	0 to 28	0.41	<0.001	70	1.372	0.0002	0.17	0.16	0.06	<0.001

Table 3.4. Effect of farm-associated factors on BW, FCR, and cumulative mortality at 35 d of male and female Ross 308 AP broilers raised under commercial tropical conditions.

Item	Category / Cluster Mean	SD	Males				Females			
			n	BW	FCR	Mortality	*n*	BW	FCR	Mortality
			flocks	--(g)--	-(g:g)-	-- (%) --	flocks	-- (g) --	-(g:g)-	--(%)--
Region	Northwest		381	1,836^{c}	1.461^{c}	2.98^{a}	385	1,729^{b}	1.514^{c}	2.68^{ab}
	Midwest		148	1,947^{a}	1.493^{b}	2.52^{b}	154	1,751^{a}	1.533^{b}	2.27^{b}
	East		669	1,882^{b}	1.515^{a}	2.85^{a}	670	1,673^{c}	1.557^{a}	2.71^{a}
	SEM ±			4	0.003	0.10		4	0.003	0.09
	CV %			4.1	3.3	26.6		4.3	2.9	27.3
Technification level	High		497	1,889^{a}	1.507^{a}	2.94	502	1,690^{b}	1.550^{a}	2.72^{a}
	Low		687	1,866^{b}	1.487^{b}	2.79	694	1,708^{a}	1.533^{b}	2.54^{b}
	SEM ±			3	0.002	0.07		3	0.002	0.07
	CV %			4.4	3.6	26.8		4.7	3.1	28.2
Altitude (m.a.s.l.)	1,041	349	376	1,873^{b}	1.522^{b}	2.69^{b}	359	1,730^{b}	1.519^{b}	1.96^{c}
	1,446	498	172	1,792^{c}	1.577^{a}	3.82^{a}	645	1,660^{c}	1.573^{a}	3.06^{a}
	1,670	434	650	1,898^{a}	1.457^{c}	2.71^{b}	205	1,774^{a}	1.475^{c}	2.43^{b}
	SEM ±			4	0.003	0.09		4	0.002	0.09
	CV %			4.0	2.2	26.1		3.9	2.0	27.4
Litter type	Rice hulls		672	1,883^{a}	1.514^{a}	2.85	676	1,674^{b}	1.556^{a}	2.69^{a}
	Wood shaving		526	1,867^{b}	1.470^{b}	2.87	533	1,733^{a}	1.519^{b}	2.54^{b}
	SEM ±			3	0.002	0.07		3	0.002	0.07
	CV %			4.4	3.4	26.8		4.3	2.9	28.9
Litter reuse cycles number	0.8	0.7	348	1,819^{b}	1.556^{a}	3.47^{a}	797	1,671^{c}	1.561^{a}	2.89^{a}
	1.3	1.2	767	1,898^{a}	1.465^{c}	2.59^{c}	297	1,769^{a}	1.481^{c}	2.10^{b}
	5.8	2.2	32	1,898^{a}	1.564^{a}	3.41^{ab}	69	1,722^{b}	1.562^{a}	2.10^{b}
	12.0	0.0	51	1,898^{a}	1.479^{b}	2.53^{bc}	46	1,718^{b}	1.522^{b}	2.24^{b}
	SEM ±			8	0.004	0.17		6	0.003	0.15
	CV %			4.0	2.4	26.0		4.0	2.3	28.1
Downtime between flocks (d)	12.7	1.0	314	1,822^{c}	1.562^{a}	3.44^{a}	678	1,662^{c}	1.569^{a}	2.94^{a}
	13.5	1.2	662	1,906^{a}	1.457^{c}	2.51^{b}	150	1,778^{a}	1.466^{c}	2.05^{b}
	15.0	1.6	222	1,859^{b}	1.510^{b}	3.11^{a}	381	1,735^{b}	1.517^{b}	2.31^{b}
	SEM ±			4	0.002	0.09		4	0.002	0.09
	CV %			4.0	2.2	25.9		3.9	2.1	28.1
Source of variation			---------- ***P*-value** ----------							
Region				<0.001	<0.001	0.019		<0.001	<0.001	0.003
Type of administration				<0.001	<0.001	0.087		<0.001	<0.001	0.008
Altitude				<0.001	<0.001	<0.001		<0.001	<0.001	<0.001
Chick source				<0.001	<0.001	0.146		<0.001	<0.001	0.349
Distance from the hatchery (km)				<0.001	<0.001	<0.001		<0.001	<0.001	<0.001
Distance from the hatchery (h)				<0.001	<0.001	<0.001		<0.001	<0.001	<0.001
Litter type				0.001	<0.001	0.657		<0.001	<0.001	0.011
Litter reuse cycles number				<0.001	<0.001	<0.001		<0.001	<0.001	<0.001
Downtime between flocks				<0.001	<0.001	<0.001		<0.001	<0.001	<0.001

$^{a-b}$ Means in columns followed by different superscript letters are statistically different by Tukey's or student's t-test ($P < 0.05$)

Table 3.5. Effect of chick source and hatchery distance on BW, FCR, and cumulative mortality at 35 d of male and female Ross 308 AP broilers raised under commercial tropical conditions.

Item	Category / Cluster Mean	SD	Males				Females			
			n	BW	FCR	Mortality	*n*	BW	FCR	Mortality
			flocks	--(g)--	-(g:g)-	-- (%) --	flocks	-- (g) --	-(g:g)-	--(%)--
Chick source	Hatchery 1		381	1,836^{b}	1.461^{b}	3.00	385	1,729^{a}	1.514^{b}	2.65
	Hatchery 2		817	1,894^{a}	1.511^{a}	2.79	824	1,687^{b}	1.552^{a}	2.62
	SEM ±			3	0.003	0.07		3	0.002	0.07
	CV %			4.2	3.4	26.8		4.5	3.0	0.1
Distance from hatchery (km)	73	71	461	1,875^{b}	1.455^{c}	2.71^{b}	322	1,758^{a}	1.491^{c}	2.18^{b}
	356	169	257	1,812^{c}	1.572^{a}	3.54^{a}	722	1,665^{c}	1.570^{a}	2.92^{a}
	454	64	480	1,909^{a}	1.492^{b}	2.65^{b}	165	1,740^{b}	1.503^{b}	2.21^{b}
	SEM ±			4	0.002	0.09		4	0.002	0.09
	CV %			4.0	2.3	26.2		3.9	2.0	28.1
Distance from hatchery (h)	2.1	1.6	429	1,873^{a}	1.449^{c}	2.73^{b}	258	1,755^{a}	1.486^{c}	2.21^{b}
	7.0	2.9	247	1,808^{b}	1.573^{a}	3.58^{a}	714	1,663^{b}	1.571^{a}	2.93^{a}
	8.2	1.8	522	1,909^{a}	1.496^{b}	2.63^{b}	237	1,750^{a}	1.507^{b}	2.16^{b}
	SEM ±			4	0.002	3.85		4	0.002	3.85
	CV %			4.0	2.2	26.2		3.9	2.0	28.1
Source of variation				----------	----------	---------- ***P*-value**	----------	----------	----------	----------
Chick source				<0.001	<0.001	0.146		<0.001	<0.001	0.349
Distance from the hatchery (km)				<0.001	<0.001	<0.001		<0.001	<0.001	<0.001
Distance from the hatchery (h)				<0.001	<0.001	<0.001		<0.001	<0.001	<0.001

$^{a\text{-}b}$ Means in columns followed by different superscript letters are statistically different by Tukey's or student's t-test ($P < 0.05$)

Table 3.6. Goodness-of-fit metrics of three supervised machine learning methods on modeling BW and FCR of broilers raised to 35 d under commercial tropical conditions.

Model	**BW**		**FCR**	
	R^2	**RMSE**	**R^2**	**RMSE**
Multiple Linear Regression	0.59	76.38	0.18	0.050
Random Forest	0.78	56.74	0.48	0.041
Neural Network	0.73	62.00	0.45	0.042

Table 3.7. Final model and variable contribution of MLR fit with growth and farm-associated conditions on BW and FCR at 35 d of Ross 308 AP chickens reared under commercial tropical conditions.

Variable	Sum Sq	Contribution (%)[1]	Df	*F*-value	*P*-value
BW					
Females	13108737.0	89.27	1	2325.7	<0.001
Feed Intake 14 d	646918.0	4.41	1	114.8	<0.001
BW Gain at 7 d	267502.8	1.82	1	47.5	<0.001
FCR at 21 d	209950.5	1.43	1	37.2	<0.001
Percentage of Retrofitted	200095.7	1.36	1	35.5	<0.001
Percentage of Open-Sided	119749.4	0.82	1	21.2	<0.001
Location State 3	79587.1	0.54	1	14.1	<0.001
Percentage of Underground Tanks	51800.2	0.35	1	9.2	0.002
FCR					
FCR at 21 d	0.41	42.41	1	162.21	<0.001
Downtime Between Flocks	0.18	18.67	1	71.41	<0.001
Feed Intake 14 d	0.17	17.63	1	67.43	<0.001
Percentage of Retrofitted	0.07	7.34	1	28.09	<0.001
Percentage of Underground Tanks	0.04	3.94	1	15.06	<0.001
Percentage of Open-Sided	0.03	2.69	1	10.29	0.001
Percentage of Concrete Floor	0.02	2.56	1	9.80	0.002
Feed Intake 21 d	0.02	2.22	1	8.51	0.004
Month at Placement	0.01	1.47	1	5.62	0.018
Mortality at 21 d	0.01	1.06	1	4.04	0.045

[1]Variable contribution of MLR models expressed as the percentage of the variable sum of squares over the sum of squares of the model.

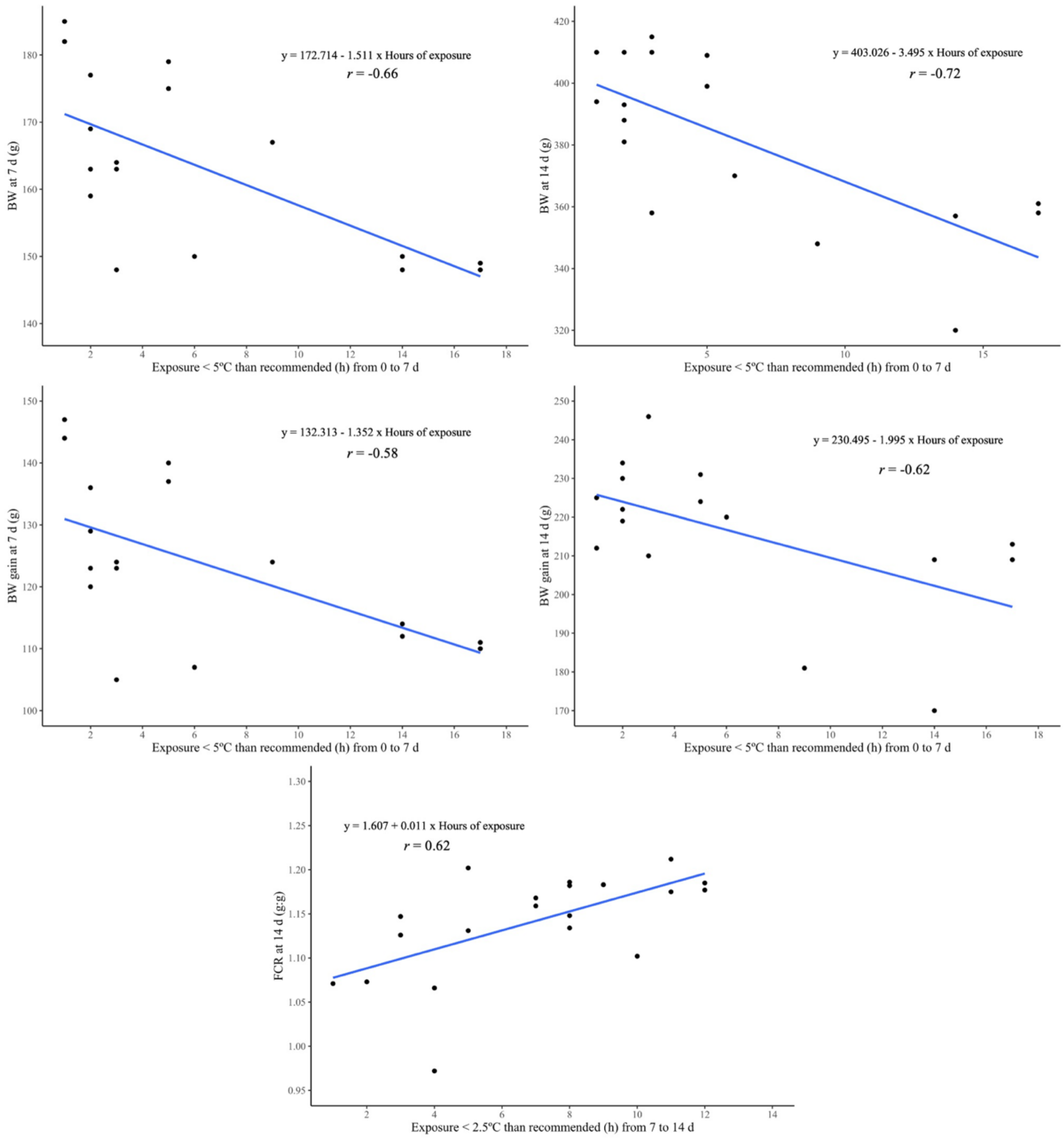

Figure 3.1. Correlation coefficients of live performance parameters from 7 to 14 d and time of exposure to temperatures below recommended values of Ross 308 AP broilers raised to 35 d.

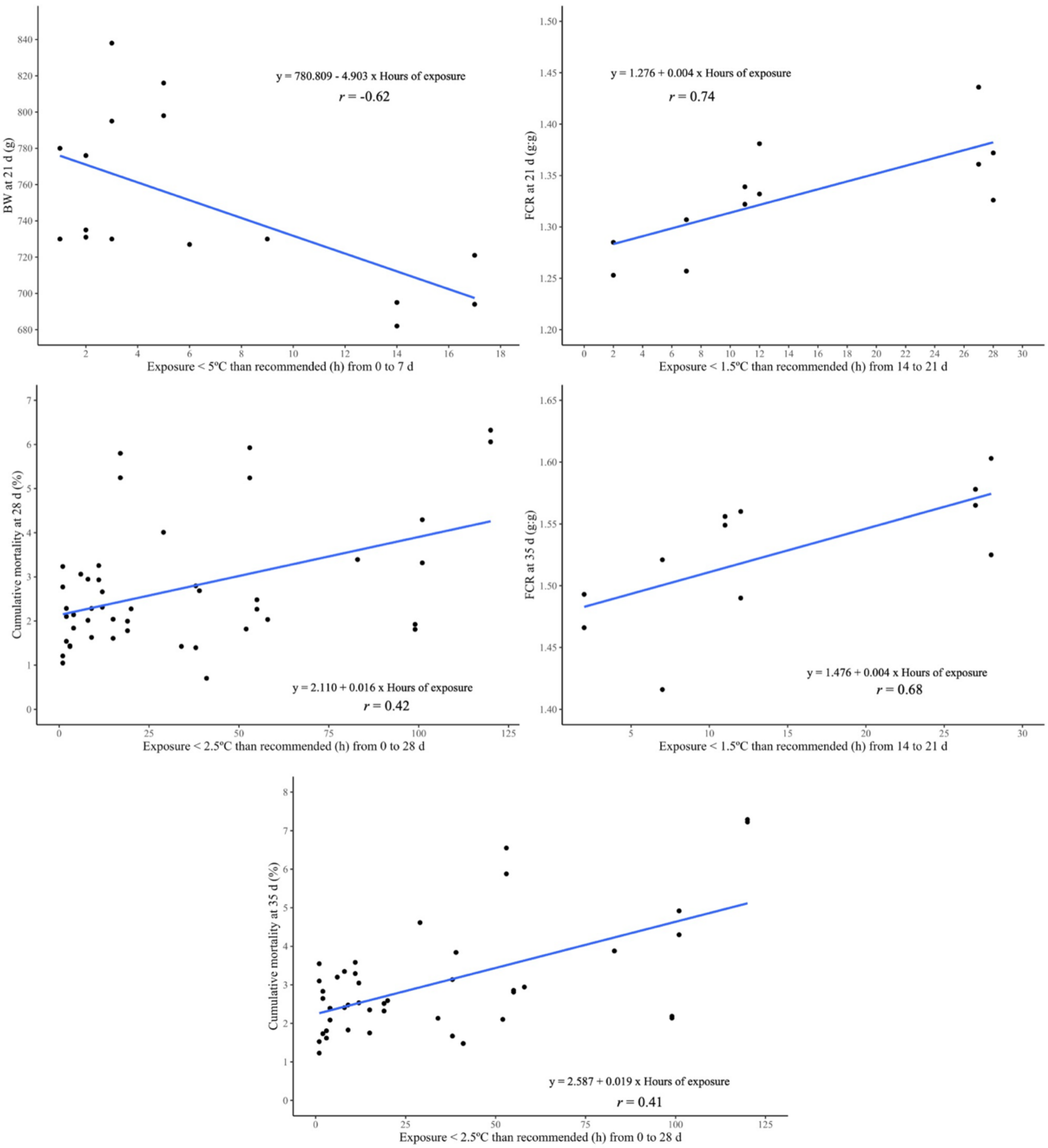

Figure 3.2. Correlation coefficients of live performance parameters from 21 to 35 d and time of exposure to temperatures below recommended values of Ross 308 AP broilers raised to 35 d.

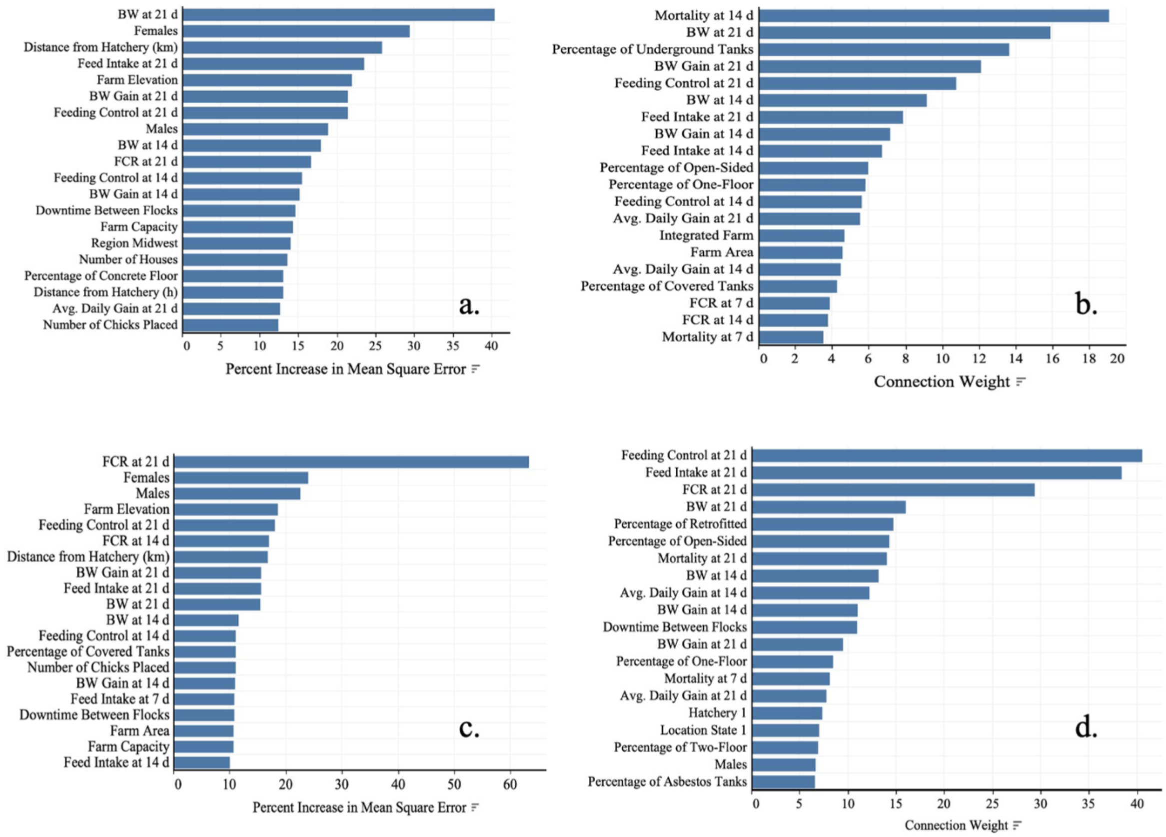

Figure 3.3. Variable importance of (a) BW with RF, (b) BW with ANN, (c) FCR with RF, and (d) FCR with ANN at 35 d on Ross 308 AP chickens raised under commercial tropical conditions.

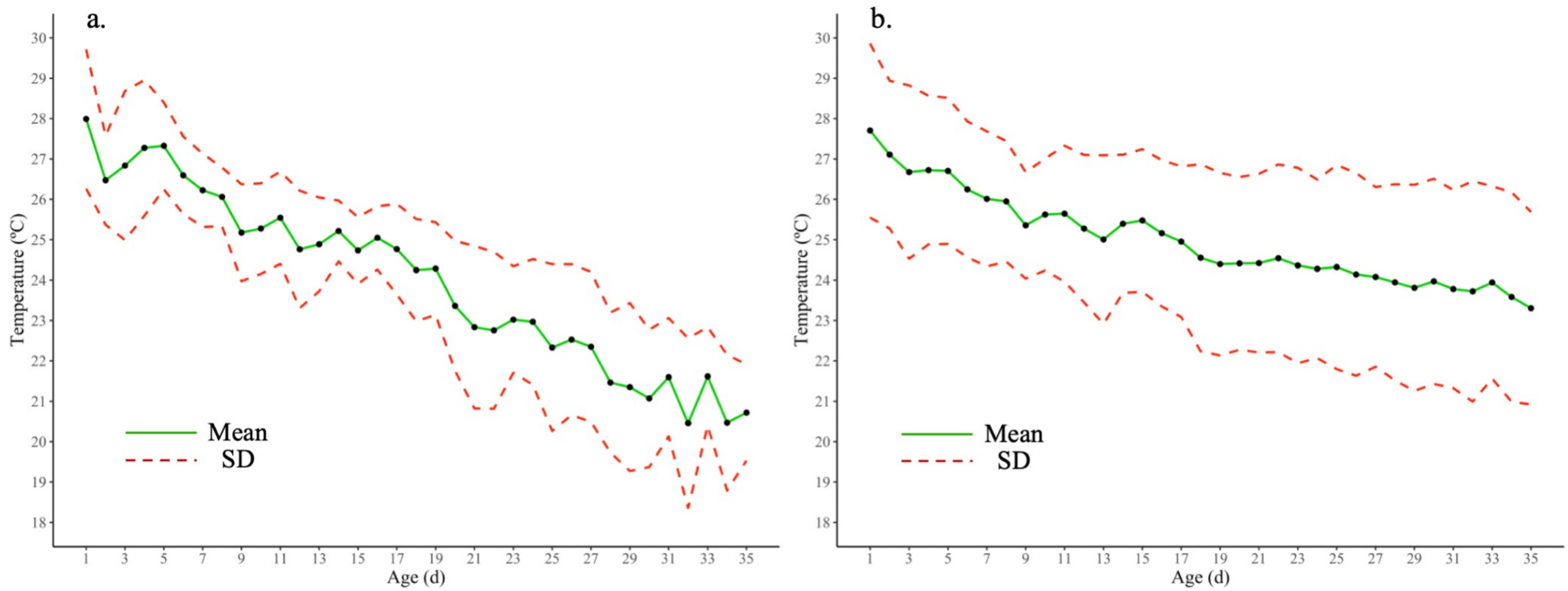

Figure 3.4. Mean ± SD of house temperature from flocks that presented (a) more than 450 h within recommended temperatures from 1 to 35 d and (b) flocks affected by cumulative exposure to temperatures lower 2.5 ºC than recommended by Aviagen (2018)

CHAPTER IV

Effect of cumulative nutrient intake on bodyweight, feed conversion ratio and mortality of broilers raised to 35 d under commercial tropical conditions

ABSTRACT

Energy and nutrient intake (NI) have been demonstrated to be important for broiler live performance under controlled experimental conditions. However, the impact of these factors in the performance of broilers raised under commercial operations has not been well explored. This data analytics study evaluated the cumulative intake (CI) of ME, CP, dLys, Ca, P and fat and their relationship with BW, FCR and mortality of broilers raised to 35 d under commercial tropical conditions in three feeding phases with control feeding across three major regions. The data analyzed included performance records of 468 male and 461 female Ross 308 AP broiler flocks placed between 2018 and 2019 for a total of 31.9 million chicks. A dataset containing the dietary nutrient composition of feed offered to chickens was joined to performance records. Nutrient intake (NI) by feeding phase and cumulative nutrient intake (CNI) up to 35 d were calculated for each flock. Correlation analyses were conducted, and linear, quadratic, and multiple linear (MLR) models were fit with performance parameters as responses and NI as predictors. Additionally, decision trees were generated with the most important management factors and CNI to model BW and FCR at 35 d. Data were analyzed using R Software in Rstudio and JMP Pro 15. No significant correlations or linear effects ($P > 0.05$) were detected between performance variables and NI during the pre-starter or starter phases. During the grower phase, positive correlations and linear effects were observed between male and female BW at 35 with the NI of all except for Ca. FCR

in males presented mild correlations while linear models resulted in poor R^2. The MLR for BW at 35 d in both males and females with CNI up to the grower phase indicated positive linear effects of Ca, P, and ME while accounting for the negative linear effects of CP. In contrast, FCR at 35 d fit either with single-phase or CNI at all feeding phases for both males and females depicted less than 16% of the variability. Decision trees indicated that CI of ME, P, dig Lys, and fat, farm altitude, distance from hatchery to farm were important factors to model BW (R^2 =0.55 -0.71) and FCR (R^2 = 0.40 – 0.48). In conclusion, male and female BW at 35 d was mainly affected by NI during the grower phase, being ME and dLys the most important nutritional factors. The variability in NI during pre-starter and starter phases was not related to the variability observed on FCR at 35 d, while minimal effects were detected during grower. Cumulative mortality at 35 d was not affected by the intake of the nutrients analyzed. Decision trees revealed important relations between environment, chick management, and nutrition.

INTRODUCTION

Feed intake in broilers has been demonstrated to be affected by different factors such as dietary nutrient composition (Leeson *et al.,* 1996) and management (Acar *et al.,* 1995; Lippens *et al.,* 2000; Butzen *et al.,* 2013), thus, affecting the intake of nutrients. Additionally, changes in feed intake (FI) can alter BW, BW gain, feed conversion ratio (FCR), carcass traits, and cost (Ahiwe *et al.,* 2018). Although broiler diets are formulated to optimize chicken growth, the variability resulting from the nutrient ingredient composition, feedstuff quality (Moss *et al.,* 2021), and feed processing (Corzo *et al.,* 2011; Chewning *et al.,* 2012) could contribute to observing different responses under commercial conditions. Consequently, some authors have reported the effects of energy (Rosa *et al.,* 2007; Massuquetto *et al.,* 2020; Maharjan *et al.,* 2021; Hu *et al.,* 2021), CP (Pesti, 2009; Kriseldi *et al.,* 2018; Chrystal *et al.,* 2020), amino acids (Farkhoy *et al.,* 2012; Barekatain *et al.,* 2021; Kidd *et al.,* 2021), fat (Tabeidian *et al.,* 2010; Poorghasemi *et al.,* 2013), and minerals (Gautier *et al.,* 2017; Fallah *et al.,* 2019) intake on broiler performance.

Metabolizable energy (ME) intake has received the greatest attention due to its relationship with a better growth rate (Rosa *et al.,* 2007; Maharjan *et al.,* 2021). Rosa *et al.* (2007) revealed that broiler BW gain at 42 d of age increased as dietary energy content increased from 2,950 to 3,450 kcal/kg. Also, Maharjan *et al.* (2021) detected a linear increase in total body mass, regardless of the genetic line (A and B) and season (hot and cool), with diets that varied between 2,800 and 3,300 kcal/kg from 22 to 42 d. However, increasing dietary energy levels could reduce FI (Leeson *et al.,* 1996; Rosa *et al.* 2007; Maharjan *et al.,* 2021) in broilers, limiting the intake of other nutrients.

Similarly, greater or lower crude protein (CP) level in broiler diets has resulted in heavier or lighter chickens at all phases, respectively (Ghahri *et al.,* 2010; Abbasi *et al.,* 2014; Gheisari *et* *al.,* 2015). In an experiment, Kamely *et al.* (2020) reported no differences in BW nor FCR at 14 or 35 d with chickens fed standard (23.78%) or reduced (21.23%) CP diets that resulted in a CI of 125.21 g and 100.63 g CP from 1 to 14 d, respectively. In contrast, Jabbar *et al.* (2021) showed that chickens that received on average 393 g of CP between 15 and 28 d from diets containing 19 or 21% CP were on average 159 g heavier (1,097 *vs.* 938 g) and 0.32 g:g more efficient (1.70 *vs.* 2.02 g:g) than those receiving 322 g of CP from a 17% CP diet. The same study indicated that the lowest dietary CP evaluated resulted in more abdominal fat, which could be a negative trait in carcasses (Jabbar *et al.,* 2021). Then, it is hypothesized that differences in NI at later growth stages influence BW and FCR at slaughter age. Unfortunately, it is common to report results concerning dietary nutrient concentration and the NI *per se* is not indicated or calculated.

On the other hand, digestible lysine (dLys) intake has been demonstrated to affect BW (Ghahri *et al.,* 2010; Kheiri and Alibeyghi, 2017) since growth and muscle protein synthesis are highly dependent on this nutrient (Costa *et al.,* 2001; Lana *et al.,* 2005; Cemin *et al.,* 2017). Kheiri and Alibeyghi (2017) revealed that chickens fed four levels of dLys (100, 110, 120, and 130%) from the NRC (1994) recommendations improved BW at 28 d as dLys level increased, while a significant decrease on this parameter was detected at the highest dLys treatment at 42 d. Likewise, Ghahri *et al.* (2010) determined that dLys level in broilers may result in quadratic effects on BW gain and FCR when using dietary content levels between 0.8 and 1.1%. A more recent report from Cemin *et al.* (2017) indicated that chickens fed dLys levels between 0.97 to 1.37, 0.77 to 1.17, and 0.68 to 1.07% in the starter, grower, and finisher phases, respectively, resulted in quadratic polynomial and quadratic broken-line responses in BW and FCR at all ages. Optimal levels of dLys were estimated at 1.16% for starter, 1.04% for the grower, and 1.00% for finisher (Cemin *et al.,* 2017). However, Lee *et al.* (2018) suggested that dLys requirements for optimal performance can be even higher in the starter phase reaching levels of 1.33% based on broken-line regressions. The quadratic effects of dLys indicate that a greater intake of dLys could be associated with a reduction in BW and efficiency at the end of the production cycle.

In contrast, some results have shown that levels of 4.34% of dietary fat in the pre-starter phase may affect BW only in early stages of growth without differences in the subsequent phases or FCR during the whole cycle compared to diets with 10.8% fat (Swennen *et al.,* 2009). Furthermore, calcium (Ca), phosphorus (P), and their relationship (Han *et al.,* 2016) might affect the broiler performance. Han *et al.* (2016) reported that the increase in the Ca:P ratio resulted in a linear rise in BW gain and FI while FCR was also improved. However, some authors indicate that high Ca intake or changes in source solubility and digestibility could be involved in reduced animal performance, macromineral absorption, and energy digestibility (Simpson and Wise, 1990; Sebastian *et al.,* 1996; Hamdi *et al.,* 2015; Li *et al.,* 2017; Kim *et al.,* 2018), thus, appropriate intake of this nutrient is necessary to avoid potential issues with other nutrients that lead to poor performance.

Although this extensive research has demonstrated different effects of individual or maximum levels of three nutrients on broiler live performance variables, data about the impact of the CI of all these nutrients simultaneously on broilers raised under commercial operations is still scarce. Furthermore, due to the impact of environmental, farm-associated factors, and the variability of data from commercial operations (Acar *et al.,* 1995; Lippens *et al.,* 2000; Butzen *et al.,* 2013; Pitesky *et al.,* 2020; Neethirajan, 2020), data mining techniques are essential to reveal the possible effects, interactions, and critical points that could affect the BW and FCR in broilers. Considering that simple and multiple linear regression (MLR) may not detect trends from commercial data due to size and a lack of dataset structure. For those reasons, the objective of this study was to evaluate the CI of ME, CP, dLys, Ca, P and fat and their relationship on BW, FCR, and mortality of broilers raised under commercial operations in three feeding phases.

MATERIALS AND METHODS

Database and statistical software

Two datasets were obtained from a broiler integration located in Colombia. One dataset contained live performance parameters from 1,347 male and 1,353 female Ross 308 AP broiler flocks collected weekly from the placement up to slaughter age. However, since not all flocks were processed at the same age, the cutoff point on the data was 35 d. Performance records included BW, BW gain, FCR, and mortality of all flocks placed between 2018 and 2020 in 86 farms, as described in the second chapter of this thesis. Briefly, after incubation in multistage machines within two company-owned hatcheries, chickens are sexed, vaccinated, boxed, and transported to farms arranged in three major poultry production regions of the country. Within each region, one feed mill provided three diets for the growth of chickens, pre-starter (150 g), starter (900 g), and grower (1,643 ± 145 g). Chicks placed mainly in litter-based open-sided houses were raised to 35 d in a feed-controlled system with an initial stocking density of 12.74 ± 1.12 chickens/m^2.

Another dataset included the dietary nutrient content represented by ME, CP, dLys, Ca, P, and fat of the three feeding phases offered to chickens in each region by date. Nutritional data coming from formulated values to each flock was joined to performance records based on manufacturing region and date. To do so, a for loop was created to join both broiler performance records and nutritional datasets considering that the manufacturing date had to be the last day before the placement date, and it could not be greater than seven days prior the placement of chicks according to the company policies. The feed quality control indicated that formulated nutrients closely match the analyzed values. Consequently, nutrient intake (NI) by feeding phase and cumulative nutrient intake (CNI) to 35 d were calculated for each flock using the amount of feed established for pre-starter and starter phases (Table 4.1). Intake during grower was calculated as the difference between the FI at 35 d and pre-starter and starter amounts. After data cleaning and organizing, 481 and 486 female and male broiler flocks accounted for all nutritional information. Data analyzed represented 31.9 million chicks, placed between January 2018 and December 2019. Data were organized and analyzed using R (R Core Team, 2021) in RStudio (RStudio Team, Boston, MA, USA) and JMP Pro 15 (SAS Institute, Cary, NC, USA).

Statistical analysis

Percentage data for cumulative mortality at 35 d were transformed to the arcsine square-root percentage for analysis. Correlation analyses were conducted among CNI and performance variables at 35 d by sex. Linear, quadratic, and MLR were fit with BW, FCR, and cumulative mortality at 35 d as response and NI either by feeding phase or CI up to pre-starter, starter, and grower phases as predictors. Additionally, the most important and common management factors detected to be important with random forests, and artificial neural networks models in the previous chapter of this thesis were selected together with total CNI to s modeling BW and FCR at 35 d using decision trees. As a criterion for selection, those variables had to be within the 20 top important variables, represent at least 15% of contribution to the previous models either in the increase of MSE or connection weight, not being related to infrastructure due to high skewness of the data, be measurable and present significant differences in the BW of FCR in the analysis of variance. The variables selected for analysis were the distance from hatchery to farm, farm altitude, and downtime between flocks. Although sex was important for most of the models, this variable was used to differentiate the response of the decision trees. Therefore, decision trees with BW and

FCR as responses were fit using the management farm-associated factors and CNI from the present study. Variable contribution analyses were conducted for the resulting models. Indoor temperature and relative humidity data were not considered for this analysis because none of the flocks analyzed in the third chapter of this thesis had nutritional information. Thus, it was impossible to determine the combination of the indoor environment, management, and nutrition variables on the BW or FCR.

RESULTS

Nutrient intake correlations and relationships with BW and FCR

No significant correlations nor linear or quadratic effects were detected among BW, FCR, and mortality with NI during pre-starter and starter phases. Positive correlations ($P < 0.05$) of NI were detected between male and female BW at 35 d and intake of all nutrients during the grower phase and cumulatively until the end of the cycle, except for Ca in males (Figure 4.1). Additionally, intake of dLys, CP, and ME during grower were positively correlated with FCR of males at 35 d. Linear models indicated that as NI during grower increased ($P < 0.001$), BW at 35 d also augmented (Table 4.2), except for Ca in both males and females, which, although significant, resulted in poor R^2 (0.04 – 0.19). Additionally, P intake in males resulted in a quadratic effect (BW at 35 d = -944.657 + 481.040 * Intake P grower - 20.185 * Intake P grower^2; $P < 0.001$; $R^2 = 0.34$) with an optimum of 11.91 g only during this phase. Linear effects ($P < 0.001$) of CI of dLys, P, CP and ME were observed in both sexes at 35 d, while fat demonstrated quadratic effects in both males (BW at 35 d = 2184.286 - 6.451 * CI of fat + 0.0267 * CI of fat^2) and females (BW at 35 d = 2,082.459 - 7.899 * CI of fat + 0.034 * CI of fat^2; $P < 0.001$; $R^2 = 0.32$).

In males ($R^2 = 0.44$) and females ($R^2 = 0.55$) the highest R^2 was detected in the linear model of ME (Figure 4.2), followed by dLys ($R^2 = 0.38$) and P ($R^2 = 0.53$), respectively. Then, model estimates indicated that chickens were on average 14 g heavier per 100 additional kcal consumed up to 35 d reaching a mean ME intake of 8,660 kcal at slaughter age. Similarly, it was estimated an increase in BW of 32 g for males and 47 g for females for each additional gram of dLys supplied until 35 d. On FCR with NI during grower phase, no significant effect of nutrient levels evaluated were observed in females, while males resulted in low R^2 of dLys (FCR at 35 d = 1.131 + 0.019 * Intake dLys grower; $P < 0.001$; $R^2 = 0.22$), CP (FCR at 35 d = 1.113 + 0.001 * Intake CP grower; $P < 0.001$; $R^2 = 0.22$) and ME (FCR at 35 d = 1.174 + 0.00001 * Intake ME grower; $P < 0.001$; $R^2 = 0.19$) similar to the results observed in FCR with CNI at the end of the cycle.

Multiple linear regression models

The MLR results demonstrated that only 16.4 and 17.8% of the variability was captured when modeling the BW at 35 d of males and females, respectively, with CNI at the culmination of the pre-starter phase. However, when including CNI up to the starter phase, females BW resulted in quadratic effects ($P < 0.05$) of Ca and CP while accounting for the linear effects of fat intake (BW at 35 d = -12,141.553 + 2.049 * CI of fat + 559.755 * CI of Ca – 26.003 * CI of Ca^2 + 96.549 * CI of CP – 0.216 * CI of CP^2; $P < 0.001$; $R^2 = 0.27$). An optimum intake of Ca was estimated in 10.76 g while 223.81 g were determined for CP. Male BW variability was explained in 19.2% when CNI up to the starter phase were used as predictors. MLR fit with CNI up to 35 d showed that male BW depended on the positive linear effects of Ca, P, and ME and the negative linear effects of CP (BW at 35 d = 679.756 + 4.847 * CI of Ca + 23.387 * CI of P – 1.057 * CI of CP + 0.142 * CI of ME; $P < 0.001$; $R^2 = 0.47$). Similarly, female BW model accounted for the effects of the same factors (BW at 35 d = 220.846 + 8.693 * CI of Ca + 35.635 * CI of P – 0.799 * cumulative intake of CP + 0.136 * CI of ME; $P < 0.001$; $R^2 = 0.61$) at the end of the grower phase. In contrast, FCR at 35 d fit either with single-phase or CNI at all feeding phases for both males and females depicted less than 16% of the variability, except for CI at slaughter age of males that exhibited quadratic effects of P and CP (FCR at 35 d = 0.917 + 0.334 * CI of P – 0.010 * CI of P^2 – 0.009 * CI of CP + 0.0001 * CI of CP^2; $P < 0.001$; $R^2 = 0.27$). The P intake that resulted in the worst response was estimated at 16.07 g while accounting for the effects of an optimum intake of 474.81 g of CP.

Decision trees with CNI and management factors

Results from decision trees are detailed in Figures 4.3 and 4.4 for BW and Figure 4.5 and Figure 4.6, for FCR. On male BW, decision trees ($R^2 = 0.55$) indicated that male flocks placed in farms located higher than 1,139 m.a.s.l. that received more than 9,530 kcal at 35 d had on average 1,989 g compared to males receiving less than 8,567 kcal of ME regardless other factors and presented a BW 197 g lighter. Variable contribution (Table 4.3) showed that cumulative ME accounted for 83% of the response, followed by altitude (8%) and distance from hatchery to farm (5%). The CI of dLys, Ca, P, and CP did not contribute (0%) to this model. Similarly, decision tree results from females determined ($R^2 = 0.71$) that the heaviest (1,804 g) chickens were those exceeding 17.0 g of the CI of P and 8,395 kcal of ME while the lightest (1,550 g) resulted from an intake of P inferior to 14.8 g, and 8,394 kcal and additionally were subject to a trip longer than 401 km between the hatchery and the farm. In that decision tree, CI of ME contributed 71% to the response, distance from hatchery to farm 13%, and CI of P 11%.

More efficient males (1.45 g:g) were observed ($R^2 = 0.48$) in chickens allocated below 2,200 m.a.s.l. with a CI of dLys lower than 32.4 g that traveled less than 401 km from the hatchery to the farm compared to chickens placed in farms at less than 1,127 m.a.s.l., and whose traveled between 401 and 456 km to reach the farm. In this model, the distance between the hatchery and the farm accounted for 64% of the variation, altitude with 12% and cumulative CP 10%. In females ($R^2 = 0.40$), the most efficient animals were observed in those traveling less than 80 km, receiving less than 8,822 kcal compared to females offered more than 7,975 kcal and traveling between 401 and 456 km. Again, distance from hatchery to farm represented 75% of the model, CI of ME 15%, and CI of fat 5%.

DISCUSSION

Nutrient intake correlations and relationships with BW and FCR

No significant correlations or linear effects were observed between NI during pre-starter and starter phases and BW, FCR, or mortality. Swennen *et al.* (2009) indicated that chicks fed pre-starter diets low either in CP (12.6 *vs.* 23.7%) or fat (4.34 *vs.* 10.8%) up to 5 d of age did not exhibit significant differences in BW at 35 d. In another study, Kamely *et al.* (2020) demonstrated that BW and FCR were not affected at 35 d when chicks were fed standard (23.78%; 125.2 g) or reduced (21.23%; 100.6 g) CP diets from 1 to 14 d. For that study, the difference in CP intake between treatments was estimated at 24.85 g. At early stages, Vieira *et al.* (2006) reported that ME intake in pre-starter between 419 and 439 kcal at 7 d did not affect BW. Likewise, no significant differences on BW at 21 d were detected by Infante-Rodriguez *et al.* (2016) when evaluating four levels of ME, 2,960, 3,000, 3,040, and 3,080 kcal/kg that resulted in an intake of 3,572, 3,672, 3,283, and 3,461 kcal, respectively. In the present study, Cumulative ME intake ranged between 420 and 496 kcal in the pre-starter and between 3,227 and 3,309 kcal in the starter. These values were estimations based on the formulated diets and the feed allowance established for pre-starter and starter phases. Although accurate feed amounts per phase are commonly recorded in commercial operations for financial and logistics purposes, these values are not usually employed as a factor that determines the performance of chickens and consequently is not included as an additional variable in live performance datasets. Thus, to develop a better approach in the analysis of NI, it is necessary to account for the actual variation of the feed delivered at early ages for each flock to reduce the error coming from estimations based on cut-off points.

Meanwhile, positive linear effects of all nutrients except Ca, indicated that mainly the NI during grower drover BW at 35 d was driven primarily by the NI during grower. Similarly, Ghahri *et al.* (2010) showed that chickens fed three levels of CP (18, 20, and 22%) and four levels of dLys (0.8, 0.9, 1.0, and 1.1%) from 21 to 42 d gained more weight as CP and dLys increased with a quadratic effect of dLys level. The CI of dLys for the same study was estimated at 21.72, 24.86, 27.49, and 30.67 g for each one of the experimental treatments, respectively. Significant differences on BW at 28 d were also observed by Hirai *et al.* (2020) due to higher dietary dLys level (1.00, 1.08, and 1.18%) that resulted in greater dLys intake at 28 d. Chickens that reached an average dLys intake of 17.6 g were 34 g lighter than their counterpart that consumed 19.1 g of dLys. However, these differences seemed to disappear at 35 d after a common finisher diet was implemented, and slight (P = 0.052) differences were reported for BW.

According to the previously reported results and also to those presented herein, NI at early stages does not affect the BW at slaughter age. Contrarily, the dietary nutrient composition and intake in the grower phase may determine the final outcome, being CP and dLys the main nutrients implied. The dLys intake in the current study ranged between 13.97 and 22.22 g from 21 and 35 d. Taghinejad-Roudbaneh *et al.* (2011) showed that chickens fed 8 levels of dLys between 21 and 42 d resulted in an intake that ranged between 25.13 and 59.58 g exhibiting a breaking point and plateau in the BW gain at 42.80 g of dLys. Considering the shorter slaughter age in the current study and the lower amount of feed offered to chickens due to the feed-controlled system, it is proposed that the linear response observed in dLys corresponds to the ascending section of the broken-line model described by Taghinejad-Roudbaneh *et al.* (2011). Then, it is suggested that a greater feed allowance during the last phase that let chickens obtain more dLys intake would improve of BW at slaughter age which is aligned with the findings reported in the second chapter of this thesis.

Multiple linear regression models

When determining the most important nutrients by the goodness-of-fit metrics, ME intake was the best fit for both males and females. Maharjan *et al.* (2021) also demonstrated positive linear effects of energy level and energy intake on BW increasing dietary energy content ranging from 2,800 to 3,300 kcal/kg. The estimated ME intake was between 10,600 and 11,656 kcal that led to greater BW from 22 and 42 d in two meat-type broiler lines. In the same study, the increase of dietary energy improved the FCR, contrary to the results from the current data analysis in which no effects were observed in females, and males resulting in mild correlations (r = 0.44) and poor R^2. In another study, Massuquetto *et al.* (2020) indicated that broilers raised from 35 to 47 d with four levels of ME (3,042, 3,121, 3,202, and 3,282 kcal/kg) only revealed lower BW when broilers were fed 3,042 kcal/kg (8,043 kcal of NI) compared to treatments that varied between 3,121 (8,193 kcal of NI) and 3,282 kcal/kg (8,464 kcal of NI). This could indicate that the ME intake to reach the maximum response in chickens can be observed after 35 d at higher levels of ME. Thus, similar to the effects described with dLys a greater feed allocation that allows greater ME intake at later stages of growth could benefit the BW at 35 d.

A linear and quadratic effects of P intake were observed in the grower phase of female and male BW, respectively. Similarly, Jiang *et al.* (2016) reported heavier chickens from 21 d onwards when high non-phytate P were offered in grower (low 0.25%, medium 0.35%, and high 0.45%) and finisher (low 0.15%, medium 0.25%, high 0.35%) diets between 8 and 42 d (low 5.51 g, medium 9.98 g, and high 14.16 g of P intake) while no differences in efficiency were detected. In contrast, Abudabos (2012) detected no significant differences in BW gain nor FCR when using four dietary levels of total P (0.51, 0.57, 0.61, and 0.67 % P) in broilers between 3 and 6 wk of age (15.68, 14.64, 18.49, and 19.90 g of P intake).

In both males and females, MLR results indicated that BW was influenced by the positive linear effects of Ca, P, and ME while accounting for the negative linear effects of CP. Some reports have detailed the effects of ME to CP ratio (Dairo *et al.* 2010), while Ca and P ratio are of great importance in poultry since deleterious effects on broilers have been observed when excessive dietary Ca and P are offered to chickens (Simpson and Wise, 1990; Sebastian *et al.,* 1996; Hamdi *et al.,* 2015, Li *et al.,* 2017). Usually, a higher ME:CP ratio, which is achieved by increasing energy levels, has improved broiler BW and FCR. Dairo *et al.* (2010) indicated that supplying a diet with ME:CP ratio of 148.71 kcal/%CP (2,995 kcal:20.14%) during finisher (5 to 8 wk) resulted in heavier and more efficient broilers compared to those fed diets containing a ME:CP ratio of 126.41 kcal (2,802.5 kcal:18.45 CP). In another study (Karomy *et al.,* 2019) it was described that an increase of both ME and CP during the whole production cycle but keeping constant ME:CP ratios within feeding phases presented the lightest chickens at 35 d when a nutrient combination of 2,886 kcal and 18.07% CP compared to chickens fed 3,204 kcal and 20.03% CP. However, lighter broilers were observed at a higher level of ME and CP. Thus, according to the results presented herein, higher ME levels combined with lower levels of CP would result in more appropriate NI while accounting for the linear effects of Ca and P to obtain better BW at 35 d. Han *et al.* (2016) demonstrated that increasing from 1.14 to 2.86 in the dietary, Ca:P ratio could improve BW.

However, Imari *et al.* (2020) demonstrated that chickens restricted up to 30% in Ca and P levels between 11 and 24 d did not exhibit differences in BW at the end of the grower and finisher phases.

Simple and MLR models observed in the current study of unstructured commercial data resulted in lower goodness-of-fit metrics than linear models previously reported for individual nutrients (Taghinejad-Roudbaneh *et al.* 2011; Cemin *et al.,* 2017; Maharjan *et al.,* 2021). It is important to consider sample size and the variability produced by the multiple combinations of nutrient levels evaluated, the different management, environmental, and farm-associated factors proper of commercial operations as reported in the previous chapters of this thesis.

Decision trees with CNI and management factors

The findings observed in the decision trees supported the results from simple and MLR, where the CI of ME drove the response in BW for both males and females. In addition, chick transportation and farm altitude affected the broiler responses. The deleterious effects of prolonged distance from the hatchery to the farm on growth and nutrient utilization have been discussed by other authors (Bergoug *et al.,* 2013; Yerpes *et al.*, 2021). The effect of farm altitude could be related for higher environmental temperatures when altitude decreased below 1,127 m.a.s.l. and cause worse male FCR (1.56 g:g). Still, under conditions of altitude higher than 1,127 m.a.s.l., CI of CP above 575.2 g caused poor FCR (1.53 g:g) which could be due to the negative impact of heat increment for additional protein digestion (Gonzalez-Esquerra and Leeson, 2006) and could explain the negative effect of CP observed in the MLR models. Several authors have concluded that reducing dietary CP is recommended when birds are exposed to moderate and cyclic but not chronic heat stress conditions (Awad *et al*., 2019). Furthermore, these models helped to determine the important effects that the distance from hatchery to farm and farm altitude play in the FCR of broilers raised to 35 d under commercial tropical conditions.

Conclusions

In conclusion, it was possible to detect NI during the grower phase that affected male and female broilers BW at 35 d under commercial conditions. ME and dLys seemed to be the most important factors influencing the response linearly. Thus, higher levels of these nutrients (9,908 kcal ME and 34.8 g dLys) either in dietary content or through greater feed allowance to obtain a superior NI at 35 d could be advised. Additionally, ME:CP ratio might be affecting both male and female BW, while increased intake of Ca (>28.1 g) and P (>19.7 g), keeping current levels (1.42:1 Ca:P ratio), could be necessary to improve the BW at slaughter age. Although statistically significant, effects of nutrients were observed in FCR low goodness of fit was obtained with this dataset. We hypothesize that this response is mainly affected in commercial operations by the environment, feed restriction programs, or probably linked to feeding ingredient digestibility, water quality, and farms health status that were not included in the present analyses. Still, the contribution of the farm-associated factors improved goodness-of-fit metrics in the decision trees compared to the MLR which could help enhance the predictive capabilities of the models and the interpretability of the interacting factors between management and nutrition.

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Table 4.1. Estimated minimum and maximum CNI by feeding phase of males and females Ross 308 AP broilers raised to 35 d under commercial tropical conditions.

Nutrient	**Pre-starter**		**Starter**		**Grower**	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**
Metabolizable energy, *kcal*	420	496	3,227	3,309	7,395	9,908
Crude protein, *g*	18.0	35.9	207.0	241.5	468.3	615.2
Digestible lysine, *g*	0.6	2.0	11.4	13.5	26.6	34.8
Fat, *g*	5.0	11.1	38.1	63.0	90.1	210.0
Calcium, *g*	1.1	5.4	8.6	13.5	17.4	28.1
Phosphorus, *g*	0.9	1.2	6.3	8.4	14.2	19.7

Table 4.2. Linear regression equations of fat, dLys, Ca, P, CP, and ME intake during grower and CNI up to 35 d on BW at 35 d of male and female Ross 308 AP broilers under commercial tropical conditions.

Nutrient	Intake during grower phase			Cumulative intake up to 35 d		
	Formula	R^2	*P*-value	Formula	R^2	*P*-value
Females						
Fat	BW at 35 d = 1,337.191 + 3.241 * Fat	0.35	< 0.001	BW at 35 d = 1,294.027 + 2.538 * Fat	0.29	< 0.001
dLys	BW at 35 d = 792.685+ 52.567 * dLys	0.54	< 0.001	BW at 35 d = 310.557 + 46.708 * dLys	0.46	< 0.001
Ca	BW at 35 d = 1,245.523 + 38.736 * Ca	0.17	< 0.001	BW at 35 d = 1,218.768 + 22.664 * Ca	0.19	< 0.001
P	BW at 35 d = 788.993 + 96.850 * P	0.54	< 0.001	BW at 35 d = 277.260 + 88.324 * P	0.53	< 0.001
CP	BW at 35 d = 809.491 + 2.920 * CP	0.47	< 0.001	BW at 35 d = 189.380 + 2.861 * CP	0.45	< 0.001
ME	BW at 35 d = 839.356 + 0.167 * ME	0.55	< 0.001	BW at 35 d = 305.791 + 0.166 * ME	0.55	< 0.001
Males						
Fat	BW at 35 d = 1,568.727 + 2.460 * Fat	0.30	< 0.001	BW at 35 d = 1,505.501 + 2.145 * Fat	0.29	< 0.001
dLys	BW at 35 d = 1,165.906 + 36.612 * dLys	0.39	< 0.001	BW at 35 d = 849.822 + 32.186 * dLys	0.38	< 0.001
Ca	BW at 35 d = 1,674.813 + 14.792 * Ca	0.04	< 0.001	BW at 35 d = 1,801.940 + 2.896 * Ca	0.02	0.275
P	BW at 35 d = 1,285.972 + 55.452 * P	0.30	< 0.001	BW at 35 d = 938.431 + 54.029 * P	0.26	< 0.001
CP	BW at 35 d = 1,241.946 + 1.844 * CP	0.29	< 0.001	BW at 35 d = 871.593 + 1.772 * CP	0.29	< 0.001
ME	BW at 35 d = 1,178.188 + 0.121 * ME	0.44	< 0.001	BW at 35 d = 794.030 + 0.120 * ME	0.44	< 0.001

Table 4.3. Variable contribution of decision trees for BW and FCR of male and female Ross 308 AP broilers raised to 35 d under commercial tropical conditions.

Variable	BW		FCR	
	Females	Males	Females	Males
R^2	0.71	0.55	0.40	0.48
	(%)			
Distance from hatchery to farm (km)	13	5	75	64
Cumulative ME intake	71	83	15	0
Cumulative fat intake	0	1	5	2
Cumulative P intake	11	0	4	0
Downtime between flocks	0	2	2	0
Cumulative dLys intake	4	0	0	9
Cumulative Ca intake	0	0	0	2
Farm altitude (m.a.s.l.)	2	8	0	12
Cumulative CP intake	0	0	0	10

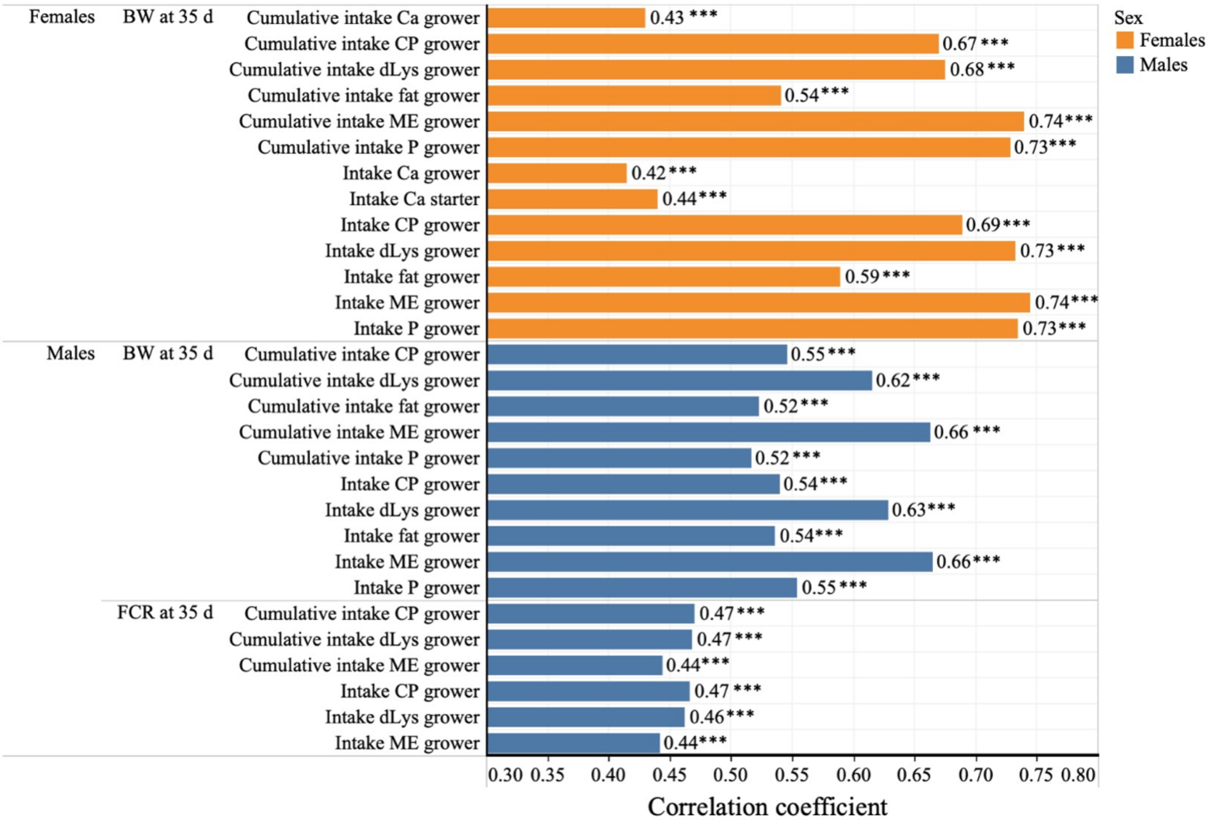

Figure 4.1. Correlation coefficients of BW and FCR at 35 d with NI during the phase or CNI up to 35 d of male and female Ross 308 AP broilers raised under commercial tropical conditions. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

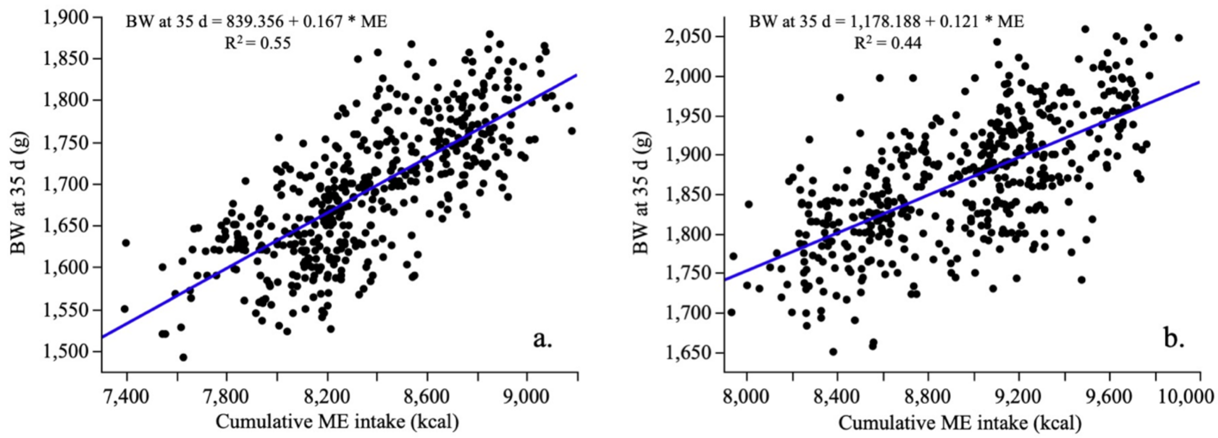

Figure 4.2. Effect of cumulative intake of ME up to 35 d on female (a) and male (b) BW of Ross 308 AP broilers raised under commercial tropical conditions.

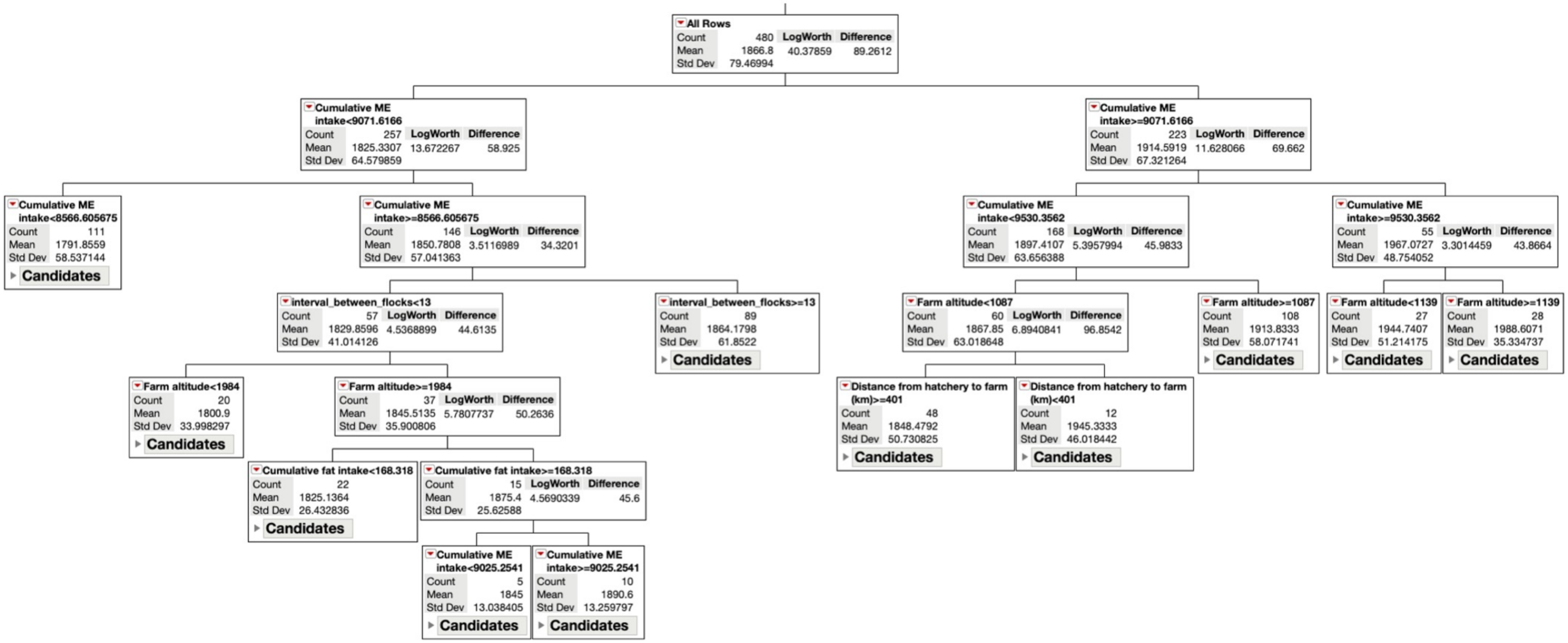

Figure 4.3. Decision tree with CNI at 35 d and farm-associated factors as predictors on male BW as response of Ross 308 broilers raised to 35 d under commercial tropical conditions ($R^2 = 0.55$; ACICc = 5,202.3).

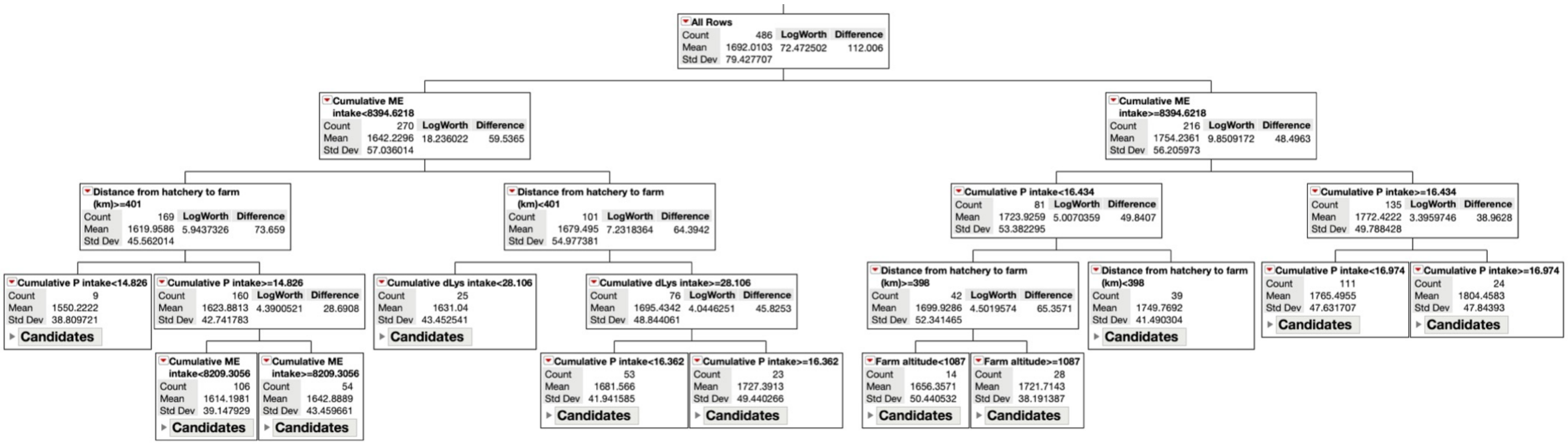

Figure 4.4. Decision tree with CNI at 35 d and farm-associated factors as predictors on female BW as response of Ross 308 broilers raised to 35 d under commercial tropical conditions ($R^2 = 0.71$; ACICc = 5,062.5).

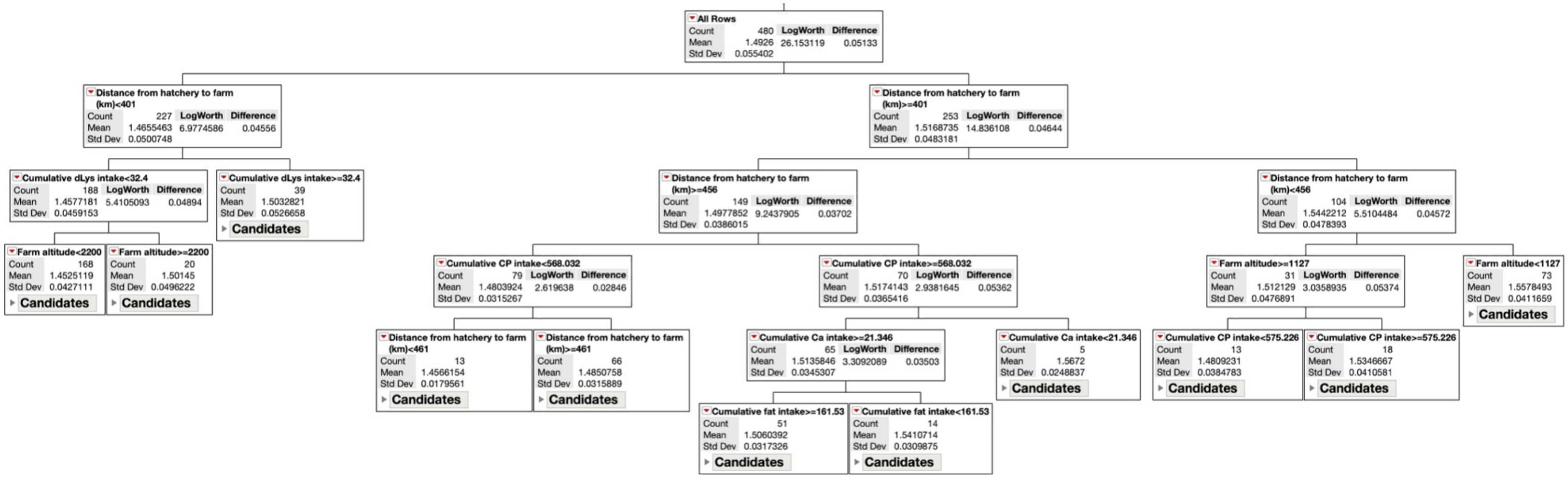

Figure 4.5. Decision tree with CNI at 35 d and farm-associated factors as predictors on male FCR as response of Ross 308 broilers raised to 35 d under commercial tropical conditions (R^2 = 0.48; ACICc = -1,708.7).

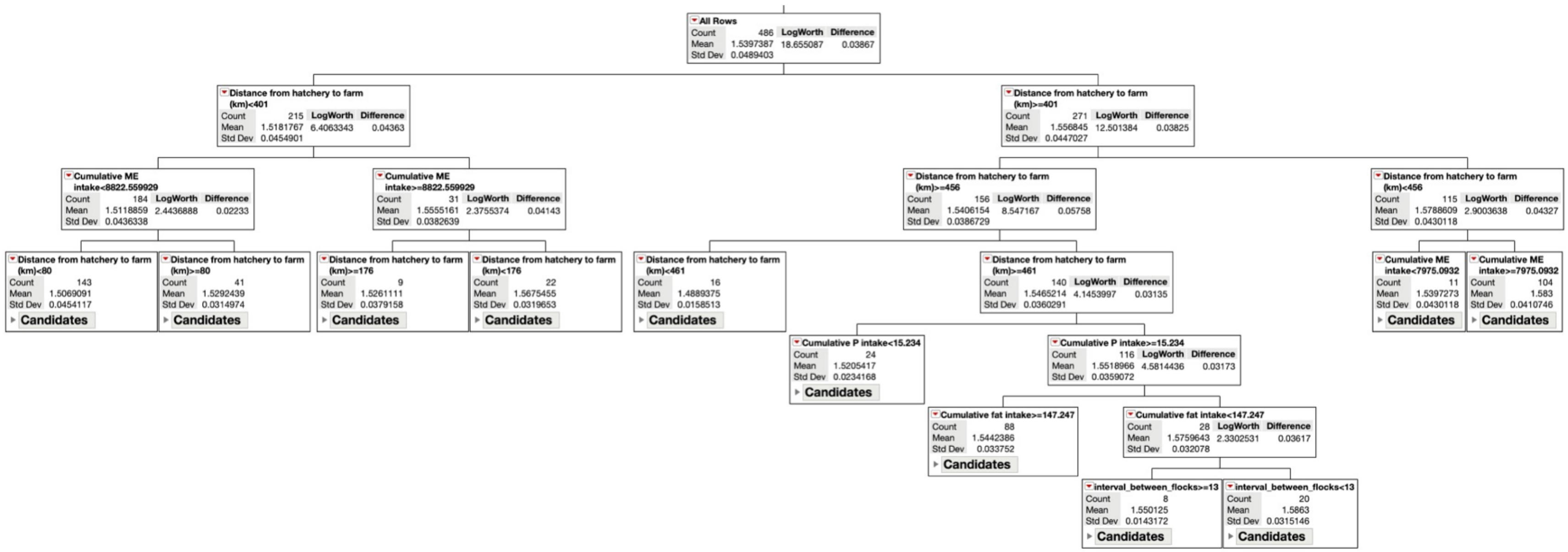

Figure 4.6. Decision tree with CNI at 35 d and farm-associated factors as predictors on female FCR as response of Ross 308 broilers raised to 35 d under commercial tropical conditions ($R^2 = 0.40$; ACICc = -1,780.5).

CONCLUSIONS AND RECOMMENDATIONS

The results from the current data analytics study of broiler production indicated that live performance parameters were affected by growth dynamics, environment, farm-associated, and nutritional factors. In the second chapter, the Logistic model determined better biological parameter estimates for the interpretability and prediction of broiler BW at 35 d compared to the Gompertz-Laird and von Bertalanffy models whose estimates exceeded the values reported for broilers. Also, the Logistic model demonstrated that low (LE) and high efficiency (HE) chickens had different growth dynamics. Both males and females from the HE group presented slower exponential growth rates that led them to reach the inflection point later than LE chickens. This effect was associated with the feeding control program with a feed restriction greater than 22% from the genetic line guideline at the second wk of age for the HE chickens, with a subsequent increase in the feed allowance in the following weeks compared to LE chickens that had a constant feed restriction between the second and the fourth week of age.

The third chapter demonstrated that all farm-associated parameters affected the BW and FCR of broilers raised to 35 d. However, the variable importance analysis indicated that from all performance and farm-associated factors included within the supervised machine learning models, the distance from the hatchery to the farm, the farm altitude, and sex played an important role in the prediction of the live performance of broilers. Chicken flocks placed near the hatcheries presented the best FCR at 35 d in both males and females, while the heaviest broilers were observed in those traveling the longest distances. Also, farms located in higher altitudes (1,670 ± 434 m.a.s.l.) resulted in the heaviest and most efficient broilers at the end of the production cycle. This condition was associated with cooler environmental temperatures as altitude increases reducing the effects of heat-stress observed in chickens placed in lowlands (1,041 ± 349 m.a.s.l). Yet, chicken flocks that were intermittently exposed to temperatures below 2.5 ºC recommendations worsened the BW, BW gain, and FCR from 7 to 21 d. At the same time, the effects of these environmental conditions increased the cumulative mortality at 28 and 35 d.

In the fourth chapter, broiler BW and FCR at 35 d were affected by the energy and nutrient intake, mainly from the grower phase. It seems that metabolizable energy (ME) and digestible lysine (dLys) influenced the performance of broilers at slaughter age. Then, the increase of intake of these nutrients up to 35 days and less crude protein (CP) intake in the grower phase may benefit both BW and FCR of broilers. Data analytics tools determined critical points and potential interactions between farm-associated factors and nutrition, not commonly explored under experimentation. ME intake was associated with distancing from the hatchery to the farm. Chickens receiving less ME and traveling long distances had the worst BW. Additionally, the lower farm altitude possibly related to warmer environmental conditions could result in less efficient males. At higher altitudes, the metabolic heat produced by high CP intake or CP levels could deteriorate the FCR at 35 d. Thus, contrary to the recommendations of several authors to include high CP levels in broiler diets, the environment and management of broiler flocks should be regarded to avoid harmful effects of nutrients on the live performance parameters.

Different models presented in the current study resulted in a moderate fit ($R^2 = 0.48 – 0.78$) compared to models coming from experimental data. However, it is important to highlight that all data coming from commercial operations is highly variable. The estimation of parameters based on fixed values such as feed amounts by feeding phase rather than using actual values may increase the error for further analysis. Better accuracy and synchronization in the data collection process would help reduce the errors often generated by a lack of traceability among integrated facilities (feed mills, hatcheries, broiler farms). Therefore, the following recommendations are developed to improve the analysis of data, increase the model fit and determine possible variables that might also be influencing the performance of broilers:

- Create a standardized system of identification for farms and broiler houses.
- Indicate accurate date and time of placement that match environmental sensors data
- Collect performance records by broiler house.
- Indicate the breeder age and incubation parameters for each flock.
- Include in the performance records the actual feed intake by feeding phase.
- Double-check periodically that environmental sensors are working properly and continuously.
- Identify the actual feed formulation and feed batch offered for each broiler flock.
- Join feed quality control with specific formulas and feed delivered in farms.