


Article

Development of Equations to Predict Percentage Empty Body and Carcass Chemical Composition Adjusted for Breed Type and Sex in Growing/Finishing Cattle

Phillip A. Lancaster 

Beef Cattle Institute, Kansas State University, Manhattan, KS 66506, USA; palancaster@vet.k-state.edu;
Tel.: +1-785-532-6323

Simple Summary: Knowledge of changes in body composition is necessary to determine the nutrient requirements of cattle, but it is often time-consuming and expensive to directly measure each chemical component (water, fat, protein, and ash). Thus, estimation of the remaining components following the direct measurement of one component is beneficial. Previously published equations have been developed using only a single cattle breed or sex and have been shown to provide erroneous results when applied to other breeds and sexes. Data were compiled from studies measuring chemical composition for diverse breed types and sexes of growing/finishing cattle, and equations were developed to predict the chemical composition of the empty body and carcass. Equations were developed to estimate chemical components across breed types and sexes. Breed type and sex affected the prediction of empty body and carcass chemical components. The current equations were more accurate and precise than the previously developed equations and should be more robust for use across diverse breed types and sexes of cattle.

Abstract: The estimation of body chemical composition is necessary to determine the nutrient requirements of growing/finishing cattle, but recent analyses indicate that published equations provide erroneous results when applied to diverse breed types and sexes. The objective of this analysis was to develop equations to estimate empty body and carcass chemical composition for different breed types and sexes. A dataset was developed from the published literature that contained 359 treatment means from 46 studies published between 1971 and 2021. Stepwise regression was used to develop prediction equations using Akaike's Information Criteria to estimate empty body and carcass fat, protein, and ash concentrations (%). Empty body fat, protein, and ash could be predicted from combinations of empty body water, empty body fat, and empty body protein (RMSE = 1.53, 1.85, and 0.67; $R^2 = 0.99, 0.98, \text{ and } 0.95$). Breed type and sex affected the intercept and (or) slope coefficients to predict empty body fat, protein, and ash. Carcass fat, protein, and ash could be predicted from combinations of carcass water, carcass fat, and carcass protein (RMSE = 1.77, 1.62, and 0.82; $R^2 = 0.97, 0.98, \text{ and } 0.93$). Breed type and sex affected the intercept and (or) slope coefficients to predict protein and ash, but not fat. Equations adjusted for breed type and sex may be more robust than previously published equations based on a single breed or sex.



Received: 18 February 2025
Revised: 15 March 2025
Accepted: 31 March 2025
Published: 2 April 2025

Citation: Lancaster, P.A. Development of Equations to Predict Percentage Empty Body and Carcass Chemical Composition Adjusted for Breed Type and Sex in Growing/Finishing Cattle. *Ruminants* **2025**, *5*, 14. <https://doi.org/10.3390/ruminants5020014>

Copyright: © 2025 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: body composition; empty body fat; empty body protein

1. Introduction

Chemical composition is critical to determining nutrient requirements and estimating the rate of gain of growing and finishing cattle [1–3]. Body composition affects maintenance energy requirements [4] as the energy required to maintain one gram of chemical fat is essentially zero, but the value necessary to maintain one gram of chemical protein is, on average, 0.245 kcal per day [5–9]. Additionally, the *Nutrient Requirements of Beef Cattle* [10–13] adjusts the relationship between retained energy (i.e., net energy for gain) and weight gain for the composition of gain. As cattle approach maturity, the proportion of fat in the gain increases [14,15], requiring greater net energy for gain intake to achieve the same rate of weight gain.

Breed type affects the percentage chemical composition of the body with regard to age and weight. British breeds, such as Angus and Hereford, mature earlier, depositing more fat at lighter weights than Continental breeds, such as Charolais and Simmental [16–20], but differ less within breed types [19,21–23]. British breeds also differ from *Bos indicus* breeds, such as Brahman and Tuli [23–25], and dairy breeds, such as Holstein [25–28]. However, little is known about the effect of breed type on the relationships among the chemical components of the body. Fortin et al. [28] reported that breed (Holstein vs. Angus) affected the relationship between the specific gravity of the carcass and the percentage of protein in the empty body. But published equations to predict percentage body composition are derived from data on single breeds of similar types: Hereford [29–31] and Hereford and Angus [32].

Sex also affects the percentage chemical composition of the body. Bulls have a greater percentage of water and a lesser percentage of fat than steers and heifers, and steers have a greater percentage of water and a lesser percentage of fat than heifers [26,33–37]. However, similar to breed type, little is known about the effect of sex on the relationships among chemical components of the body. Published equations to predict percentage body composition are derived from data on single or combined sexes: steers [29,32], heifers [31], and bulls, steers, and heifers [30].

Currently available equations to predict percentage body composition likely provide erroneous results for breeds and sexes other than those used to develop the equations, particularly for protein [38]. Protein is predicted from fat-free dry matter [29], assuming that fat-free dry matter has a constant percentage of protein, although a recent analysis indicates significant variation [38], or it is predicted from water and fat separately [30–32], which does not account for variation in the percentage of protein in the fat-free matter [38]. Inaccurate estimation of protein in the empty body and net protein requirements would lead to either under-feeding of protein, limiting animal performance, or over-feeding of protein, increasing the environmental impacts of nitrogen excretion. Thus, a sufficient analysis of the effect of breed type and sex on the relationships among chemical components of the body is needed. The hypothesis is that breed type and sex impact the prediction of the chemical components of the empty body and carcass. The objective of this analysis was to develop a set of equations to estimate the percentage empty body and carcass chemical composition for different breed types and sexes.

2. Materials and Methods

This analysis was based on data from the published literature and involved no live animals; thus, no Institutional Animal Care and Use Committee approval was required.

2.1. Database Creation

A literature search was performed to identify experiments measuring empty body and carcass chemical composition using PubMed, Web of Science, and Google Scholar.

Multiple combinations of search terms “cattle”, “empty body weight”, “carcass weight”, “chemical composition”, “carcass fat”, “carcass protein”, “empty body fat”, and “empty body protein” returned 3 to 22 records in PubMed, 204 and 583 records in Web of Science, and 92 and 677 records in Google Scholar. Records were screened first by title, second by species, breed, and sex, and third by methodology. Records on growing/finishing steers and heifers were included, but studies using growing/finishing bulls, mature cows or bulls, *Bos indicus* breeds, and mixed sex groups were excluded. Growing/finishing bulls and *Bos indicus* breeds were excluded due to limited numbers of bulls, especially within breed types other than *Bos indicus*-influenced cattle, leading to highly confounded breed and sex effects. Mature animals were defined as those 2+ years old, as well as cows that were gestating or lactating, and were excluded such that this analysis was comparable to those using previously published equations utilizing only growing animals. Mixed sex groups were excluded due to the lack of ability to assign a sex category to the data. Only records using proximate analysis to determine empty body and carcass composition were included. Empty body was defined as shrunken body weight minus the gastrointestinal tract contents. Studies that did not measure weights and chemical composition of all body tissues were excluded. Carcass was defined as the hanging carcass plus trim following evisceration and removal of hide, head, and feet.

The final dataset contained 359 observations with treatment means of empty body and carcass weight and concentrations of water, fat, protein, and ash from 46 studies published between 1971 and 2021. Records were classified as heifers or steers and breeds were categorized into British, ContCross, and Dairy. The British breed type comprised breeds originating in Great Britain and included Angus, Hereford, Brangus, Angus × Hereford, Angus × MARC III, and Hereford × MARC III breeds. The ContCross breed type comprised breeds originating in Continental Europe and their crosses with British breeds, and included Simmental, Charolais, Belgian Blue × (Angus, Hereford, MARC III), Piedmontese × (Angus, Hereford, MARC III) Limousin × Gelbvieh, Charolais, Charolais × Hereford, Charolais × Angus, and Simmental × Angus × Hereford. The Dairy breed type comprised breeds used for dairy rather than beef purposes and included Friesian and Holstein breeds, which are generally the same breed with different names around the world.

Observations were subdivided into 3 datasets: Empty Body dataset, Carcass dataset, and Empty Body–Carcass dataset. The Empty Body dataset included studies that reported data on the chemical composition of the empty body, contained 287 observations from 40 studies, and was used to develop equations to predict empty body fat, water, protein, and ash concentrations (%). The numbers of observations for steers and heifers for each breed type were as follows: British had 92 steer and 24 heifer observations, ContCross had 32 steer and 17 heifer observations, and Dairy had 87 steer and 35 heifer observations. The Carcass dataset included studies that reported data on the chemical composition of the carcass, contained 220 observations from 23 studies, and was used to develop equations to predict carcass fat, water, protein, and ash concentrations (%). The numbers of observations for steers and heifers for each breed type were as follows: British had 104 steer and 23 heifer observations, ContCross had 10 steer and 12 heifer observations, and Dairy had 45 steer and 26 heifer observations. The Empty Body–Carcass dataset included studies that reported data on the chemical composition of the empty body and carcass of the same animals, contained 148 observations from 17 studies, and was used to develop equations relating chemical components (%) of the carcass with the same component of the empty body. The numbers of observations for steers and heifers for each breed type were as follows: British had 68 steer and 21 heifer observations, ContCross had 10 steer and 12 heifer observations, and Dairy had 17 steer and 20 heifer observations.

2.2. Statistical Analyses

All statistical analyses were performed using R statistical software (version 4.2.1; 22 June 2022) with published functions and packages. Data were evaluated for normality using Q-Q plots and non-constant variance using residual plots. Pearson correlation coefficients were computed among chemical components of the empty body and carcass using the *correlation* function of the *correlation* package [39]. The *lm* function of the base statistical package [40] was used to compare the mean body composition among breed types and sexes with empty body or carcass weight as a covariate. The model included breed type, sex, and the covariate as fixed effects. The *emmeans* function of the *emmeans* package [41] was used to perform pairwise comparisons of the empty body and carcass chemical components among breed types and sexes with Tukey's adjustment for multiple pairwise comparisons.

Equations to predict empty body and carcass chemical components were developed using the *lm* function of the base statistical package. Terms included in the model were linear and quadratic variables of chemical components (water, fat, protein, ash) as percentages, breed type, sex, and interaction terms of chemical components with either breed type or sex. The random effect of study was not included in models because many studies used a single breed and/or sex, and including study as a random factor would have masked the differences between breed types and sexes. The objective was to estimate the best model using fixed effects that could be applied to future studies. The primary differences between studies were controlled in two ways: (1) inclusion of only studies that used proximate analysis to determine body composition, and (2) expressing chemical components as a percentage of empty body or carcass weight. Other factors besides breed and sex, such as diet, may influence the relationships among chemical components of the empty body and carcass, but were not available in all studies, and were not evaluated.

Equations were developed such that chemical components could be sequentially estimated from preceding chemical components, starting with either direct measurement of water or fat. The *stepAIC* function of the *mass* package [42] was used to select the most influential independent variables based on minimizing the Bayesian Information Criterion (BIC) using both forward inclusion and backward elimination. Multicollinearity among independent variables was assessed using variance inflation factor. Collinearity among linear and quadratic variables of chemical components was expected and not considered problematic for prediction. Several equations with different dependent and independent variables were developed and evaluated using the concordance correlation coefficient (CCC), index of agreement (d), mean bias (MB), and linear regression observed for predicted values. The CCC and MB were computed using the *epi.ccc* function of the *epiR* package [43], and Wilmot's index of agreement was computed using the *dr* function of the *ie2misc* package [44]. A 'best' equation for each chemical component (fat, water, protein, ash) was selected based on the above criteria and a final model for each was further evaluated. K-fold cross validation was performed on the final models using the leave-one-group-out method. Folds ($k = 10$) were created to equally partition the data across breed type and sex combinations. Additionally, k-fold cross validation was performed using equations of Garrett and Hinman [29] as the model prediction. The Garrett and Hinman equations were chosen for comparison because these equations are the most frequently cited equations for estimation of empty body and carcass composition. The *train* function in the *caret* package [45] of R statistical software was used to perform cross validation. The final model and equations of Garrett and Hinman [29] were compared within breed types and sexes using CCC and MB computed as described above. The *Anova* function of the *car* package [46] was used to determine the significance of terms in the final models. Model terms were considered significant at $p \leq 0.05$. The *emmeans* and *emtrends* functions of the *emmeans* package were used to determine regression coefficients when breed type and

(or) sex affected the intercept or slope coefficients with Tukey's adjustment for multiple pairwise comparisons.

3. Results

Mean empty body water was 59.87 (7.49) and 58.07 (7.04)% in the Empty Body and Empty Body–Carcass datasets, respectively, and mean carcass water was 55.12 (7.79) and 56.91 (7.41)% in the Carcass and Empty Body–Carcass datasets, respectively, with a similar range in all the datasets (Table 1). The mean fat was 18.05 (8.84) and 20.25 (8.59)% in the empty body compared to 23.38 (9.86) and 21.26 (9.37)% in the carcass among the datasets in which the minimum and maximum fat concentrations were similar between empty body and carcass. The mean protein and ash were similar between the empty body and carcass in the datasets. The minimum protein in the empty body was 13.00% compared to 12.37% in the carcass, and the maximum protein concentration was 21.10% in the empty body and 22.20 and 21.57% in the carcass in the datasets. The minimum ash concentrations were similar between the empty body and carcass among the datasets, but the maximum ash concentrations were 6.64 and 6.59% in the empty body compared to 8.17 and 8.17% in the carcass. Overall, the chemical composition of the empty body and carcass were within expected ranges, and the empty body and carcass chemical composition were similar among the datasets. The descriptive statistics for the empty body and carcass chemical components by breed type and sex are presented in Tables S1–S3.

Table 1. Descriptive statistics for chemical components of growing/finishing cattle in the Empty Body, Carcass, and Empty Body–Carcass datasets.

Component ¹	N	Mean	SD	Min	Max
Empty Body					
Fat, %	287	18.05	8.84	2.00	40.33
Water, %	287	59.87	7.49	43.46	74.40
Protein, %	287	17.77	1.67	13.00	21.10
Ash, %	287	4.33	0.90	1.73	6.64
Carcass					
Fat, %	220	23.38	9.86	1.80	44.51
Water, %	220	55.12	7.79	39.32	74.30
Protein, %	220	16.95	2.09	12.37	22.20
Ash, %	220	4.50	1.01	1.76	8.17
Empty Body–Carcass					
Empty Body fat, %	148	20.25	8.59	2.00	40.33
Empty Body water, %	148	58.07	7.04	43.46	73.40
Empty Body protein, %	148	17.65	1.80	13.00	21.10
Empty Body ash, %	148	4.05	0.93	1.73	6.59
Carcass fat, %	148	21.26	9.37	1.80	44.51
Carcass water, %	148	56.91	7.41	40.20	74.30
Carcass protein, %	148	17.18	2.07	12.37	21.57
Carcass ash, %	148	4.62	1.15	1.76	8.17

¹ Empty Body dataset includes studies that reported chemical components of the empty body; Carcass dataset includes studies that reported chemical components of the carcass; Empty Body–Carcass dataset includes studies that reported chemical components of the empty body and carcass of the same animals.

The dataset was not balanced for weight or age among the studies, and age was not known for most of the studies; thus, empty body or carcass weight were used as covariates to compare breed types and sexes. Overall, breed type and sex affected the chemical composition of cattle, indicating that breed type and sex may be important predictors of chemical composition. There was a breed type × sex interaction for all the chemical components in the Empty Body dataset after adjusting for empty body (Table S4). Heifers

had greater ($p \leq 0.05$) empty body fat than steers for British and Dairy, but not ContCross. Heifers had less ($p \leq 0.05$) empty body water than steers in all the breed types, but the magnitude of the difference was greater in British than in ContCross and Dairy. Empty body protein was not different between heifers and steers for any breed type, but heifers had slightly less protein in British and Dairy and slightly more protein in ContCross, leading to a significant interaction of breed type and sex. ContCross heifers had less ($p \leq 0.05$) empty body ash than ContCross steers, but there was no difference ($p > 0.05$) between heifers and steers in British and Dairy.

British had greater ($p \leq 0.05$) carcass fat and less ($p \leq 0.05$) carcass water than Dairy, which had greater ($p \leq 0.05$) carcass fat and less ($p \leq 0.05$) carcass water than ContCross in the Carcass dataset. ContCross had greater ($p \leq 0.05$) carcass protein than Dairy, which had greater ($p \leq 0.05$) carcass protein than British. Heifers had greater ($p \leq 0.05$) carcass fat, less ($p \leq 0.05$) carcass water, and less ($p \leq 0.05$) carcass protein than steers. Carcass ash was not affected ($p > 0.05$) by breed type or sex.

In the Empty Body–Carcass dataset, there were no interactions between breed type and sex for empty body or carcass chemical components. For both empty body and carcass chemical components, heifers had greater ($p \leq 0.05$) fat, less ($p \leq 0.05$) water, and less ($p \leq 0.05$) protein than steers. British had greater ($p \leq 0.05$) empty body and carcass fat than Dairy, which had greater ($p \leq 0.05$) empty body and carcass fat than ContCross. ContCross had greater ($p \leq 0.05$) empty body and carcass water than Dairy, which had greater ($p \leq 0.05$) empty body and carcass water than British. ContCross had greater ($p \leq 0.05$) empty body and carcass protein than British and Dairy, which were not different ($p > 0.05$). Empty body and carcass ash were not affected ($p > 0.05$) by breed type or sex.

Water was strongly (≥ 0.60) negatively correlated ($p \leq 0.05$) with fat and protein in the empty body and carcass (Table 2). Water was moderately ($0.30 \leq r < 0.60$) positively correlated ($p \leq 0.05$) with ash in the carcass, but not in the empty body. Fat was strongly negatively correlated ($p \leq 0.05$) with protein in the empty body and carcass and weakly (< 0.30) to moderately negatively correlated ($p \leq 0.05$) with ash in the empty body and carcass. Protein was weakly to moderately positively correlated ($p \leq 0.05$) with ash in the empty body and carcass. Each chemical component (water, fat, protein, ash) in the carcass was strongly positively correlated ($p \leq 0.05$) with the same chemical component in the empty body, as would be expected, since the carcass is a large component of the empty body. Thus, relationships exist among chemical components in the empty body and carcass, allowing for the prediction of the other chemical components. The correlations among the chemical components of the empty body and carcass and between the empty body and carcass are presented by breed type and sex in Table S5.

Table 2. Pearson correlation coefficients among chemical components of the empty body (above diagonal), carcass (below diagonal), and between empty body and carcass (diagonal) in growing/finishing cattle¹.

Component	Fat	Water	Protein	Ash
Fat	<u>0.99</u> *	−0.98 *	−0.79 *	−0.21 *
Water	−0.98 *	<u>0.99</u> *	0.69 *	0.09
Protein	−0.85 *	0.76 *	<u>0.96</u> *	0.20 *
Ash	−0.44 *	0.33 *	0.35 *	<u>0.97</u> *

* Correlation coefficients are significantly different from zero at $p \leq 0.05$. ¹ Empty Body dataset includes studies that reported chemical components of the empty body; Carcass dataset includes studies that reported chemical components of the carcass; Empty Body–Carcass dataset includes studies that reported chemical components of the empty body and carcass of the same animals.

3.1. Prediction of Empty Body Chemical Components

Two equations were evaluated to predict empty body fat from empty body water; in one equation, fat was expressed as a percentage of the whole empty body, and in the other, fat was expressed as a percentage of the empty body dry matter (Table S6). The equation expressing fat as a percentage of the whole empty body had an intercept closer to zero (-0.213 vs. -0.626), slightly better R^2 (0.9751 vs. 0.9475), and better d (0.9289 vs. 0.8943) than the equation expressing fat as a percentage of the empty body dry matter, and it was selected as the final model to predict empty body fat.

Both breed type and sex affected ($p \leq 0.05$) the prediction of empty body fat from empty body water (Table 3). The Dairy breeds had a greater ($p \leq 0.05$) intercept, lesser ($p \leq 0.05$) linear slope coefficient, and greater ($p \leq 0.05$) quadratic slope coefficient than the British and ContCross breeds, which were not different ($p > 0.05$). The cross-fold validation resulted in an RMSE of 1.53, R^2 of 0.98, mean absolute percentage error (MAPE) of 7.651%, and Akaike's Information Criterion (AIC) of 134.9 (Table 4). The relationship between the observed and predicted empty body fat is presented in Figure S1.

The prediction of empty body fat from the equation of Garrett and Hinman [29] had an intercept greater than zero (1.363), a slope of less than one (0.897), and a mean bias greater than that for the proposed equation (2.68 vs. 0.05%; Table S7). The cross-fold validation of the Garrett and Hinman equation had an RMSE of 1.73, MAPE of 10.912%, and AIC of 143.9, all of which are greater than that for the proposed equation, but the R^2 was similar (0.978 and 0.975) between the equations. When compared to the proposed equation for empty body fat within breed type and sex, the Garrett and Hinman equation had similar CCC but a mean bias further from zero than the proposed equation for all the breed types and sexes (Table S10).

Two equations were evaluated to predict empty body water from empty body fat; in one equation, water was expressed as a percentage of the whole empty body, and in the other, water was expressed as a percentage of the empty body fat-free matter (Table S6). The equation expressing water as a percentage of the whole empty body had an intercept closer to zero (0.751 vs. 5.109), a slope closer to one (0.988 vs. 0.931), greater R^2 (0.9721 vs. 0.3900), greater CCC (0.9860 vs. 0.5777), and greater d (0.9205 vs. 0.5946) than the equation expressing water as a percentage of the empty body fat-free matter and was selected as the final model to predict empty body fat.

Breed type, but not sex, affected ($p \leq 0.05$) the prediction of empty body water from empty body fat (Table 3). The ContCross breeds had a lesser ($p \leq 0.05$) intercept than the British and Dairy breeds, which were not different ($p > 0.05$). There was no effect ($p > 0.05$) of breed type on the linear or quadratic slope coefficients. The cross-fold validation resulted in an RMSE of 1.35, R^2 of 0.98, MAPE of 1.926%, and AIC of 123.6 (Table 4). The relationship between the observed and predicted empty body water is presented in Figure S2.

The prediction of empty body water from the equation of Garrett and Hinman [29] had an intercept of less than zero (-4.870), a slope greater than one (1.077), and a mean bias greater than that of the proposed equation (0.42 vs. -0.03% ; Table S7). The cross-fold validation of the Garrett and Hinman equation had an RMSE of 1.48, MAPE of 2.166%, and AIC of 130.7, all of which were greater than those for the proposed equation, but the R^2 was similar (0.977 and 0.974) between the equations. When compared to the proposed equation for empty body water within breed type and sex, the Garrett and Hinman equation had similar CCC, but a mean bias that was slightly further from zero than the proposed equation for all the breed types and sexes (Table S10).

Table 3. Coefficients for predictors in the final models to predict empty body water, fat, protein, and ash in growing/ finishing cattle.

Component ¹	Breed Type	Sex	Intercept (±SE)	Slope Coefficients (±SE)					
				Water	Fat	Protein	Water2	Fat2	Protein2
Fat	British	Heifers	109.488 ± 14.513 ^{*Aa}	-1.808 ± 0.493 ^{*Ba}	-	-	0.00467 ± 0.0042 ^{Ab}	-	-
		Steers	63.674 ± 9.181 ^{*Ab}	-0.281 ± 0.326 ^{Bb}	-	-	-0.00798 ± 0.0029 ^{*Aa}	-	-
	ContCross	Heifers	121.907 ± 15.586 ^{*Aa}	-2.281 ± 0.520 ^{*Ba}	-	-	0.00886 ± 0.0043 ^{*Ab}	-	-
		Steers	76.093 ± 12.161 ^{*Ab}	-0.754 ± 0.422 ^{Bb}	-	-	-0.00379 ± 0.0036 ^{Aa}	-	-
	Dairy	Heifers	191.552 ± 17.282 ^{*Ba}	-4.657 ± 0.563 ^{*Aa}	-	-	0.02908 ± 0.0046 ^{*Bb}	-	-
		Steers	145.738 ± 12.881 ^{*Bb}	-3.130 ± 0.407 ^{*Ab}	-	-	0.01643 ± 0.0032 ^{*Ba}	-	-
Water	British	Heifers/Steers	76.904 ± 0.387 ^{*B}	-	-1.092 ± 0.040 [*]	-	-	0.00659 ± 0.0010 [*]	-
	ContCross		76.291 ± 0.386 ^{*A}	-		-			
	Dairy		77.146 ± 0.332 ^{*B}	-		-			
Protein ²	British	Heifers	82.663 ± 0.603 ^{*y}	-	-	-	-	-	-
		Steers	81.624 ± 0.520 ^{*xy}	-	-	-	-	-	-
	ContCross	Heifers	82.730 ± 0.521 ^{*y}	-	-0.831 ± 0.009 ^{*2}	-	-	-	-
		Steers	80.816 ± 0.523 ^{*x}	-		-	-	-	-
	Dairy	Heifers	81.015 ± 0.496 ^{*x}	-		-	-	-	-
		Steers	81.638 ± 0.345 ^{*xy}	-		-	-	-	-
Ash ²	British	Heifers	63.297 ± 6.052 ^{*Ba}	-	-0.638 ± 0.061 ^{*Ab2}	-0.548 ± 0.074 ^{*Ab2}	-	-	-
		Steers	93.912 ± 2.436 ^{*Bb}	-	-0.940 ± 0.025 ^{*Aa2}	-0.925 ± 0.030 ^{*Aa2}	-	-	-
	ContCross	Heifers	69.437 ± 5.444 ^{*Ba}	-	-0.699 ± 0.055 ^{*Ab2}	-0.624 ± 0.067 ^{*Ab2}	-	-	-
		Steers	100.052 ± 3.669 ^{*Bb}	-	-1.001 ± 0.038 ^{*Aa2}	-1.001 ± 0.045 ^{*Aa2}	-	-	-
	Dairy	Heifers	38.305 ± 6.203 ^{*Aa}	-	-0.368 ± 0.063 ^{*Bb2}	-0.244 ± 0.077 ^{*Bb2}	-	-	-
		Steers	68.920 ± 2.961 ^{*Ab}	-	-0.670 ± 0.031 ^{*Ba2}	-0.622 ± 0.036 ^{*Ba2}	-	-	-

¹ Chemical components (water, fat, protein, ash) are in percentage (%); Water2, Fat2, and Protein2 are the quadratic model terms for water, fat, and protein, respectively; British includes Angus, Hereford, Brangus, Angus × Hereford, Angus × MARC III, and Hereford × MARC III breeds; ContCross includes Simmental, Charolais, Belgian Blue × (Angus, Hereford, MARC III), Peidmontese × (Angus, Hereford, MARC III) Limousin × Gelbvieh, Charolais, Charolais × Hereford, Charolais × Angus, and Simmental × Angus × Hereford breeds; Dairy includes Friesian and Holstein breeds; intercept and slopes are coefficient ± SE; ² chemical component is expressed as a percentage of empty body dry matter; ^{AB} coefficients for breed type without a common superscript letter within column and chemical component differ at $p \leq 0.05$; ^{ab} coefficients for sex without a common superscript letter within column and chemical component differ at $p \leq 0.05$; ^{xy} coefficients for breed type × sex interaction without a common superscript letter within column and chemical component differ at $p \leq 0.05$; * coefficient differs from zero at $p \leq 0.05$.

Table 4. Cross-fold validation of proposed equations and equations of Garrett and Hinman (1969)¹ to predict chemical components in growing/finishing cattle for the Empty Body, Carcass, and Empty Body–Carcass datasets.

Component	RMSE (SD) ²		R ² (SD)		MAPE (SD)		AIC (SD)	
	Proposed	Garrett & Hinman	Proposed	Garrett & Hinman	Proposed	Garrett & Hinman	Proposed	Garrett & Hinman
Empty Body								
Fat	1.534 (0.402)	1.729 (0.391)	0.978 (0.009)	0.975 (0.011)	7.651 (1.484)	10.912 (3.129)	134.9 (60.5)	143.9 (56.1)
Water	1.354 (0.323)	1.481 (0.360)	0.977 (0.008)	0.974 (0.011)	1.926 (0.492)	2.166 (0.566)	123.6 (49.2)	130.7 (51.4)
Protein	1.854 (0.433)	0.791 (0.177)	0.980 (0.010)	0.753 (0.224)	3.357 (0.845)	3.462 (0.793)	89.2 (43.2)	96.9 (45.1)
Ash	0.674 (0.174)	0.761 (0.208)	0.945 (0.031)	0.287 (0.228)	4.318 (0.597)	16.972 (9.573)	−4.5 (25.2)	95.7 (46.2)
Carcass								
Fat	1.774 (0.573)	1.869 (0.500)	0.972 (0.018)	0.971 (0.017)	6.900 (1.888)	8.036 (2.972)	123.5 (60.4)	126.1 (60.8)
Water	1.293 (0.398)	1.434 (0.437)	0.973 (0.014)	0.971 (0.017)	1.899 (0.599)	2.160 (0.592)	108.0 (55.1)	111.7 (57.6)
Protein	1.624 (0.747)	0.716 (0.293)	0.981 (0.014)	0.884 (0.116)	3.392 (1.116)	3.099 (1.189)	65.4 (47.0)	70.8 (47.9)
Ash	0.816 (0.455)	0.946 (0.237)	0.930 (0.065)	0.170 (0.170)	4.729 (1.391)	19.030 (7.400)	3.3 (19.5)	82.0 (43.4)
Empty Body–Carcass								
Fat	1.569 (0.379)	1.217 (0.397)	0.984 (0.005)	0.981 (0.009)	2.842 (0.447)	4.868 (1.223)	44.5 (19.3)	66.0 (24.3)
Water	1.332 (0.300)	1.069 (0.269)	0.963 (0.022)	0.980 (0.009)	1.782 (0.225)	1.528 (0.451)	57.3 (21.8)	63.4 (27.4)
Protein	1.515 (0.445)	0.528 (0.059)	0.981 (0.008)	0.923 (0.016)	3.253 (1.153)	2.569 (0.327)	38.5 (20.1)	36.4 (13.7)
Ash	0.501 (0.142)	0.252 (0.057)	0.943 (0.047)	0.879 (0.123)	4.273 (1.178)	5.117 (0.635)	−10.1 (8.4)	−1.7 (11.5)

¹ Garrett and Hinman [29]; ² RMSE = root mean squared error; SD = standard deviation; R² = R-squared (coefficient of determination); MAPE = mean absolute percentage error; AIC = Akaike's Information Criterion.

Four equations were evaluated to predict empty body protein. In the first equation, protein was expressed as a percentage of the whole empty body, with the predictor being the empty body fat-free dry matter percentage. In the second equation, protein was expressed as a percentage of the whole empty body, with predictors of empty body water and fat. In the third equation, protein was expressed as a percentage of the empty body dry matter, with empty body fat as a percentage of empty body dry matter as the predictor. In the fourth equation, protein was expressed as a percentage of empty body fat-free matter, with empty body water expressed as a percentage of empty body fat-free matter as the predictor (Table S6). Expressing protein as a percentage of the fat-free matter resulted in the least precise equation, with a slope of less than one (0.987 vs. 0.996, 1.006, 1.006) and lower R^2 (0.6884 vs. 0.8214, 0.8702, 0.9779), CCC (0.8172 vs. 0.9012, 0.9301, 0.9888), and d (0.7521 vs. 0.8098, 0.8442, 0.9344) than the other equations. Expressing protein as a percentage of the whole empty body with either empty body fat-free dry matter or empty body fat and water as the predictors resulted in similar intercept (-0.070 and -0.086), slope (1.006 and 1.006), CCC (0.9012 and 0.9301), d (0.8098 and 0.8442), and mean bias (-0.204 and -0.120). Additionally, multicollinearity was detected when empty body water and fat were included as the predictors for empty body protein expressed as a percentage of the whole empty body. Expressing protein as a percentage of empty body dry matter with the predictor of empty body fat expressed as a percentage of dry matter had a slope close to one (0.996) and a mean bias similar to those of the other equations (-0.198 vs. -0.110 , -0.120 , -0.204), but had an R^2 (0.9779 vs. 0.6884, 0.8214, 0.8702), CCC (0.9888 vs. 0.8172, 0.9012, 0.9301), and d (0.9344 vs. 0.7521, 0.8098, 0.8442) greater than those of the other equations, and it was selected as the final model.

There was a breed type \times sex interaction for the intercept of the equation to predict empty body protein (Table 3). Steers had a lower ($p \leq 0.05$) intercept than the heifers for ContCross, but not for British and Dairy. There was no effect ($p > 0.05$) of breed type or sex on the linear slope coefficient, and the quadratic slope coefficient was not different ($p > 0.05$) from zero. The cross-fold validation resulted in an RMSE of 1.85, R^2 of 0.98, MAPE of 3.357%, and AIC of 89.2 (Table 4). The relationship between the observed and predicted empty body protein is presented in Figure S3.

The prediction of empty body protein from the equation of Garrett and Hinman [29] had an intercept greater than zero (1.454), a slope of less than one (0.890), lower R^2 and CCC than the proposed equation (0.79 and 0.84 vs. 0.98 and 0.99), and a mean bias greater than that in the proposed equation (3.14 vs. -0.20% ; Table S7). The cross-fold validation of the Garrett and Hinman equation had an RMSE of 0.79 and AIC of 96.9, both of which were less than those for the proposed equation. However, the proposed equation is based on protein expressed as a percentage of empty body dry matter, which had a mean of 46.42% compared to empty body protein expressed as a percentage of the whole empty body, which had a mean of 17.77%. When comparing the MAPE, the values for both the proposed equation and the equation of Garrett and Hinman were similar (3.357 vs. 3.462%). The cross-fold R^2 for the Garrett and Hinman equation was considerably lower than that for the proposed equation (0.753 vs. 0.980).

When compared to the proposed equation for empty body protein within breed type and sex, the Garrett and Hinman equation had similar CCC values for the British breeds and for heifers, but a lower CCC for the ContCross and Dairy breeds and for steers (Table S10). Additionally, the mean bias was further from zero for the Garrett and Hinman equation than for the proposed equation for all breed types and sexes.

Four equations were evaluated to predict empty body ash. In the first equation, ash was expressed as a percentage of the whole empty body, with the predictors being water, fat, and protein expressed as a percentage of the whole empty body. In the second equation, ash

was expressed as a percentage of the empty body dry matter, with predictors of empty body fat and protein expressed as a percentage of empty body dry matter. In the third equation, ash was expressed as a percentage of the empty body fat-free matter, with empty body water and protein as a percentage of empty body fat-free matter as predictors. In the second equation, ash was expressed as a percentage of empty body fat-free dry matter, with empty body protein expressed as a percentage of empty body fat-free dry matter as the predictor (Table S6). Multicollinearity was detected in all the models. Expressing ash as a percentage of the fat-free dry matter resulted in the intercept and slope values that were furthest from zero (-0.446 vs. -0.026 , -0.009 , -0.049) and one (1.026 vs. 1.011 , 1.004 , 1.008), respectively, and slightly lower R^2 (0.9348 vs. 0.9493 , 0.9578 , 0.9608), CCC (0.9651 vs. 0.9737 , 0.9781 , 0.9799), and d (0.8681 vs. 0.8943 , 0.9066 , 0.9173) than the other equations. Expressing ash as a percentage of the whole empty body or as a percentage of the empty body fat-free matter had similar intercept (-0.026 and -0.049) and slope (1.008 and 1.011) and the least mean bias (-0.172 and -0.192 vs. -0.271 and -0.316). Expressing ash as a percentage of empty body dry matter had the intercept closest to zero (-0.009 vs. -0.026 , -0.049 , -0.446), the slope closest to one (1.004 vs. 1.008 , 1.011 , 1.026), and slightly greater R^2 (0.9608 vs. 0.9348 , 0.9493 , 0.9578), CCC (0.9799 vs. 0.9651 , 0.9737 , 0.9781), and d (0.9173 vs. 0.8681 , 0.8943 , 0.9066) than the other equations, and it was selected as the final model.

Breed type and sex affected ($p \leq 0.05$) the prediction of empty body ash (Table 3). Dairy had a lower ($p \leq 0.05$) intercept and more positive ($p \leq 0.05$) linear and quadratic slope coefficients than British and ContCross, which were not different ($p > 0.05$). Steers had a lower ($p \leq 0.05$) intercept and more negative ($p \leq 0.05$) linear and quadratic slope coefficients than heifers. The cross-fold validation resulted in an RMSE of 0.67, R^2 of 0.94, MAPE of 4.318%, and AIC of -4.5 (Table 4). The relationship between the observed and predicted empty body ash is presented in Figure S4.

Garrett and Hinman [29] do not report an equation to predict empty body ash. Thus, the predicted empty body ash was computed as 100 minus the predicted percentages of water, fat, and protein, resulting in all of the error of prediction falling to empty body ash. The prediction of empty body ash had an intercept greater than zero (4.771), a negative slope of less than zero (-0.147), lower R^2 and CCC than the proposed equation (0.27 and -0.24 vs. 0.96 and 0.98), and a greater mean bias than the proposed equation (-30.22 vs. -0.32% ; Table S7). The cross-fold validation of the Garrett and Hinman prediction had an RMSE of 0.76, MAPE of 16.972%, and AIC of 95.7, all of which were greater than the values for the proposed equation. The cross-fold R^2 for the Garrett and Hinman equation was considerably lower than for the proposed equation (0.29 vs. 0.94). When compared to the proposed equation for empty body ash within breed type and sex, the Garrett and Hinman prediction had a lower CCC and a mean bias further from zero than the proposed equation for all breed types and sexes (Table S10).

3.2. Prediction of Carcass Chemical Components

Two equations were evaluated to predict carcass fat from carcass water; in one equation, fat was expressed as a percentage of the whole carcass, and in the other, fat was expressed as a percentage of the carcass dry matter (Table S8). The equation expressing fat as a percentage of the whole carcass had an intercept closer to zero (-0.185 vs. -0.527) and a slightly better R^2 (0.9678 vs. 0.9348), CCC (0.9828 vs. 0.9648), and d (0.9172 vs. 0.8769) than the equation expressing fat as a percentage of the carcass dry matter, and it was selected as the final model to predict carcass fat.

Breed type and sex did not ($p > 0.05$) affect the prediction of carcass fat from carcass water (Table 5). The linear and quadratic slope coefficients were different ($p \leq 0.05$) from zero. The cross-fold validation resulted in an RMSE of 1.77, R^2 of 0.97, MAPE of 6.900%, and

AIC of 123.5 (Table 4). The relationship of observed and predicted carcass fat is presented in Figure S5.

The prediction of carcass fat from the equation of Garrett and Hinman [29] had an intercept greater than zero (1.007), a slope of less than one (0.929), and a mean bias further from zero than the proposed equation (2.96 vs. -1.12% ; Table S7). The cross-fold validation of the Garrett and Hinman equation had an RMSE of 1.87, MAPE of 8.036%, and AIC of 126.1, all of which were greater than for the proposed equation. When compared to the proposed equation for carcass fat within breed type and sex, the Garrett and Hinman equation had similar CCC, but a mean bias further from zero than the proposed equation for Dairy breeds and steers (Table S11).

Two equations were evaluated to predict carcass water from carcass fat; in one equation, water was expressed as a percentage of the whole carcass, and in the other, water was expressed as a percentage of the carcass fat-free matter (Table S8). The equation expressing water as a percentage of the whole carcass had an intercept closer to zero (0.425 vs. 7.829), a slope closer to one (0.995 vs. 0.893), and higher R^2 (0.9706 vs. 0.2075), CCC (0.9850 vs. 0.3658), and d (0.9217 vs. 0.5372) than the equation expressing water as a percentage of the carcass fat-free matter, and it was selected as the final model to predict carcass water.

Like the prediction of carcass fat, breed type and sex did not ($p > 0.05$) affect the prediction of carcass water from carcass fat (Table 5). The linear and quadratic slope coefficients were different ($p \leq 0.05$) from zero. The cross-fold validation resulted in an RMSE of 1.29, R^2 of 0.97, MAPE of 1.899%, and AIC of 108.0 (Table 4). The relationship between the observed and predicted carcass water is presented in Figure S6.

The prediction of carcass water from the equation of Garrett and Hinman [29] had an intercept of less than zero (-4.190) and a slope greater than one (1.067), but the mean bias was similar to that of the proposed equation (0.80 vs. -0.26% ; Table S7). The cross-fold validation of the Garrett and Hinman equation had an RMSE of 1.43, MAPE of 2.160%, and AIC of 111.7, all of which were greater than for the proposed equation. When compared to the proposed equation for carcass water within breed type and sex, the Garrett and Hinman equation had similar CCC and mean bias compared to the proposed equation for all breed types and sexes (Table S11).

Table 5. Coefficients for predictors in the final models to predict carcass water, fat, protein, and ash in growing/finishing cattle.

Component ¹	Breed Type	Sex	Intercept (±SE)	Slope Coefficients (±SE)					
				Water	Fat	Protein	Water2	Fat2	Protein2
Fat	British ContCross Dairy	Heifers /Steers	111.436 ± 6.365 *	-1.979 ± 0.224 *	-	-	0.00670 ± 0.0019 *	-	-
Water	British ContCross Dairy	Heifers /Steers	75.782 ± 0.420 *	-	-1.065 ± 0.043 *	-	-	0.00636 ± 0.0010 *	-
Protein ²	British	Heifers	78.939 ± 2.604 **	-	-0.730 ± 0.124 *y ²	-	-	-0.00085 ± 0.0014 x ¹	-
		Steers	99.221 ± 5.438 *y	-	-1.591 ± 0.203 **x ²	-	-	0.00756 ± 0.0018 *y ¹	-
	ContCross	Heifers	79.910 ± 1.815 **	-	-0.761 ± 0.118 *y ²	-	-	-0.00049 ± 0.0017 x ¹	-
		Steers	81.925 ± 6.137 *xy	-	-0.903 ± 0.281 **xy ²	-	-	0.00124 ± 0.0031 xy ¹	-
	Dairy	Heifers	84.952 ± 2.276 *xy	-	-1.136 ± 0.145 **xy ²	-	-	0.00407 ± 0.0021 xy ¹	-
		Steers	81.070 ± 1.986 **	-	-0.895 ± 0.109 *y ²	-	-	0.00096 ± 0.0013 x ¹	-
Ash ²	British	Heifers	55.642 ± 7.954 **	-	0.708 ± 0.192 *z ²	-	-	0.02104 ± 0.0035 *z ²	-
		Steers	89.475 ± 2.674 *z	-	-0.846 ± 0.132 *w ²	-	-	0.00045 ± 0.0023 w ²	-
	ContCross	Heifers	51.378 ± 8.582 **	-	0.791 ± 0.164 *z ²	Heifers: -2.103 ± 0.318 *a ²	-	Heifers: -0.01237 ± 0.00203 *a ²	0.02140 ± 0.0031 *z ²
		Steers	81.499 ± 8.590 *xyz	-	-0.745 ± 0.152 *wx ²	Steers: -0.917 ± 0.173 *b ²	-	Steers: -0.00054 ± 0.00118 b ²	0.00220 ± 0.0023 wx ²
	Dairy	Heifers	95.513 ± 8.310 *yz	-	0.153 ± 0.143 y ²	-	-	-	0.01370 ± 0.0029 *y ²
		Steers	72.987 ± 5.495 *xy	-	-0.624 ± 0.101 **x ²	-	-	-	0.00367 ± 0.00165 **x ²

¹ Chemical components (water, fat, protein, ash) are in percentage form (%); Water2, Fat2, and Protein2 are the quadratic model terms for carcass water, fat, and protein, respectively; British includes Angus, Hereford, Brangus, Angus × Hereford, Angus × MARC III, and Hereford × MARC III breeds; ContCross includes Simmental, Charolais, Belgian Blue × (Angus, Hereford, MARC III), Peidmontese × (Angus, Hereford, MARC III) Limousin × Gelbvieh, Charolais, Charolais × Hereford, Charolais × Angus, and Simmental × Angus × Hereford breeds; Dairy includes Friesian and Holstein breeds; intercept and slopes are coefficient ± SE; ² chemical component expressed as a percentage of carcass dry matter; ^{ab} coefficients for sex without a common superscript letter within column and chemical component differ at $p \leq 0.05$; ^{wxyz} coefficients for breed type × sex interaction without a common superscript letter within column and chemical component differ at $p \leq 0.05$; * coefficient differs from zero at $p \leq 0.05$.

Four equations were evaluated to predict carcass protein. In the first equation, protein was expressed as a percentage of the whole carcass, with the predictor being carcass fat-free dry matter percentage. In the second equation, protein was expressed as a percentage of the whole carcass, with predictors of carcass water and fat. In the third equation, protein was expressed as a percentage of the carcass dry matter, with carcass fat as a percentage of carcass dry matter as the predictor. In the fourth equation, protein was expressed as a percentage of carcass fat-free matter, with carcass water expressed as a percentage of carcass fat-free matter as the predictor (Table S8). Expressing protein as a percentage of the fat-free matter resulted in the least precise equation, with lower R^2 (0.5863 vs. 0.8557, 0.8840, 0.9793), CCC (0.7440 vs. 0.9224, 0.9393, 0.9895), and d (0.6988 vs. 0.8437, 0.8750, 0.9415) than the other equations. Expressing protein as a percentage of the whole carcass with either carcass fat-free dry matter or carcass fat and water as the predictors resulted in similar R^2 (0.8557 and 0.8840), CCC (0.9224 and 0.9393), d (0.8437 and 0.8750), and mean bias (-0.066 and -0.067), but the equation using carcass fat-free dry matter as the predictor had an intercept closer to zero (-0.052 vs. 0.332) and a slope closer to one (0.997 vs. 0.981). Additionally, multicollinearity was detected when carcass water and fat were included as predictors for carcass protein expressed as a percentage of the whole carcass. Expressing protein as a percentage of carcass dry matter with the predictor of carcass fat expressed as a percentage of carcass dry matter had a slope close to one (0.997) and R^2 (0.9793 vs. 0.5863, 0.8557, 0.8840), CCC (0.9895 vs. 0.7440, 0.9224, 0.9393), and d (0.9415 vs. 0.6988, 0.8437, 0.8750) greater than in the other equations, and it was selected as the final model.

There was a breed type \times sex interaction for the intercept and linear and quadratic slope coefficients of the equation to predict carcass protein (Table 5). Steers had a greater ($p \leq 0.05$) intercept than heifers for British, but not ($p > 0.05$) for ContCross and Dairy. Steers had a more negative ($p \leq 0.05$) linear slope coefficient and a more positive ($p \leq 0.05$) quadratic slope coefficient than heifers for British, but not ($p > 0.05$) for ContCross and Dairy. The cross-fold validation resulted in an RMSE of 1.62, R^2 of 0.98, MAPE of 3.392%, and AIC of 65.4 (Table 4). The relationship between the observed and predicted carcass protein is presented in Figure S7.

The prediction of carcass protein from the equation of Garrett and Hinman [29] had an intercept greater than zero (1.439), a slope of less than one (0.916), and lower R^2 and CCC than the proposed equation (0.85 and 0.92 vs. 0.98 and 0.99), but the mean bias was similar to that of the proposed equation (-0.06 vs. -0.25% ; Table S7). The cross-fold validation of the Garrett and Hinman equation resulted in an RMSE of 0.72 and a MAPE of 3.099%, both of which were lower than for the proposed equation. However, the cross-fold R^2 for the Garrett and Hinman equation was considerably lower (0.88 vs. 0.98), and the AIC was greater (70.8 vs. 65.4) than for the proposed equation.

When compared to the proposed equation for carcass protein within breed type and sex, the Garrett and Hinman equation had similar CCC values for all breed types and sexes (Table S11). However, the mean bias was further from zero for the Garrett and Hinman equation than for the proposed equation for ContCross and Dairy, and for heifers.

Four equations were evaluated to predict carcass ash. In the first equation, ash was expressed as a percentage of the whole carcass, with the predictors being water, fat, and protein expressed as a percentage of the whole carcass. In the second equation, ash was expressed as a percentage of the carcass dry matter, with predictors of carcass fat and protein expressed as a percentage of carcass dry matter. In the third equation, ash was expressed as a percentage of the carcass fat-free matter, with carcass water and protein as a percentage of carcass fat-free matter as predictors. In the fourth equation, ash was expressed as a percentage of carcass fat-free dry matter, with carcass protein expressed as a percentage of carcass fat-free dry matter as the predictor (Table S8). Multicollinearity was

detected in all the models. Expressing ash as a percentage of the fat-free dry matter resulted in the intercept and slope that were furthest from zero (-0.437 vs. -0.066 , -0.065 , 0.058) and one (1.028 vs. 1.018 , 1.016 , 1.001), respectively, and slightly lower R^2 (0.9157 vs. 0.9451 , 0.9482 , 0.9724), CCC (0.9536 vs. 0.9710 , 0.9727 , 0.9858), and d (0.8414 vs. 0.8777 , 0.8871 , 0.9300) than the other equations. Expressing ash as a percentage of the whole carcass or as a percentage of the carcass fat-free matter had similar intercept (-0.065 and -0.066) and slope (1.018 and 1.016) values and the least mean bias (-0.333 and -0.440 vs. -0.614 and -0.706). Expressing ash as a percentage of carcass dry matter had the intercept closest to zero (0.058 vs. -0.065 , -0.066 , -0.437), the slope closest to one (1.001 vs. 1.016 , 1.018 , 1.028), and slightly greater R^2 (0.9724 vs. 0.9157 , 0.9451 , 0.9482), CCC (0.9858 vs. 0.9536 , 0.9710 , 0.9727), and d (0.9300 vs. 0.8414 , 0.8777 , 0.8871) than the other equations, and it was selected as the final model.

There was a breed type \times sex interaction for the intercept, linear slope coefficient for carcass fat, and quadratic slope coefficient for carcass protein in the prediction of carcass ash (Table 5). Additionally, sex affected the linear slope coefficient for carcass protein and the quadratic slope coefficient for carcass fat. Steers had a greater ($p \leq 0.05$) intercept than heifers for British, but not for ContCross and Dairy. Steers had a more negative ($p \leq 0.05$) linear slope coefficient for carcass fat than heifers in all breed types, but the difference between steers and heifers was narrower for Dairy than for British and ContCross, resulting in an interaction. Steers had a less positive ($p \leq 0.05$) quadratic slope coefficient for carcass protein in all breed types, but the difference between steers and heifers was narrower for Dairy than for British and ContCross, resulting in an interaction. Heifers had a more negative ($p \leq 0.05$) linear slope coefficient for carcass protein and a more negative ($p \leq 0.05$) quadratic slope coefficient for carcass fat than steers. The cross-fold validation resulted in an RMSE of 0.82 , R^2 of 0.93 , MAPE of 4.729% , and AIC of 3.3 (Table 4). The relationship between the observed and predicted carcass ash is presented in Figure S8.

Garrett and Hinman [29] do not report an equation to predict carcass ash. Thus, the predicted carcass ash was computed as 100 minus the predicted percentages of water, fat, and protein, resulting in all of the error of the prediction falling to carcass ash. The prediction of carcass ash had an intercept greater than zero (4.852), a negative slope of less than zero (-0.101), lower R^2 and CCC than the proposed equation (0.11 and -0.17 vs. 0.97 and 0.98), and a mean bias further from zero than that of the proposed equation (-23.85 vs. -0.61% ; Table S7). The cross-fold validation of the Garrett and Hinman prediction had an RMSE of 0.95 , MAPE of 19.030% , and AIC of 82.0 , all of which were greater than for the proposed equation. The cross-fold R^2 for the Garrett and Hinman equation was considerably lower than for the proposed equation (0.17 vs. 0.93). When compared to the proposed equation for carcass ash within breed type and sex, the Garrett and Hinman prediction had a lower CCC than the proposed equation for all breed types and sexes and a mean bias that was further from zero than that of the proposed equation for all breed types and sexes, except heifers (Table S11).

3.3. Prediction of Empty Body from Carcass Chemical Components

Two equations were evaluated to predict empty body fat from carcass fat; in one equation, fat was expressed as a percentage of the whole empty body or carcass, and in the other, fat was expressed as a percentage of the empty body or carcass dry matter (Table S9). The equation expressing fat as a percentage of the dry matter had an intercept closer to zero (0.010 vs. 0.074) and slightly better R^2 (0.9882 vs. 0.9829), CCC (0.9940 vs. 0.9914), d (0.9477 vs. 0.9396), and mean bias (0.335 vs. 0.461) than the equation expressing fat as a percentage of the whole empty body or carcass, and it was selected as the final model to predict empty body fat.

Breed type affected ($p \leq 0.05$) the prediction of empty body fat from carcass fat (Table 6). The intercept was greater ($p \leq 0.05$) for Dairy than for British and ContCross, which were not different ($p > 0.05$). The linear and quadratic slope coefficients were different ($p \leq 0.05$) from zero. Sex had no effect ($p > 0.05$) on the prediction of empty body fat from carcass fat. The cross-fold validation resulted in an RMSE of 1.57, R^2 of 0.98, MAPE of 2.842%, and AIC of 44.5 (Table 4). The relationship between the observed and predicted empty body fat is presented in Figure S9.

The prediction of empty body fat from the equation of Garrett and Hinman [29] had an intercept greater than zero (1.574) and a mean bias further from zero than that of the proposed equation (-6.14 vs. 0.33% ; Table S7), but a slope closer to one, and R^2 and CCC similar to those of the proposed equation. The cross-fold validation of the Garrett and Hinman equation revealed an RMSE of 1.22, which was lower than for the proposed equation. However, the proposed equation is based on fat expressed as a percentage of empty body dry matter, which had a mean of 46.14%, compared to empty body fat expressed as a percentage of whole empty body, which had a mean of 20.25%. When compared based on the MAPE, the proposed equation was more accurate than the equation of Garrett and Hinman (2.842 vs. 4.868%). Additionally, the equation of Garrett and Hinman had a greater AIC (66.0 vs. 44.5). When compared to the proposed equation for empty body fat within breed type and sex, the Garrett and Hinman equation had a slightly lower CCC and a mean bias further from zero than the proposed equation for all breed types and sexes (Table S12).

Table 6. Coefficients for predictors in the final models to predict empty body water, fat, protein, and ash from carcass chemical components in growing/finishing cattle.

Component ¹	Breed Type	Sex	Intercept (\pm SE)	Slope Coefficients (\pm SE)	
				Carcass Comp.	Carcass Comp.2
Fat ²	British	Heifers/Steers	-1.552 ± 1.008^A	$1.072 \pm 0.044^{*2}$	$-0.00128 \pm 0.0005^{*2}$
	ContCross		-0.756 ± 0.937^A		
	Dairy		0.223 ± 0.938^B		
Water	British	Heifers	3.159 ± 10.423^Z	$1.033 \pm 0.365^{*Y}$	-0.00115 ± 0.0031^Z
		Steers	-4.250 ± 11.387^{YZ}	$1.228 \pm 0.430^{*YZ}$	-0.00228 ± 0.0040^{YZ}
	ContCross	Heifers	-3.974 ± 18.322^{YZ}	1.158 ± 0.593^{YZ}	-0.00156 ± 0.0047^{YZ}
		Steers	$79.262 \pm 29.579^{*Z}$	-1.685 ± 1.043^Y	$0.02278 \pm 0.0091^{*Z}$
	Dairy	Heifers	-9.700 ± 19.849^{YZ}	$1.346 \pm 0.638^{*YZ}$	-0.00284 ± 0.0051^{YZ}
		Steers	$-73.923 \pm 22.125^{*Y}$	$3.532 \pm 0.708^{*Z}$	$-0.02093 \pm 0.0056^{*Y}$
Protein ²	British	Heifers	$3.360 \pm 0.706^{*Z}$	$0.985 \pm 0.014^{*2}$	-
		Steers	$2.920 \pm 0.551^{*Z}$		
	ContCross	Heifers	$2.356 \pm 0.900^{*YZ}$		
		Steers	$2.277 \pm 0.835^{*YZ}$		
	Dairy	Heifers	1.280 ± 0.775^Y		
		Steers	$3.015 \pm 0.900^{*Z}$		
Ash ²	British	Heifers	$2.164 \pm 0.895^{*YZ}$	Heifers: $0.544 \pm 0.151^{*a2}$ Steers: $0.999 \pm 0.057^{*b2}$	Heifers: 0.01100 ± 0.0059^{b2} Steers: $-0.00826 \pm 0.0025^{*a2}$
		Steers	0.027 ± 0.317^Y		
	ContCross	Heifers	$1.967 \pm 0.942^{*YZ}$		
		Steers	0.493 ± 0.362^Z		
	Dairy	Heifers	$2.078 \pm 0.970^{*YZ}$		
		Steers	0.539 ± 0.351^Z		

¹ Chemical components (water, fat, protein, ash) are in %; Carcass Comp = equivalent carcass chemical component (i.e., water vs. water); Carcas Comp.2 = quadratic model term for the carcass chemical component; British includes Angus, Hereford, Brangus, Angus \times Hereford, Angus \times MARC III, and Hereford \times MARC III breeds; ContCross includes Simmental, Charolais, Belgian Blue \times (Angus, Hereford, MARC III), Peidmontese \times (Angus, Hereford, MARC III) Limousin \times Gelbvieh, Charolais, Charolais \times Hereford, Charolais \times Angus, and Simmental \times Angus \times Hereford breeds; Dairy includes Friesian and Holstein breeds; intercept and slopes are coefficient \pm SE; ² chemical component is expressed as a percentage of empty body or carcass dry matter; ^{AB} coefficients for breed type without a common superscript letter within column and chemical component differ at $p \leq 0.05$; ^{ab} coefficients for sex without a common superscript letter within column and chemical component differ at $p \leq 0.05$; ^{yz} coefficients for breed type \times sex interaction without a common superscript letter within column and chemical component differ at $p \leq 0.05$; * coefficient differs from zero at $p \leq 0.05$.

Two equations were evaluated to predict empty body water from carcass water; in one equation, water was expressed as a percentage of the whole empty body or carcass,

and in the other, water was expressed as a percentage of the empty body or carcass fat-free matter (Table S9). The equation expressing water as a percentage of the whole empty body or carcass had better R^2 (0.9831 vs. 0.9227), CCC (0.9915 vs. 0.9598), d (0.9376 vs. 0.8497), and mean bias (0.000 vs. 0.060) than the equation expressing water as a percentage of the empty body or carcass fat-free matter, and it was selected as the final model to predict carcass water.

Breed type \times sex interaction affected ($p \leq 0.05$) the prediction of empty body water from carcass water (Table 6). There was no difference ($p > 0.05$) between steers and heifers for any breed type, but the difference between steers and heifers was narrower for British than ContCross and Dairy, resulting in an interaction. The linear and quadratic slope coefficients were not different ($p > 0.05$) between heifers and steers for any breed type, but the difference between steers and heifers was narrower for British than ContCross and Dairy, resulting in an interaction. The cross-fold validation resulted in RMSE of 1.33, R^2 of 0.96, MAPE of 1.782%, and AIC of 57.3 (Table 4). The relationship between the observed and predicted empty body water is presented in Figure S10.

The prediction of empty body water from the equation of Garrett and Hinman [29] had an intercept close to zero (0.762), but a slope of less than one (0.969) and a mean bias further from zero than the proposed equation (1.85 vs. 0.00%; Table S7). The cross-fold validation of the Garrett and Hinman equation revealed an RMSE of 1.07, R^2 of 0.980, and MAPE of 1.528%, all of which were better than for the proposed equation. However, the Garrett and Hinman equation had a greater AIC (63.4 vs. 57.3). When compared to the proposed equation for carcass water within breed type and sex, the Garrett and Hinman equation had a slightly lower CCC, especially for ContCross, and a mean bias further from zero than the proposed equation for all breed types and sexes (Table S12).

Four equations were evaluated to predict empty body protein from carcass protein. In the first equation, protein was expressed as a percentage of the whole empty body, with the predictor being carcass protein as a percentage of whole carcass. In the second equation, protein was expressed as a percentage of the empty body dry matter, with the predictor being carcass protein expressed as a percentage of carcass dry matter. In the third equation, protein was expressed as a percentage of the empty body fat-free matter, with carcass protein as a percentage of carcass fat-free matter as the predictor. In the fourth equation, protein was expressed as a percentage of empty body fat-free dry matter, with carcass protein expressed as a percentage of carcass fat-free dry matter as the predictor (Table S9). Expressing protein as a percentage of the fat-free dry matter resulted in an intercept greater than zero (5.724 ± 2.494), a slope of less than one (0.928 ± 0.030), and the lowest R^2 (0.8638 vs. 0.8820, 0.9492, 0.9843), CCC (0.9290 vs. 0.9378, 0.9737, 0.9921), and d (0.7987 vs. 0.8265, 0.8951, 0.9390) compared to the other equations. Expressing protein as a percentage of the fat-free matter had an intercept close to zero (0.200) and a slope close to one (0.991), but the R^2 (0.8820 vs. 0.8638), CCC (0.9378 vs. 0.9290), and d (0.8265 vs. 0.7987) were only slightly improved compared with protein expressed as a percentage of fat-free dry matter. Expressing protein as a percentage of the whole empty body had the intercept closest to zero (-0.049 vs. 0.200, 0.417, 5.724) and the slope closest to one (1.004 vs. 0.928, 0.991, 0.991) but it lower had R^2 (0.9492 vs. 0.9843), CCC (0.9737 vs. 0.9921), and d (0.8951 vs. 0.9390) than expressing protein as a percentage of the dry matter. Expressing protein as a percentage of empty body dry matter with the predictor of carcass protein expressed as a percentage of carcass dry matter had an intercept that was not different from zero (0.417 ± 0.469), a slope that was not different from one (0.991 ± 0.010), and R^2 (0.9843 vs. 0.8638, 0.8820, 0.9492), CCC (0.9921 vs. 0.9290, 0.9378, 0.9737), and d (0.9390 vs. 0.7987, 0.8265, 0.8951) greater than those of the other equations, and it was selected as the final model.

There was a breed type \times sex interaction for the intercept of the equation to predict carcass protein (Table 5). Steers had a greater ($p \leq 0.05$) intercept than heifers for Dairy, but not ($p > 0.05$) for ContCross and British. The linear slope coefficient was different ($p \leq 0.05$) from zero and not affected ($p > 0.05$) by breed type or sex, and the quadratic slope coefficient was not different ($p > 0.05$) from zero. The cross-fold validation resulted in an RMSE of 1.51, R^2 of 0.98, MAPE of 3.253%, and AIC of 38.5 (Table 4). The relationship between the observed and predicted empty body protein is presented in Figure S11.

The prediction of empty body protein from the equation of Garrett and Hinman [29] had an intercept of less than zero (-1.463), a slope greater than one (1.073), lower R^2 and CCC than in the proposed equation (0.92 and 0.95 vs. 0.98 and 0.99), and a mean bias further from zero than in the proposed equation (0.90 vs. -0.10% ; Table S7). The cross-fold validation of the Garrett and Hinman equation revealed an RMSE of 0.53 , MAPE of 2.569% , and AIC of 36.4 , all of which were less than for the proposed equation. However, the cross-fold R^2 for the Garrett and Hinman equation was lower than for the proposed equation (0.923 vs. 0.981).

When compared to the proposed equation for empty body protein within breed type and sex, the Garrett and Hinman equation had a lower CCC for the ContCross and Dairy breeds and heifers (Table S12). However, the mean bias was further from zero for the Garrett and Hinman equation than for the proposed equation for all breed types, except for British, and for all sexes.

Four equations were evaluated to predict empty body ash from carcass ash. In the first equation, ash was expressed as a percentage of the whole empty body, with the predictor being carcass ash expressed as a percentage of the whole carcass. In the second equation, ash was expressed as a percentage of the empty body dry matter, with the predictor being carcass ash expressed as a percentage of carcass dry matter. In the third equation, ash was expressed as a percentage of the empty body fat-free matter, with carcass ash as a percentage of carcass fat-free matter as the predictor. In the fourth equation, ash was expressed as a percentage of empty body fat-free dry matter, with carcass ash expressed as a percentage of carcass fat-free dry matter as the predictor (Table S9). Expressing ash as a percentage of the fat-free matter or fat-free dry matter resulted in the intercept and slope that were furthest from zero (0.286 and 0.950 vs. 0.149 and 0.161) and one (0.947 and 0.950 vs. 0.965 and 0.985), respectively, and slightly lower R^2 (0.9389 and 0.9437 vs. 0.9447 and 0.9879), CCC (0.9686 and 0.9712 vs. 0.9719 and 0.9879), and d (0.8505 and 0.8587 vs. 0.8704 and 0.9257) than in the other equations. Expressing ash as a percentage of the whole empty body or empty body dry matter had similar intercept (0.149 and 0.161) and mean bias (-0.158 and -0.163) values, but expressing ash as a percentage of dry matter had a slope closer to one (0.985 vs. 0.965) and slightly improved R^2 (0.9761 vs. 0.9447), CCC (0.9879 vs. 0.9719), and d (0.9257 vs. 0.8704), and it was selected as the final model.

There was a breed type \times sex interaction for the intercept, and an effect of sex for the linear and quadratic slope coefficients in the prediction of empty body ash (Table 6). There was no difference ($p > 0.05$) in the intercept between steers and heifers for any breed type, but the difference between steers and heifers was slightly narrower for ContCross than for British and Dairy, resulting in an interaction. Steers had a more positive ($p \leq 0.05$) linear slope coefficient and more negative ($p \leq 0.05$) quadratic slope coefficient than heifers. The cross-fold validation resulted in an RMSE of 0.50 , R^2 of 0.94 , MAPE of 4.273% , and AIC of -10.1 (Table 4). The relationship between the observed and predicted carcass ash is presented in Figure S12.

The prediction of empty body ash from the equation of Garrett and Hinman [29] had an intercept of less than zero (-0.524), a slope greater than one (1.136), and R^2 and CCC values that were slightly lower than in the proposed equation (0.93 and 0.95 vs. 0.98 and

0.99), but a similar mean bias to that in the proposed equation (-0.55 vs. -0.16% ; Table S7). The cross-fold validation of the Garrett and Hinman prediction revealed an RMSE of 0.25, which was less than that in the proposed equation. However, the proposed equation is based on ash expressed as a percentage of empty body dry matter, which had a mean of 10.02%, compared to protein expressed as a percentage of whole empty body, which has a mean of 4.05%. When compared based on the MAPE, the proposed equation was more accurate than the equation of Garrett and Hinman (4.273 vs. 5.117%). The cross-fold R^2 for the Garrett and Hinman equation was lower (0.879 vs. 0.943), and the AIC was greater (-1.7 vs. -10.1), than for the proposed equation. When compared to the proposed equation for empty body ash within breed type and sex, the Garrett and Hinman prediction had a lower CCC than the proposed equation for all breed types, especially ContCross and Dairy, and sexes and mean bias further from zero than the proposed equation for all breed types, except for the British, and for sexes (Table S12).

4. Discussion

4.1. Comparison with Previously Published Equations

The linear coefficients for empty body water with empty body fat were generally more negative (average = -2.152 vs. -1.266 , -1.34 , and -1.301), and the linear coefficient for empty body fat with empty body water was more negative (-1.092 vs. -0.774) than those of Garrett and Hinman [29], Gil et al. [30], and Ferrell et al. [31]. However, these authors did not evaluate quadratic terms as predictors in their analyses, which would have impacted the linear coefficients. Ferrell et al. [31] reported a similar correlation (-0.99 vs. -0.98) between empty body water and fat to the current study, and Gil et al. [30] reported a standard error of the estimate to predict empty body fat from empty body water similar to the RMSE in the current study (1.53 vs. 1.84).

Similar to the empty body, the linear coefficients for carcass water with carcass fat (-1.979 vs. -1.337 , -1.35 , and -1.328) and for carcass fat with carcass water (-1.065 vs. -0.727 and -0.765) were more negative than those of previous studies [29–32]. The correlation between carcass water and fat in the current study (-0.98 and -0.99) was similar to that found by Ferrell et al. [31], and the coefficient of determination (0.97 and 0.99) for the prediction of carcass fat in the current study was similar to that obtained by Gil et al. [30], but the RMSE for the prediction of carcass water in the current study was considerably greater (1.29 vs. 0.45) than the standard error of the estimate obtained by Preston et al. [32].

It is not surprising that breed type and sex had little influence on the prediction of empty body and carcass water from empty body and carcass fat, respectively. The correlation coefficient has been strong and the linear regression coefficient has been highly consistent between fat and water across studies [29–32]. Additionally, the prediction of empty body and carcass fat from water was the most accurate and precise prediction of the chemical components in previously published equations, and it was the least affected by breed type and sex [38]. Interestingly, the prediction of empty body fat from water was affected by breed type and sex, suggesting that the proportion of fat in the empty body dry matter may vary with breed type and sex. The analysis of variance indicated that the breed type \times sex interaction for fat expressed as a percentage of the empty body dry matter had a probability of 0.12, whereas the breed type \times sex interaction for water expressed as a percentage of the empty body fat-free matter had a probability of 0.99, suggesting that breed type and sex interact to affect water composition, which is consistent with the tendency for a breed type \times sex interaction for water in the empty body and carcass in all three datasets (Table S4). Additionally, water as a percentage of fat-free matter was highly consistent with the coefficient of variation in the empty body and carcass, with values of

3.0 and 2.8%, respectively, compared with the coefficient of variation for fat as a percentage of the dry matter, with values of 34 and 30%, respectively.

Previous studies have predicted empty body and carcass protein from fat-free dry matter [29] or water and fat in separate equations [30–32]. Fat-free dry matter is calculated as 100 minus the sum of water and fat, such that different values of water and fat can result in the same fat-free dry matter value; thus, using water and fat together in the equation may provide more information than fat-free dry matter alone. Equations to predict empty body or carcass protein from empty body or carcass fat-free dry matter, respectively, resulted in greater RMSE (Empty Body: 0.71 vs. 0.60; Carcass: 0.80 vs. 0.71) and lesser coefficient of determination (Empty Body: 0.82 vs. 0.87; Carcass: 0.85 vs. 0.88).

The best equation to predict empty body and carcass protein expressed protein as a percentage of the dry matter, which is likely to have been due to differences among breed types and sexes in water composition, as discussed previously. However, the intercept and slope coefficients for the prediction of empty body and carcass protein were still affected by breed type and sex. The linear coefficients for empty body or carcass fat with empty body or carcass protein were negative in the current study, as in previous studies [31,32], but the correlations between fat and protein (−0.79 and −0.85 vs. −0.90 to −0.97) were lower in the current study. However, the correlations between fat and protein, expressed as a percentage of both empty body or carcass dry matter, were strong (−0.99 and −0.99), again suggesting that the water composition varies considerably, but the RMSE for the prediction of carcass protein in the current study was considerably greater (1.62 vs. 0.51) than the standard error of the estimate reported by Preston et al. [32].

The empty body and carcass ash could be computed as 100 minus the sum of water, fat, and protein; however, this approach forces all of the errors in the prediction of these components into the estimate of ash. Lancaster [38] reported that the empty body and carcass ash estimated as 100 minus the sum of water, fat, and protein, with the fat and protein being predicted from published equations, had no relationship ($r = 0.03$ and 0.00) with the observed empty body and carcass ash. By developing a prediction equation for empty body and carcass ash, ash can be predicted independently of the cumulative errors if the water, fat, and protein are known. A negative of this approach is that it does not ensure that the sum of water, fat, protein, and ash equals 100.

The best equation to predict the empty body and carcass ash expressed ash as a percentage of the dry matter. No previous studies have evaluated predicting the ash percentage from protein and (or) fat; only prediction from the water percentage has been examined. Preston et al. [32] reported a stronger correlation between carcass water and ash (0.79 vs. 0.33) than in the current study. However, the RMSE for the prediction of carcass ash as a percentage of the whole carcass in the current study was similar (0.23 and 0.28) to the standard error of the estimate provided by Preston et al. [32].

Multicollinearity was detected in the models used to predict empty body and carcass ash, as the predictors of fat and protein are strongly correlated. However, all the predictors included in the final models explained a significant amount of variation, indicating that they did not provide the same information regarding the variation in the empty body or carcass ash. The stepwise model selection based on the AIC resulted in a model with both fat and protein included, indicating that this combination of predictors provided the best explanation of the data, with the least complexity. The inclusion of both fat and protein may have occurred because fat and protein have different relationships with ash among breed types and sexes, as evidenced by the intra-breed type and intra-sex correlation coefficients. Multicollinearity makes the interpretation of the coefficients difficult, as the predictors are not independent of each other [47,48]. However, multicollinearity does not necessarily affect prediction, as it is the total amount of variation explained that is of interest [47,48].

The application of the proposed equation with collinear predictors to future data depends upon the correlations between the predictors in future datasets. The correlation between fat and protein was highly consistent among breed types and sexes in the current study, and has been consistently strong in previous studies (-0.94 , -0.97 , -0.90) [31,32].

When comparing the same chemical component of the carcass to that of the empty body, previous studies [29,31] reported positive linear coefficients of less than one for all chemical components. In the current study, most of the linear coefficients for the carcass chemical components are positive, but many are not less than one. The difference is likely to be due to the inclusion of quadratic terms in the current model, whereas these terms were not included in previous models [29,31]. The quadratic term was significant for all the chemical components except protein, with the coefficients for water and ash interacting with either breed type or sex. The breed types with linear coefficients greater than one generally have quadratic coefficients that are negative, and vice versa. In both the current study and previous studies [29,31] the correlation between the same chemical component in the carcass and empty body was very strong (>0.95) and positive. However, the RMSE of models in the current study was greater (fat: 1.57 vs. 0.53 and 0.59; water: 1.33 vs. 0.74; protein: 1.51 vs. 0.31 and 0.33; ash: 0.50 vs. 0.09 and 0.08) than the standard error of the estimate in previous studies [29,31], although the predictions of fat, protein, and ash as a percentage of the empty body dry matter in the current study were roughly double or triple the mean and standard deviation.

The equations to predict the empty body and carcass protein and ash are arguably more complex than the equations to predict empty body and carcass water and fat, being adjusted to empty body or carcass dry matter composition and breed type \times sex interactions for intercepts and slope coefficients. This aligns with the results of Lancaster [38], who reported that equations developed from single breed type and sex datasets poorly predicted protein and ash in a dataset of diverse breed types and sexes. In the dataset of Lancaster [38], which is a portion of the dataset used in the current study, the protein and ash as percentages of the empty body or carcass fat-free dry matter were quite variable, having coefficients of variation ranging from 6 to 34%. The coefficients of variation for protein and ash as a percentage of empty body or carcass dry matter in the current study ranged from 26 to 33%. Expressing fat, protein, and ash as a percentage of dry matter significantly increased the correlations among the variables in the empty body (fat and protein = -0.79 vs. -0.99 ; fat and ash = -0.21 vs. -0.83 ; protein and ash = 0.20 vs. 0.73) and carcass (fat and protein = -0.85 vs. -0.99 ; fat and ash = -0.44 vs. -0.87 ; protein and ash = 0.35 vs. 0.79).

From the above discussion, the relationships among the chemical components of the empty body and carcass in the current analysis, which uses data from multiple studies, breed types, and sexes, are not as strong as those in previous studies [29–32] using a single breed type and sex. However, breed type and sex did not explain the same amount of the variation among data from multiple studies as what is reported in these previous studies indicating that either measurement error occurred among studies even though all studies used proximate analysis to determine chemical components or additional unknown factors are affecting the variation in body composition. Thus, part of the strong relationships observed in previous studies may be due to measurement being determined by a single laboratory.

4.2. Effects of Breed Type and Sex

It is likely that the effect of breed type and sex on intercepts and regression coefficients is due to differences in fat composition and relationships among chemical components. Lancaster [38] hypothesized that the deviation between observed and predicted values associated with breed type in their analysis was likely due to differences in the intercept

of the prediction equation, when using prediction equations based on a single breed type. Breed types differ in mean empty body and carcass chemical composition, which is likely to be the reason why breed type affected the intercept for the majority of the current models. In the current study and in previous studies [22–24,49–52], British breed types have greater empty body and carcass fat and less empty body and carcass water than Continental breed types at similar ages and weights; thus, the differences in model intercepts among breed types are not surprising.

However, breed type also affected many of the slope coefficients, indicating that the relationship among the chemical components differs among breed types. Berg et al. [53] indicated that breeds differed in the relationship between the physically separable fat and muscle of the carcass. In contrast, Short et al. [16] reported no differences in the rate of change in empty body or carcass fat and protein with days on feed in Charolais and Line 1 Hereford-sired calves. There has been little research evaluating the relationships among the chemical components of the empty body and carcass between breeds.

Earlier-maturing British cattle generally had more positive relationships between fat and water in the empty body than later-maturing ContCross. Garrett and Hinman [29] and Ferrell et al. [31] reported that fat replaced water in the empty body at a rate of 0.77 kg of water per kg of fat. Additionally, Basarab et al. [54] reported that the water content of the fat-free gain decreased as steers became fatter. Later-maturing Continental breeds have a greater relationship between fat accretion and empty body weight than British breed types [52], indicating differences in relationships between empty body fat and other chemical components of the empty body. The relationship between water and protein may be altered in British compared with Continental breeds, as the proportion of water in the fat-free matter decreases with greater fat deposition.

Like breed type, the differences in the intercepts of the models due to sex are likely to be due to the differences in fat composition of steers vs. heifers observed in the current and previous studies [27,36,37,55,56], with heifers generally fatter than steers at common empty body and carcass weights. Water and fat are strongly inversely related in the empty body and carcass [29–32,57] and have the most consistent relationship of any two chemical components across breed types and sexes, as reported in the supplemental tables. Sex affected the slope coefficients for empty body fat, indicating that the displacement of water with fat, as discussed above, may be different between steers and heifers. But there has been little research on the effect of sex on the relationships among the chemical components of the empty body and carcass.

4.3. Comparison with Garrett and Hinman Equations

The equations of Garrett and Hinman [29] are still used today; however, the current analysis points out some limitations of using these equations across breed types and sexes. The primary limitation of the Garrett and Hinman equations is that these equations were developed using a single breed and sex, with the assumption that fat-free dry matter is a constant proportion of protein and ash. The Garrett and Hinman equations were relatively precise and accurate in predicting the water and fat composition, but much less precise and accurate in predicting the protein and ash composition. Lancaster [38] demonstrated that the composition of the fat-free dry matter across breed types and sexes was highly variable, with protein concentrations ranging from 70 to 94% and ash ranging from 6 to 30% of the fat-free dry matter. The Garrett and Hinman equations use fat-free dry matter as the predictor of empty body and carcass protein, resulting in erroneous results when the fat-free dry matter composition is not similar to that of the cattle in the dataset used to create the equations.

Lancaster [38] reported that previous equations developed using single breed types and sexes were adequate predictors of empty body and carcass fat and water, although breed type and sex accounted for variation in the residual. However, previous equations were very poor predictors of empty body and carcass protein and ash [38]. In the current study, similar results were observed in the cross-fold validation, with the R^2 being similar between the proposed equations and those of Garrett and Hinman [29] for empty body and carcass fat and water, although the R^2 was lower for empty body protein and ash. Evaluating prediction ability by breed type and sex, the Garrett and Hinman equations were less precise for the prediction of protein for the ContCross and Dairy, especially in the empty body, than for the British. Garrett and Hinman [29] used data from Hereford steers to develop their equations. Thus, it appears that breed type and sex, although significant predictors, may have a minimal impact on the prediction of empty body and carcass fat and water, but breed type and sex appear to be integral to the accurate and precise prediction of empty body and carcass protein and ash.

Empty body protein has a significant role in maintenance energy requirements and net protein requirements, but it is more difficult to predict. Empty body protein composition is an important driver of variation in maintenance energy requirements [7,58] due to variation in visceral organs [59,60] and skeletal muscle [4]. The estimated maintenance energy requirement for protein is greater than for fat (188 vs. 20 kcal/kg, respectively) [5–9]. As reported by Lancaster [38], offal protein explained a large proportion of the difference between empty body protein values predicted from carcass protein using the Garrett and Hinman equation. The variability in offal protein is mainly due to variability in the mass of visceral and splanchnic tissues [60,61], which are affected by nutrition [60,62–67] and breed [22,23,64,68], and it is likely to be the reason for the less precise and accurate predictions obtained from the equations of Garrett and Hinman. Previous nutrition was not accounted for in the current study and may be an important predictor of empty body protein, which should be evaluated in future research.

Additionally, the net protein requirements for growth (retained protein) are less precisely predicted ($R^2 = 0.74$) from retained energy. This most likely due to variation in empty body protein, as fat gain has a strong relationship ($R^2 = 0.94$) with retained energy [12,13]. The comparison of the observed versus predicted retained protein had a slope greater than one (1.11) and an intercept of less than zero (-23.9), with an RMSE of 33.8 g/d. The R^2 for the prediction of retained protein across varied breed types and sexes is similar to the R^2 of the predicted empty body protein from the Garrett and Hinman equations in the current study. Thus, the proposed equations may provide better estimates of retained protein across a range of breed types and sexes.

The proposed equations in the current analysis will allow improved estimation of empty body and carcass composition across breed types and sexes compared to the Garrett and Hinman equations. The improved estimation of body chemical composition could lead to improved feeding standards for maintenance and growth requirements for energy and protein. New feeding standards would allow more precise diet formulation, resulting in the improved efficiency and profitability of cattle feeding, as well as potentially reducing the environmental impact of cattle feeding operations.

5. Conclusions

Previous equations relating chemical components of the empty body and carcass were developed using a single breed and sex or did not evaluate the effect of sex on the relationships. Breed type affected the majority of the models in predicting empty body and carcass chemical components, with differences generally between British and ContCross breed types. The greater fat deposition in the British compared with the ContCross is

likely to be the reason for the differences in the model intercepts and slope coefficients. Likewise, sex affected many of the models in predicting empty body and carcass chemical components, probably due to the differences in fat deposition between steers and heifers. Because breeds and sexes deposit fat at different rates and, thus, displace water in the fat-free matter at different rates, separate prediction equations are needed to relate the chemical components of the empty body and carcass. The equations developed should improve estimates of chemical composition, enhancing the determination of the energy and protein requirements for the maintenance and gain of growing and finishing cattle of diverse breed types and sexes. Future research should further evaluate these equations in *Bos indicus* breeds and growing bulls, as well as evaluating the use of these questions to predict the energy and protein requirements of diverse breeds and sexes in different production systems.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/ruminants5020014/s1>. Table S1: Descriptive statistics of chemical components for breed type and sex of growing/finishing cattle in the Empty Body dataset; Table S2: Descriptive statistics of chemical components for breed type and sex of growing/finishing cattle in the Carcass dataset; Table S3: Descriptive statistics of chemical components for breed type and sex of growing/finishing cattle in the Empty Body–Carcass dataset; Table S4: Effect of breed type and sex on chemical composition in the Empty Body, Carcass, and Empty Body–Carcass datasets, accounting for empty body or carcass weight of growing/finishing cattle; Table S5: Pearson correlation coefficients among chemical components of the empty body (above diagonal) and carcass (below diagonal), and between empty body and carcass (diagonal) for breed type and sex of growing/finishing cattle; Table S6: Comparison of models to predict empty body water, fat, protein, and ash in growing/finishing steers and heifers; Table S7: Evaluation of predicting empty body and carcass water, fat, protein, and ash in growing/finishing steers and heifers of different breed types using equations of Garrett and Hinman (1969) [29]; Table S8: Comparison of models to predict carcass water, fat, protein, and ash in growing/finishing steers and heifers; Table S9: Comparison of models to predict empty body water, fat, protein, and ash from carcass chemical components in growing/finishing steers and heifers; Table S10: Comparison of proposed equations with those of Garrett and Hinman (1969) [29] to predict empty body fat, water, protein, and ash in growing/finishing steers and heifers of different breed types and sexes; Table S11: Comparison of proposed equations with those of Garrett and Hinman (1969) [29] to predict carcass fat, water, protein, and ash in growing/finishing steers and heifers of different breed types and sexes; Table S12: Comparison of proposed equations with those of Garrett and Hinman (1969) [29] to predict empty body fat, water, protein, and ash from carcass chemical components in growing/finishing steers and heifers of different breed types and sexes; Figure S1: Plot of observed against predicted empty body fat (EBF) from the Empty Body dataset; Figure S2: Plot of observed against predicted empty body water (EBWA) from the Empty Body dataset; Figure S3: Plot of observed against predicted empty protein (EBP) from the Empty Body dataset; Figure S4: Plot of observed against predicted empty ash (EBA) from the Empty Body dataset; Figure S5: Plot of observed against predicted carcass fat (CF) from the Carcass dataset; Figure S6: Plot of observed against predicted carcass water (CWA) from the Carcass dataset; Figure S7: Plot of observed against predicted carcass protein (CP) from the Carcass dataset; Figure S8: Plot of observed against predicted carcass ash (CA) from the Carcass dataset; Figure S9: Plot of observed against predicted empty body fat (EBF) from the Empty Body–Carcass dataset; Figure S10: Plot of observed against predicted empty body water (EBWA) from the Empty Body–Carcass dataset; Figure S11: Plot of observed against predicted empty body protein (EBP) from the Empty Body–Carcass dataset; Figure S12: Plot of observed against predicted empty body ash (EBA) from the Empty Body–Carcass dataset.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The following datasets used for analysis are available at www.mdpi.com/xxx/s1: Final Empty Body Comp Data.xlsx; Final Carcass Comp Data.xlsx; Final Empty Body-Carcass Comp Data.xlsx.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

British	Cattle originating in Great Britain
ContCross	Cattle originating in Continental Europe
Dairy	Cattle with primary purpose of milk production
CCC	Concordance correlation coefficient
MB	Mean bias
RMSE	Root mean squared error
R2	Coefficient of determination
MAE	Mean absolute error

References

1. Guioy, P.J.; Fox, D.G.; Tedeschi, L.O.; Baker, M.J.; Cravey, M.D. Predicting Individual Feed Requirements of Cattle Fed in Groups. *J. Anim. Sci.* **2001**, *79*, 1983–1995. [[CrossRef](#)] [[PubMed](#)]
2. Fox, D.G.; Tedeschi, L.O.; Tylutki, T.P.; Russell, J.B.; Van Amburgh, M.E.; Chase, L.E.; Pell, A.N.; Overton, T.R. The Cornell Net Carbohydrate and Protein System Model for Evaluating Herd Nutrition and Nutrient Excretion. *Anim. Feed Sci. Technol.* **2004**, *112*, 29–78. [[CrossRef](#)]
3. Tedeschi, L.O.; Fox, D.G.; Guioy, P.J. A Decision Support System to Improve Individual Cattle Management. 1. A Mechanistic, Dynamic Model for Animal Growth. *Agric. Syst.* **2004**, *79*, 171–204. [[CrossRef](#)]
4. Ferrell, C.L. Energy Metabolism. In *The Ruminant Animal: Digestive Physiology and Nutrition*; Church, D.C., Ed.; Prentice Hall: Englewood Cliffs, NJ, USA, 1988; pp. 250–268.
5. Ferrell, C.L.; Crouse, J.D.; Field, R.A.; Chant, J.L. Effects of Sex, Diet and Stage of Growth upon Energy Utilization by Lambs. *J. Anim. Sci.* **1979**, *49*, 790–801. [[CrossRef](#)]
6. Thompson, W.R.; Meiske, J.C.; Goodrich, R.D.; Rust, J.R.; Byers, F.M. Influence of Body Composition on Energy Requirements of Beef Cows during Winter. *J. Anim. Sci.* **1983**, *56*, 1241–1252. [[CrossRef](#)]
7. Tess, M.W.; Dickerson, G.E.; Nienaber, J.A.; Ferrell, C.L. The Effects of Body Composition on Fasting Heat Production in Pigs. *J. Anim. Sci.* **1984**, *58*, 99–110. [[CrossRef](#)]
8. Solis, J.C.; Byers, F.M.; Schelling, G.T.; Long, C.R.; Greene, L.W. Maintenance Requirements and Energetic Efficiency of Cows of Different Breed Types. *J. Anim. Sci.* **1988**, *66*, 764–773. [[CrossRef](#)]
9. DiCostanzo, A.; Meiske, J.C.; Plegge, S.D.; Peters, T.M.; Goodrich, R.D. Within-Herd Variation in Energy Utilization for Maintenance and Gain in Beef Cows. *J. Anim. Sci.* **1990**, *68*, 2156–2165. [[CrossRef](#)]
10. National Research Council. *Nutrient Requirements of Beef Cattle*, 5th ed.; National Academies Press: Washington, DC, USA, 1976; ISBN 0-309-02419-6.
11. National Research Council. *Nutrient Requirements of Beef Cattle*, 6th ed.; National Academies Press: Washington, DC, USA, 1984; ISBN 978-0-309-03447-0.
12. National Research Council. *Nutrient Requirements of Beef Cattle*, 7th ed.; National Academy Press: Washington, DC, USA, 2000; ISBN 978-0-309-38813-9.
13. National Academies of Sciences, Engineering, and Medicine. *Nutrient Requirements of Beef Cattle: Eighth Revised Edition*, 8th ed.; Animal Nutrition Series; The National Academies Press: Washington, DC, USA, 2016; ISBN 978-0-309-31702-3.
14. Owens, F.N.; Dubeski, P.; Hanson, C.F. Factors That Alter the Growth and Development of Ruminants. *J. Anim. Sci.* **1993**, *71*, 3138–3150. [[CrossRef](#)]
15. Owens, F.N.; Gill, D.R.; Secrist, D.S.; Coleman, S.W. Review of Some Aspects of Growth and Development of Feedlot Cattle. *J. Anim. Sci.* **1995**, *73*, 3152–3172. [[CrossRef](#)]
16. Short, R.E.; Grings, E.E.; MacNeil, M.D.; Heitschmidt, R.K.; Williams, C.B.; Bennett, G.L. Effects of Sire Growth Potential, Growing-Finishing Strategy, and Time on Feed on Performance, Composition, and Efficiency of Steers. *J. Anim. Sci.* **1999**, *77*, 2406–2417. [[CrossRef](#)]
17. Coleman, S.W.; Evans, B.C.; Guenther, J.J. Body and Carcass Composition of Angus and Charolais Steers as Affected by Age and Nutrition. *J. Anim. Sci.* **1993**, *71*, 86–95. [[CrossRef](#)] [[PubMed](#)]

18. Old, C.A.; Garrett, W.N. Effects of Energy Intake on Energetic Efficiency and Body Composition of Beef Steers Differing in Size at Maturity. *J. Anim. Sci.* **1987**, *65*, 1371–1380. [[CrossRef](#)]
19. Buckley, B.A. Relationship of Body Composition and Fasting Heat Production in Three Biological Types of Growing Beef Heifers. Ph.D. Dissertation, University of Nebraska, Lincoln, NE, USA, 1985.
20. Bidner, T.D.; Wyatt, W.E.; Humes, P.E.; Franke, D.E.; Blouin, D.C. Influence of Brahman-Derivative Breeds and Angus on Carcass Traits, Physical Composition, and Palatability. *J. Anim. Sci.* **2002**, *80*, 2126–2133. [[CrossRef](#)] [[PubMed](#)]
21. Bailey, C.B.; Lawson, J.E. Carcass and Empty Body Composition of Hereford and Angus Bulls from Lines Selected for Rapid Growth on High-Energy or Low-Energy Diets. *Can. J. Anim. Sci.* **1989**, *69*, 583–594. [[CrossRef](#)]
22. Ferrell, C.L.; Jenkins, T.G. Body Composition and Energy Utilization by Steers of Diverse Genotypes Fed a High-Concentrate Diet during the Finishing Period: I. Angus, Belgian Blue, Hereford, and Piedmontese Sires. *J. Anim. Sci.* **1998**, *76*, 637–646. [[CrossRef](#)]
23. Ferrell, C.L.; Jenkins, T.G. Body Composition and Energy Utilization by Steers of Diverse Genotypes Fed a High-Concentrate Diet during the Finishing Period: II. Angus, Boran, Brahman, Hereford, and Tuli Sires. *J. Anim. Sci.* **1998**, *76*, 647–657. [[CrossRef](#)]
24. Lunt, D.K.; Smith, G.C.; Murphey, C.E.; Savell, J.W.; Carpenter, Z.L.; Petersen, H.D. Carcass Characteristics and Composition of Brahman, Angus and Brahman × Angus Steers Fed for Different Times-on-Feed. *Meat Sci.* **1985**, *14*, 137–152. [[CrossRef](#)]
25. Cole, J.W.; Ramsey, C.B.; Hobbs, C.S.; Temple, R.S. Effects of Type and Breed of British, Zebu, and Dairy Cattle on Production, Carcass Composition, and Palatability. *J. Dairy Sci.* **1964**, *47*, 1138–1144. [[CrossRef](#)]
26. Fortin, A.; Reid, J.T.; Maiga, A.M.; Sim, D.W.; Wellington, G.H. Effect of Level of Energy Intake and Influence of Breed and Sex on Growth of Fat Tissue and Distribution in the Bovine Carcass. *J. Anim. Sci.* **1981**, *53*, 982–991. [[CrossRef](#)]
27. Fortin, A.; Simpfendorfer, S.; Reid, J.T.; Ayala, H.J.; Anrique, R.; Kertz, A.F. Effect of Level of Energy Intake and Influence of Breed and Sex on the Chemical Composition of Cattle. *J. Anim. Sci.* **1980**, *51*, 604–614. [[CrossRef](#)]
28. Fortin, A.; Reid, J.T.; Simpfendorfer, S.; Ayala, H.J.; Anrique, R.; Kertz, A.F.; Maiga, A.M.; Sim, D.W.; Wellington, G.H. Chemical Composition and Carcass Specific Gravity in Cattle: Effect of Level of Energy Intake and Influence of Breed and Sex. *Can. J. Anim. Sci.* **1981**, *61*, 871–882. [[CrossRef](#)]
29. Garrett, W.N.; Hinman, N. Re-Evaluation of the Relationship between Carcass Density and Body Composition of Beef Steers. *J. Anim. Sci.* **1969**, *28*, 1–5. [[CrossRef](#)]
30. Gil, E.A.; Johnson, R.R.; Cahill, V.R.; McClure, K.E.; Klosterman, E.W. An Evaluation of Carcass Specific Volume, Dye Dilution and Empty Body Parameters as Predictors of Beef Carcass Composition over a Wide Range of Fatness. *J. Anim. Sci.* **1970**, *31*, 459–469. [[CrossRef](#)]
31. Ferrell, C.L.; Garrett, W.N.; Hinman, N. Estimation of Body Composition in Pregnant and Non-Pregnant Heifers. *J. Anim. Sci.* **1976**, *42*, 1158–1166. [[CrossRef](#)]
32. Preston, R.L.; Vance, R.D.; Cahill, V.R.; Kock, S.W. Carcass Specific Gravity and Carcass Composition in Cattle and the Effect of Bone Proportionality on This Relationship. *J. Anim. Sci.* **1974**, *38*, 47–51. [[CrossRef](#)]
33. Arthaud, V.H.; Mandigo, R.W.; Koch, R.M.; Kotula, A.W. Carcass Composition, Quality and Palatability Attributes of Bulls and Steers Fed Different Energy Levels and Killed at Four Ages². *J. Anim. Sci.* **1977**, *44*, 53–64. [[CrossRef](#)]
34. Jacobs, J.A.; Hurst, C.E.; Miller, J.C.; Howes, A.D.; Gregory, T.L.; Ringkob, T.P. Bulls versus Steers. I. Carcass Composition, Wholesale Yields and Retail Values. *J. Anim. Sci.* **1977**, *45*, 695–698. [[CrossRef](#)]
35. Keane, M.G.; Drennan, M.J. Lifetime Growth and Carcass Composition of Heifers and Steers Non-Implanted or Sequentially Implanted with Anabolic Agents. *Anim. Sci.* **1987**, *45*, 359–369. [[CrossRef](#)]
36. Steen, R.W.J.; Kilpatrick, D.J. Effects of Plane of Nutrition and Slaughter Weight on the Carcass Composition of Serially Slaughtered Bulls, Steers and Heifers of Three Breed Crosses. *Livest. Prod. Sci.* **1995**, *43*, 205–213. [[CrossRef](#)]
37. Blanco, M.; Ripoll, G.; Delavaud, C.; Casasús, I. Performance, Carcass and Meat Quality of Young Bulls, Steers and Heifers Slaughtered at a Common Body Weight. *Livest. Sci.* **2020**, *240*, 104156. [[CrossRef](#)]
38. Lancaster, P.A. Assessment of Equations to Predict Body Weight and Chemical Composition in Growing/Finishing Cattle and Effects of Publication Year, Sex, and Breed Type on the Deviation from Observed Values. *Animals* **2022**, *12*, 3554. [[CrossRef](#)] [[PubMed](#)]
39. Makowski, D.; Wiernik, B.M.; Patil, I.; Lüdecke, D.; Ben-Shachar, M.S. Correlation: Methods for Correlation Analysis 2022. Available online: <https://cran.r-project.org/web/packages/correlation/index.html> (accessed on 12 March 2025).
40. R Core Team. *R: A Language and Environment for Statistical Computing 2022*; R Foundation for Statistical Computing: Vienna, Austria, 2022.
41. Lenth, R.V. Emmeans: Estimated Marginal Means, Aka Least-Squares Means. 2023. Available online: <https://cran.r-project.org/web/packages/emmeans/index.html> (accessed on 12 March 2025).
42. Venables, W.N.; Ripley, B.D. *Modern Applied Statistics with S*, 4th ed.; Springer: New York, NY, USA, 2002; ISBN 0-387-95457-0.
43. Stevenson, M.; Sergeant, E.; Nunes, T.; Heuer, C.; Marshall, J.; Sanchez, J.; Thornton, R.; Reiczigel, J.; Robison-Cox, J.; Sebastiani, P.; et al. epiR: Tools for the Analysis of Epidemiological Data 2023. Available online: <https://cran.r-project.org/web/packages/epiR/index.html> (accessed on 12 March 2025).

44. Embry, I.; Hoos, A.; Diehl, T.H. Ie2misc: Irucka Embry's Miscellaneous USGS Functions 2023. Available online: <https://cran.r-project.org/web/packages/ie2misc/index.html> (accessed on 12 March 2025).
45. Kuhn, M. Building Predictive Models in R Using the Caret Package. *J. Stat. Softw.* **2008**, *28*, 1–26. [CrossRef]
46. Fox, J.; Weisberg, S. *An R Companion to Applied Regression*, 3rd ed.; SAGE Publications, Inc.: Thousand Oaks, CA, USA, 2019.
47. Kutner, M.H.; Nachtsheim, C.J.; Neter, J.; Li, W. *Applied Linear Statistical Models*; McGraw-Hill: New York, NY, USA, 2005; ISBN 978-0-07-238688-2.
48. Seber, G.A.F.; Wild, C.J. Least Squares. In *Methods in Experimental Physics*; Stanford, J.L., Vardeman, S.B., Eds.; Statistical Methods for Physical Science; Academic Press: San Diego, CA, USA, 1994; Volume 28, pp. 245–281.
49. Pringle, T.D.; Williams, S.E.; Lamb, B.S.; Johnson, D.D.; West, R.L. Carcass Characteristics, the Calpain Proteinase System, and Aged Tenderness of Angus and Brahman Crossbred Steers. *J. Anim. Sci.* **1997**, *75*, 2955–2961. [CrossRef] [PubMed]
50. Huffman, R.D.; Williams, S.E.; Hargrove, D.D.; Johnson, D.D.; Marshall, T.T. Effects of Percentage Brahman and Angus Breeding, Age-Season of Feeding and Slaughter End Point on Feedlot Performance and Carcass Characteristics. *J. Anim. Sci.* **1990**, *68*, 2243–2252. [CrossRef]
51. Talamantes, M.A.; Long, C.R.; Smith, G.C.; Jenkins, T.G.; Ellis, W.C.; Cartwright, T.C. Characterization of Cattle of a Five-Breed Diallel: VI. Fat Deposition Patterns of Serially Slaughtered Bulls. *J. Anim. Sci.* **1986**, *62*, 1259–1266. [CrossRef]
52. Gonzalez, L.A.; Burgess, J.; Imaz, A.; Tedeschi, L.O. Determining the Body Weight to Body Fat Conversion Factor for Angus, Charolais, and Brahman Growing Steers. *J. Anim. Sci.* **2023**, *101*, 82–83. [CrossRef]
53. Berg, R.T.; Andersen, B.B.; Liboriussen, T. Growth of Bovine Tissues 1. Genetic Influences on Growth Patterns of Muscle, Fat and Bone in Young Bulls. *Anim. Sci.* **1978**, *26*, 245–258. [CrossRef]
54. Basarab, J.A.; Price, M.A.; Aalhus, J.L.; Okine, E.K.; Snelling, W.M.; Lyle, K.L. Residual Feed Intake and Body Composition in Young Growing Cattle. *Can. J. Anim. Sci.* **2003**, *83*, 189–204. [CrossRef]
55. Chizzotti, M.L.; Valadares Filho, S.C.; Tedeschi, L.O.; Chizzotti, F.H.M.; Carstens, G.E. Energy and Protein Requirements for Growth and Maintenance of F1 Nellore × Red Angus Bulls, Steers, and Heifers1. *J. Anim. Sci.* **2007**, *85*, 1971–1981. [CrossRef]
56. de Castro Menezes, G.C.; de Campos Valadares Filho, S.; Ruas, J.R.M.; Detmann, E.; de Castro Menezes, A.; Zanett, D.; Mariz, L.D.S.; Rennó, L.N.; da Silva Junior, J.M. Meat Production in a Feedlot System of Zebu—Holstein Steers and Heifers with Dairy Genetics: Productive and Biological Analyses. *Sci. World J.* **2014**, *2014*, e371968. [CrossRef]
57. Kraybill, H.F.; Bitter, H.L.; Hankins, O.G. Body Composition of Cattle. II. Determination of Fat and Water Content from Measurement of Body Specific Gravity. *J. Appl. Physiol.* **1952**, *4*, 575–583. [CrossRef]
58. Birnie, J.W.; Agnew, R.E.; Gordon, F.J. The Influence of Body Condition on the Fasting Energy Metabolism of Nonpregnant, Nonlactating Dairy Cows. *J. Dairy Sci.* **2000**, *83*, 1217–1223. [CrossRef] [PubMed]
59. Koong, L.J.; Ferrell, C.L.; Nienaber, J.A. Assessment of Interrelationships among Levels of Intake and Production, Organ Size and Fasting Heat Production in Growing Animals. *J. Nutr.* **1985**, *115*, 1383–1390. [CrossRef] [PubMed]
60. Ferrell, C.L.; Koong, L.J.; Nienaber, J.A. Effect of Previous Nutrition on Body Composition and Maintenance Energy Costs of Growing Lambs. *Br. J. Nutr.* **1986**, *56*, 595–605. [CrossRef] [PubMed]
61. Ferrell, C.L. Contribution of Visceral Organs to Animal Energy Expenditure. *J. Anim. Sci.* **1988**, *66*, 23–34. [CrossRef]
62. Burrin, D.G.; Ferrell, C.L.; Britton, R.A.; Bauer, M.L. Level of Nutrition and Visceral Organ Size and Metabolic Activity in Sheep. *Br. J. Nutr.* **1990**, *64*, 439–448. [CrossRef]
63. Drouillard, J.S.; Klopfenstein, T.J.; Britton, R.A.; Bauer, M.L.; Gramlich, S.M.; Wester, T.J.; Ferrell, C.L. Growth, Body Composition, and Visceral Organ Mass and Metabolism in Lambs during and after Metabolizable Protein or Net Energy Restrictions. *J. Anim. Sci.* **1991**, *69*, 3357–3375. [CrossRef]
64. Jenkins, T.G.; Ferrell, C.L. Changes in Proportions of Empty Body Depots and Constituents for Nine Breeds of Cattle under Various Feed Availabilities. *J. Anim. Sci.* **1997**, *75*, 95–104. [CrossRef]
65. Hersom, M.J.; Krehbiel, C.R.; Horn, G.W. Effect of Live Weight Gain of Steers during Winter Grazing: II. Visceral Organ Mass, Cellularity, and Oxygen Consumption. *J. Anim. Sci.* **2004**, *82*, 184–197. [CrossRef]
66. McCurdy, M.P.; Krehbiel, C.R.; Horn, G.W.; Lancaster, P.A.; Wagner, J.J. Effects of Winter Growing Program on Visceral Organ Mass, Composition, and Oxygen Consumption of Beef Steers during Growing and Finishing. *J. Anim. Sci.* **2010**, *88*, 1554–1563. [CrossRef] [PubMed]
67. Sainz, R.D.; Bentley, B.E. Visceral Organ Mass and Cellularity in Growth-Restricted and Refed Beef Steers. *J. Anim. Sci.* **1997**, *75*, 1229–1236. [CrossRef] [PubMed]
68. Jenkins, T.G.; Ferrell, C.L. Productivity through Weaning of Nine Breeds of Cattle under Varying Feed Availabilities: I. Initial Evaluation. *J. Anim. Sci.* **1994**, *72*, 2787–2797. [CrossRef] [PubMed]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.