FULL-LENGTH ARTICLE

Effect of seaweed (*Ecklonia maxima*) on apparent nutrient digestibility, growth performance, and physiological and meat quality parameters in Boschveld cockerels

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ABSTRACT Despite being touted as a rich source of nutrients and functional bioactive compounds, the amount of brown seaweed (*Ecklonia maxima*) that can be included in diets of Boschveld indigenous chickens is unknown. This study, therefore, investigated the effect of feeding graded levels of brown seaweed meal (**BSM**) on apparent nutrient digestibility, growth performance, and physiological and meat quality parameters in Boschveld cockerels. A total of 225, five-wk-old Boschveld cockerels (316.4 ± 23.01 g live weight) were raised on 5 isoenergetic and isonitrogenous experimental diets formulated by incorporating BSM in a standard grower diet at a concentration of 0 (**BSM0**), 20 (**BSM2**), 40 (**BSM4**), 60 (**BSM6**), and 80 g/kg (**BSM8**). Feeding graded levels of dietary BSM induced neither quadratic nor linear effects ($P > 0.05$) on apparent nutrient digestibility, growth performance, hematological parameters, and meat quality characteristics in Boschveld cockerels. However, it resulted in linear increases for overall feed intake ($R^2 = 0.397$; $P = 0.021$), ceca weight ($R^2 = 0.417$; $P = 0.013$), duodenum length ($R^2 = 0.537$; $P = 0.04$), and small intestine length ($R^2 = 0.305$; $P = 0.041$). Negative quadratic responses were recorded for alanine aminotransferase ($R^2 = 0.530$; $P = 0.0009$) and ileum length ($R^2 = 0.457$; $P = 0.045$) as BSM levels increased. In conclusion, dietary inclusion of BSM improved feed intake and some internal organ sizes, altered alanine transaminase levels, but had no significant effect on apparent nutrient digestibility, growth performance, and carcass and meat quality attributes of Boschveld indigenous cockerels.

Key words: blood profile, brown seaweed, growth performance, indigenous chicken, meat quality

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INTRODUCTION

Poultry products (meat and eggs) are a major source of affordable animal protein in South Africa with an overall per capita consumption of 48.22 kg (SAPA, 2020). However, the poultry industry is under pressure to increase production to meet the high demand for animal protein in response to a rapidly growing human population (Nhlane et al., 2021). This suggests a need to develop strategies that will allow sustainable intensification of indigenous chickens (*Gallus gallus domesticus*) as a main source of animal protein for people in rural South Africa. Indigenous chicken farming plays significant socioeconomic and nutritional roles by providing income, employment, and essential macro- and micronutrients for many rural households (Magothe et al., 2012; Manyelo et al., 2020). These birds possess desirable traits such as disease resistance, thermo-tolerance, firm texture, succulent meat, high fertility and hatchability, and hard eggshells (Dessie, 2011; Atela et al., 2019). However, their large-scale intensification is currently restricted by high feeding costs due to their low growth rates and poor feed conversion ratios (Larbi et al., 2013; Hussain et al., 2018). From a nutritional point of view, the use of functional feed ingredients such as seaweeds can improve indigenous chicken production and thus allow for their sustainable intensification. This is because the production of seaweed, also known as marine macro-algae, does not require land, fresh water, fertilizers, pesticides, or machinery. Moreover, seaweeds can be considered as environmentally friendly ingredients whose bioactive compounds and nutrients have growth boosting, health promoting, gut modulating, and meat enhancing properties (Michalak et al., 2022). Indeed, Nhlane et al. (2020) reported that seaweeds

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contain nutraceuticals that can provide subtherapeutic and nutritional benefits when included in poultry diets.

Seaweeds also contain bioactive compounds such as polyphenols, chlorophyll, carotenoids, fucoidan, phlorotannins, and carrageenan, to mention a few, that can mitigate against stressors imposed by large-scale intensification (Michalak et al., 2022). Michalak and Mahrose (2020) stated that the inclusion of seaweeds in poultry diets can improve poultry performance and health while enriching poultry products with active compounds. Furthermore, seaweeds are rich sources of minerals that can be used to aid in bone mineralization, improve eggshell quality, enrich egg mineral content, and prevent elemental deficiencies in poultry (Michalak et al., 2010). Other scholars have reported that seaweeds contain polyunsaturated fatty acids that can enhance the n-3 fatty acid content of poultry products (González-Esquerra and Leeson, 2001). In addition, seaweed bioactive compounds have antioxidant, antimicrobial, anti-inflammatory, antitumoral, antiallergic, antithrombotic, hypoglycemic, hypocholesterolemic, and neuroprotective properties that could enhance the performance of indigenous chickens and ensure that these birds continue to contribute to household food and nutrition security (Michalak and Mahrose, 2020; Nhlane et al., 2021).

Despite their desirable nutraceutical properties, large amounts of seaweeds are frequently washed into beach inshore areas, causing anaerobic degradation and the release of non-volatile and volatile compounds (Resiere et al., 2020). Ammonia and hydrogen sulphide are some of the toxic gases released by seaweed heaps that have detrimental effects on animal, human and environmental health (Resiere et al., 2020). Thus, the inclusion of seaweeds in indigenous chicken diets would help protect the environment and allow for sustainable intensification of the birds. However, no studies have evaluated the effect of feeding brown seaweed (*Ecklonia maxima*) meal in Boschveld indigenous cockerels, hence the amount that can be safely included in their diets is unknown. This study, therefore, evaluated the effect of feeding graded levels of brown seaweed meal (**BSM**) on apparent nutrient digestibility, growth performance, blood indices, visceral organ sizes, carcass characteristics, and meat quality traits of Boschveld cockerels. The study tested the hypothesis that the inclusion of BSM will improve nutrient digestibility, and physiological and meat quality parameters in Boschveld cockerels.

MATERIALS AND METHODS

Animal Ethics Statement

The feeding, handling, and slaughtering procedures employed in this study were approved (NWU-00809-21-A5) by the Research Ethics Committee for Animal Production studies at the North-West University, South Africa.

Harvesting Site and Analyses

The brown seaweed (*Ecklonia maxima*) was hand-picked on the Sunset beach, along the Sea Point Promenade (33° 54′55″ S, 18°23′33″ E) in Cape Town (Western Cape, South Africa). It was collected following a day of a high tide accompanied by rough waves that move the seaweed to the beach shorelines. The seaweed was then washed with tap water to remove the excess salt from the ocean before being sun-dried in an oyster net until constant weight. The seaweed was then milled (2-mm; Retsch Cutting Mill BSM 100, Retsch, Germany) to produce the meal (BSM), which was used for proximate analysis. Triplicate samples of BSM were used to determine DM, ash, organic matter (**OM**) and CP following the Association of Official Analytical Chemist methods (AOAC, 2005). The Waters Acquity Ultra Performance Liquid Chromatograph equipped with a photodiode array detector (UPLC-PDA) was used for the determination of amino acids. The neutral detergent fiber (**NDF**) and acid detergent fiber (**ADF**) were analyzed using the ANKOM^{2000} Fiber analyzer (ANKOM Technology, New York, NY) following the detergent methods by van Soest et al. (1991). A heat-stable amylase was used to analyze the NDF, and the results were expressed inclusive of residual ash. The cellulose in the ADF residue bags was dissolved for 3 h in 72% H_2SO_4 to determine the acid detergent lignin (**ADL**). The guidelines by the Agri-Laboratory Association of Southern Africa were used to determine the mineral content of BSM (AgriLASA, 1998). Metabolizable energy (**ME**) of the BSM was calculated using the formula $[ME\ (kcal/kg) = (35.3 \times CP\ \%) + (79.5 \times EE\ \%) + (40.6 \times NFE\ \%) + 199.0]$ by Carpenter and Clegg (1956).

Formulation of Experimental Diets

Five dietary treatments (in mash form) were formulated using a nutritional software (Format) as follows: 1) BSM0 = a standard grower diet without brown seaweed meal; BSM2 = a standard grower diet containing 20 g/kg brown seaweed meal; BSM4 = a standard grower diet containing 40 g/kg brown seaweed meal; BSM6 = a standard grower diet containing 60 g/kg brown seaweed meal; BSM8 = a standard grower diet containing 80 g/kg brown seaweed meal, as shown in Table 1. The diets were formulated to have the same levels of protein and energy. The nutritional composition of the diets was determined as described for the BSM samples.

Growth Trial and Bird Management

The feeding trial was performed in summer (December 2021−February 2022) at the North-West University Experimental Farm (25°86′00″ S, 25°64′52″ E) in South Africa. The ambient temperatures ranged between 17°C and 35°C. A total of 225, 4-wk-old Boschveld cockerels were bought from Boschveld Ranching (PTY) LTD located in Bela-Bela (Limpopo, South Africa). In a completely randomized design, the cockerels were weighed and randomly assigned to the 5 experimental

Table 1. Gross ingredient and nutritional composition (g/kg, as-fed basis) of the experimental diets.

[1]Experimental diets	BSM	BSM0	BSM2	BSM4	BSM6	BSM8
Brown seaweed meal		0	20	40	60	80
Maize yellow		556.4	531.1	505.8	477.2	455.5
Soybean meal (44%)		360.6	361.9	363.3	365.3	366.0
Palm oil		48.10	54.20	60.30	67.50	68.60
Dicalcium phosphate		14.70	14.50	14.40	14.30	14.20
Common salt		4.60	2.60	0.50	0.00	0.00
Limestone		11.10	11.20	11.20	11.20	11.20
DL-methionine		2.00	2.00	2.00	2.00	2.00
[2]Premix		2.00	2.00	2.00	2.00	2.00
Choline Cl70		0.50	0.50	0.50	0.50	0.50
Nutritional composition (g/kg DM, unless stated otherwise)						
Crude protein	101.3	205.1	205.0	205.1	205.1	205.2
Calculated ME (MJ/kg)	7.40	12.98	12.98	12.98	12.98	12.98
DM (g/kg)	871.0	918.5	907.6	909.3	901.4	905.3
Ash	262.3	570.0	548.0	589.0	637.0	674.0
Organic matter	608.7	861.3	852.8	850.4	837.7	839.2
Lysine (%)	1.01	1.21	1.22	1.22	1.23	1.23
Methionine (%)	0.36	0.54	0.54	0.54	0.55	0.55
Crude fat	370.2	657.5	619.5	886.9	838.1	894.6
Phosphorus	0.45	4.5	4.5	4.5	4.5	4.5
Neutral detergent fibre	486.8	142.1	191.6	192.3	193.4	206.6
Acid detergent fibre	226.6	131.7	141.6	149.5	152.1	158.1
Acid detergent lignin	40.65	23.49	32.76	33.00	34.98	37.44

[1]Experimental diets: BSM = brown seaweed meal; BSM0 = a standard grower diet without brown seaweed meal; BSM2 = a standard grower diet containing 20 g/kg brown seaweed meal; BSM4 = a standard grower diet containing 40 g/kg brown seaweed meal; BSM6 = a standard grower diet containing 60 g/kg brown seaweed meal; BSM8 = a standard grower diet containing 80 g/kg brown seaweed meal.

[2]Premix contains: copper sulphate 8.0 mg; zinc sulphate 79 mg; ferrous sulphate 80 mg; niacin 30 mg; magnesium sulphate 100 mg; vitamin A 11,000 IU; potassium iodide 0.34 mg; pantothenic acid 10 mg; folic acid 0.7 mg; biotin 0.12 g; vitamin B6 5.1 mg; vitamin B1 2.5 mg; vitamin B2 4.5 mg; vitamin D3 2,500 IU; vitamin E 25 IU; vitamin K3 2.0 mg; and sodium selenite, 0.25 mg.

diets, which were replicated 5 times per dietary treatment. Each replicate pen (experimental unit), measuring 3.5 m Length × 1.0 m Width × 1.85 m Height, carried 9 birds. The pens were constructed using steel wire mesh and removable polythene plastics were used to cover the floors. The birds were accustomed to the dietary treatments for 7 d before the commencement of the feeding trial at wk 5 of age. A stress-control pack (Phenix stress-pac, Virbac) containing vitamins and electrolytes was mixed into drinking water and offered to the birds for the first three days of the adaptation period. The diets and fresh clean water were offered to the birds using poultry tube feeders and drinkers, respectively, without any restrictions. Ventilation was achieved by opening the house curtains in the morning and closing them in the evenings. The average house temperature (32°C) and humidity (60%) were monitored using a Thermo-Hygrometer (IN-OUT, Alla France Automatic Control Equipment Co., Ltd, PRC). The rearing of the birds was carried out under natural lighting from the morning until the evening (12 h of daylight). No mortalities were recorded during the 11-wk feeding trial.

Growth Performance Measurements

The initial body weights (316.4 ± 23.01 g) of the birds were measured at 5 wk of age and thereafter weighed on weekly intervals to determine average weekly body weight gain (**ABWG**). Daily feed intake was measured by calculating the difference between the feed offered and feed refused. The daily feed intake data was computed to determine the average weekly feed intake (**AWFI**). The data for weekly feed intake and weight gain were then used to calculate feed conversion ratio (**FCR**).

Blood Collection and Analysis

Fresh blood samples (4 mL) were collected in the morning a day before slaughter from 2 randomly selected birds per pen. The blood was collected by puncturing the brachial vein using sterilized 5 mL syringes and 23-gauge needles. The blood samples were stored using whole blood (with an anticoagulant) and serum (without an anti-coagulant) tubes. The whole blood tubes were stored in a cooler and the blood was analyzed within 48 h of collection (Washington and van Hoosier, 2012). Hematological indices (monocytes, hematocrits, lymphocytes, white cell counts (**WCC**), heterophils, and platelets) were analyzed using an automated IDEXX LaserCyte Haematology Analyser (model no. 93−30001−01, IDEXX Laboratories (Pty) Ltd., Gauteng, South Africa). The collected blood in serum tubes was centrifuged at 4,000 rpm for 5 min (Cryste Varispin 4 Multipurpose centrifuge, Cryste CO. LTD, Korea) to generate sera (Washington and van Hoosier, 2012). Serum biochemical indices (glucose, total protein, phosphorus, albumin, symmetric dimethyl arginine (**SDMA**), urea, total bilirubin, calcium, globulin alanine aminotransferase (**ALT**), lipase, albumin/globulin ratio, alkaline phosphatase (**ALKP**), amylase, and cholesterol) were analyzed using an automated IDEXX Catalyst One Chemistry Analyzer (model no. 89−92525−00, IDEXX Laboratories (Pty) Ltd., Gauteng, South Africa).

Nutrient Digestibility Trial

At 16 wk of age, 2 birds per pen (making a total of 50), were randomly selected from the growth trial and housed in metabolic cages (0.51 m L × 0.49 m B × 0.36 m H) for measurements of apparent nutrient digestibility. The cockerels were offered the same experimental diets as in the growth trial and were allowed a 3-d adaptation period before a 5-d collection period. Feed refusals were collected daily and used to determine nutrient intake, whereas the excreta were collected, weighed, and stored pending analysis. The samples were then analyzed as described for the BSM above and the values were used to calculate the apparent digestibility of DM, OM, CP, NDF, and ADF as described by Nhlane et al. (2020), using the following formula:

$$Apparent\ nutrient\ digestibility\ (\%) = \frac{nutrient\ intake - nutrient\ excreta}{nutrient\ intake} \times 100$$

Slaughter, Carcass Traits and Internal Organs

At 16 wk of age, all the cockerels were weighed to determine slaughter weight but only 175 birds (excluding those in the digestibility trial) were transported by road to a local abattoir. After a resting period of 1 to 2 h at the abattoir, the birds were electrically stunned and slaughtered by cutting the jugular vein with a sharp knife. The carcasses were then eviscerated by hand and immediately weighed using a digital scale (Model 330 Weighing, Richter Scale (Pty) Ltd., Gauteng, South Africa) to determine hot carcass weight (**HCW**). The carcasses were reweighed after 24 h of chilling at 16°C to obtain cold carcass weight (**CCW**). The dressing percentage was calculated as the proportion of HCW to slaughter weight. The weights of carcass cuts (breast, drumstick, thigh, and wing) were measured using the weighing scale described above. The weights of the visceral organs (liver, proventriculus, cleaned gizzard, gizzard fat, spleen, duodenum, jejunum, ileum, small intestines, caecum, colon, and large intestines) were determined using the digital weighing scale (Explorer EX224, OHAUS Corp, NJ). A tape measure (cm) was used to determine intestinal lengths.

Meat Quality Measurements

A digital meter equipped with a spear-piercing electrode (HI98163 Professional Portable pH Meter, Hanna instruments (Pty) Ltd, JHB, South Africa) was used to measure breast meat pH at 1 h and 24 h post-slaughter. Standard solutions (pH 4, 7 and 10) were used to calibrate the meter for each replicate pen. Breast meat color coordinates: lightness (L^*), redness (a^*) and yellowness (b^*) were examined at 1 and 24 h postmortem using a color spectrophotometer (Konica Minolta Chroma Meter CR-400, Narich (Pty) Ltd, Japan) with a 20 mm diameter measurement area, an illuminant D65-daylight, and a 10° observation angle (CIE, 1976). Chroma and hue angle values were computed using the a^* and b^* coordinates (Priolo et al., 2002). Breast meat was used to determine the water-holding capacity (WHC) using the filter-paper method (Honikel, 1987), whereby pressure (60 kg) was applied for 5 minutes on the samples (8 g) held in-between 2 filter papers. Drip loss was measured using the method by Honikel (1998), whereby breast meat samples (~2 g; wet weight, w1) are hooked and suspended using wire steel and placed in a cold room (4°C) for 72 h. Breast meat cooking losses were assessed after the samples were cooked to a core temperature of 75°C (Honikel, 1998).

Data Analysis

Repeated measures analysis option in the general linear model (**GLM**) procedure of SAS (2010) was used to determine the interaction effect between time and diet on average weekly FI, BWG, and FCR data. Overall FI, BWG, and FCR data were reported because no significant diet × time (cockerel age) interaction effects were observed. Polynomial contrasts were used to evaluate apparent nutrient digestibility, overall growth performance, and physiological and meat quality parameters data for linear and quadratic effects. Response surface regression analysis procedure in SAS (2010) was employed to determine the optimum dietary inclusion level of BSM, according to the following nonlinear model: $y = ax^2 + bx + c$, where y is the dependent variable; a and b are the coefficients of the model; c is the intercept; x is dietary BSM inclusion level (g/kg); and $-b/2a$ is the x value for optimal response. For all the statistical tests, significance was considered at $P < 0.05$.

RESULTS

Nutrient Digestibility and Performance

Feeding graded levels of dietary BSM had no linear or quadratic effects ($P > 0.05$) on DM, OM, CP, NDF, and ADF digestibility (Table 2).

Repeated measures analysis revealed no diet × week (bird age) interaction effects on ABWG ($P = 0.995$), FI ($P = 0.765$), and FCR ($P = 0.998$). Neither linear nor

Table 2. Apparent nutrient digestibility (g/kg DM, unless stated otherwise) in Boschveld cockerels ($n = 50$) fed with diets containing graded levels of brown seaweed meal.

	[1]Experimental diets						Significance	
[2]Parameters	BSM0	BSM2	BSM4	BSM6	BSM8	SEM	Linear	Quadratic
DM	632.9	588.8	602.3	618.6	543.4	44.12	0.883	0.673
OM	631.3	625.6	641.4	630.0	589.4	37.64	0.913	0.640
CP	307.4	281.0	174.4	308.2	277.1	79.20	0.667	0.910
NDF	397.3	359.9	351.5	446.7	366.0	68.54	0.611	0.414
ADF	235.8	299.5	294.2	358.3	226.4	90.46	0.941	0.738

[1]Experimental diets: BSM0 = a standard grower diet without brown seaweed meal; BSM2 = a standard grower diet containing 20 g/kg brown seaweed meal; BSM4 = a standard grower diet containing 40 g/kg brown seaweed meal; BSM6 = a standard grower diet containing 60 g/kg brown seaweed meal; BSM8 = a standard grower diet containing 80 g/kg brown seaweed meal.

[2]Parameters: DM, dry matter; OM, organic matter; NDF, neutral detergent fibre; ADF, acid detergent fibre; ADL, acid detergent lignin.

Table 3. Overall feed intake (g/bird), overall body weight gain (g/bird) and overall feed conversion ratio in Boschveld cockerels ($n = 225$) fed with diets containing graded levels of brown seaweed meal.

	[1]Experimental diets						Significance	
	BSM0	BSM2	BSM4	BSM6	BSM8	SEM	Linear	Quadratic
Overall FI	5,993.2	6,022.1	6,236.3	6,514.4	6,684.9	162.3	0.001	0.367
Overall BWG	1,827.6	1,814.0	1,889.7	1,888.7	1,840.1	45.73	0.490	0.392
Overall FCR	3.28	3.35	3.30	3.46	3.62	0.096	0.147	0.206

Abbreviations: BWG, body weight gain; FCR, feed conversion ratio; FI, feed intake.
[1]Experimental diets: BSM0 = a standard grower diet without brown seaweed meal; BSM2 = a standard grower diet containing 20 g/kg brown seaweed meal; BSM4 = a standard grower diet containing 40 g/kg brown seaweed meal; BSM6 = a standard grower diet containing 60 g/kg brown seaweed meal; BSM8 = a standard diet containing 80 g/kg brown seaweed meal.

quadratic effects ($P > 0.05$) were observed for overall BWG and FCR, except for overall FI which linearly increased [$y = 44.21\ (\pm 88.02)\ x + 5964.6\ (\pm 148.6)$; $R^2 = 0.397$; $P = 0.021$] with increasing BSM levels (Table 3).

Hematobiochemical Parameters

Feeding graded levels of dietary BSM induced neither linear nor quadratic effects ($P > 0.5$) for hematological and serum biochemical parameters, except for alanine aminotransferase (**ALT**) (Table 4). A negative quadratic response was observed for ALT [$y = 1.48\ (\pm 0.361)\ x^2 - 12.94\ (\pm 3.221)\ x + 54.91\ (\pm 6.361)$; $R^2 = 0.530$; $P = 0.0009$] from which an optimum of 44 g/kg of BSM inclusion level was calculated.

Internal Organs, and Carcass and Meat Quality Parameters

Table 5 shows that feeding different levels of dietary BSM linearly increased ceca weight [$y = 0.019\ (\pm 0.030)\ x + 0.858\ (\pm 0.045)$; $R^2 = 0.417$; $P = 0.013$], duodenum length [$y = 0.016\ (\pm 0.361)\ x + 28.75\ (\pm 0.550)$; $R^2 = 0.537$; $P = 0.04$] and small intestines length [$y = 1.237\ (\pm 3.005)\ x + 148.9\ (\pm 4.456)$; $R^2 = 0.305$; $P = 0.041$]. Ileum length showed a negative quadratic response [$y = 0.238\ (\pm 0.106)\ x^2 - 1.141\ (\pm 0.887)\ x + 62.66\ (\pm 1.315)$; $R^2 = 0.457$; $P = 0.0450$] to the increasing BSM inclusion levels.

Neither linear nor quadratic effects ($P > 0.05$) were recorded for all the breast meat quality parameters as dietary BSM levels increased (Table 6).

Table 4. Hematological and serum biochemical parameters of 16-wk-old Boschveld cockerels ($n = 50$) fed with diets containing graded levels of brown seaweed meal.

	[1]Experimental diets						Significance	
[2]Parameters	BSM0	BSM2	BSM4	BSM6	BSM8	SEM	Linear	Quadratic
Hematocrit (%)	36.30	34.60	35.30	35.90	35.00	1.04	0.997	0.630
WCC ($\times 10^9$/L)	16.99	18.31	16.49	15.05	16.85	2.07	0.294	0.319
Platelets ($\times 10^9$/L)	46.30	41.90	42.20	45.10	49.70	4.42	0.208	0.301
Heterophils ($\times 10^9$/L)	9.77	11.06	10.27	8.38	9.79	1.04	0.274	0.670
Lymphocytes (%)	26.70	23.90	25.00	25.50	24.60	2.96	0.666	0.495
Monocytes (%)	14.50	13.40	14.00	18.20	15.90	1.86	0.163	0.600
Calcium (mmol/L)	2.68	2.63	2.31	1.83	2.55	0.194	0.555	0.162
Glucose (mmol/L)	3.65	4.66	4.24	4.36	3.96	0.752	0.805	0.958
Phosphorus (mmol/L)	3.25	3.95	3.45	2.92	3.11	0.393	0.250	0.910
SDMA (μg/dL)	41.50	26.88	37.90	35.40	30.30	7.734	0.828	0.628
Urea (mmol/L)	0.760	0.840	0.700	0.840	0.750	0.075	0.348	0.259
Total protein (g/L)	32.25	30.13	37.50	35.30	32.80	6.93	0.986	0.256
Albumin (g/L)	17.60	16.90	16.90	17.60	17.90	0.822	0.684	0.528
Globulin (g/L)	19.00	21.00	22.20	23.63	20.30	3.90	0.804	0.371
Albumin/globulin ratio	0.525	2.50	0.610	1.63	0.440	0.904	0.498	0.577
ALT (U/L)	43.30	41.50	26.20	28.50	41.00	6.16	0.772	0.000
ALKP (U/L)	150.9	258.0	153.1	202.6	167.3	29.18	0.360	0.508
Bilirubin (umol/L)	5.10	3.90	4.20	5.40	5.40	0.988	0.683	0.763
Cholesterol (mmol/L)	2.39	2.34	2.52	2.21	2.53	0.337	0.551	0.776
Amylase (U/L)	248.4	267.2	250.3	281.7	270.1	48.73	0.991	0.931
Lipase (U/L)	135.0	162.9	143.1	108.4	138.6	23.09	0.583	0.949

[1]Experimental diets: BSM0 = a standard grower diet without brown seaweed meal; BSM2 = standard grower diet containing 20 g/kg brown seaweed meal; BSM4 = a standard grower diet containing 40 g/kg brown seaweed meal; BSM6 = a standard grower diet containing 60 g/kg brown seaweed meal; BSM8 = a standard grower diet containing 80 g/kg brown seaweed meal.
[2]Parameters: WCC, white cell count; SDMA, symmetric dimethylarginine; ALT, alanine aminotransferase; ALKP, alkaline phosphatase; ALB/GLOB, albumin/globulin ratio.

Table 5. Carcass characteristics and visceral organs (% CCW, unless stated otherwise) of 16-wk-old Boschveld cockerels ($n = 175$) fed with diets containing graded levels of brown seaweed meal.

	[1]Experimental diets						Significance	
[2]Parameters	BSM0	BSM2	BSM4	BSM6	BSM8	SEM	Linear	Quadratic
Slaughter weight (g)	1,780.3	1,753.6	1,848.6	1,830.9	1,846.4	43.53	0.097	0.987
HCW (g)	1,204.6	1,183.5	1,267.6	1,281.5	1,252.2	41.10	0.196	0.939
CCW (g)	1,149.2	1,150.7	1,244.2	1,252.4	1,222.7	38.92	0.390	0.560
Dressing (%)	67.70	67.33	68.54	69.98	67.82	1.24	0.920	0.905
Breast	10.28	10.40	10.20	9.991	10.30	0.402	0.857	0.661
Drumstick	8.06	7.79	7.95	7.81	7.87	0.202	0.316	0.432
Thigh	8.04	7.46	7.61	7.08	7.48	0.231	0.162	0.392
Wing	6.52	6.45	6.34	6.33	6.40	0.150	0.651	0.802
Liver	2.77	2.73	2.73	2.53	2.83	0.098	0.656	0.271
Gizzard	2.54	2.57	2.55	2.53	2.72	0.084	0.073	0.173
Gizzard fats	0.816	0.669	0.675	0.785	0.696	0.150	0.940	0.874
Proventriculus	0.614	0.609	0.530	0.588	0.605	0.020	0.719	0.119
Spleen	0.309	0.284	0.311	0.293	0.317	0.021	0.455	0.736
Duodenum	1.39	1.43	1.32	1.35	1.45	0.056	0.142	0.119
Jejunum	2.22	2.26	2.35	2.13	2.07	0.190	0.844	0.653
Ileum	1.63	1.42	1.38	1.54	1.84	0.108	0.063	0.077
Caecum	0.83	0.89	0.94	0.96	1.08	0.041	0.013	0.903
Small intestines	5.28	5.15	5.09	5.06	5.40	0.252	0.238	0.128
Large intestines	0.216	0.233	0.293	0.190	0.229	0.031	0.829	0.214
Duodenum (cm)	28.90	29.86	30.64	30.02	31.03	0.608	0.004	0.383
Jejunum (cm)	62.20	63.65	74.10	69.20	62.51	4.06	0.302	0.445
Ileum (cm)	61.18	57.26	59.67	61.51	64.22	2.11	0.044	0.045
Caecum (cm)	18.78	17.78	19.83	18.75	19.18	0.522	0.674	0.813
Small intestines (cm)	151.1	149.9	163.3	160.7	157.8	4.35	0.041	0.864
Large intestines (cm)	5.70	5.18	7.52	5.70	6.01	0.760	0.700	0.296

[1]Experimental diets: BSM0 = a standard grower diet without seaweed meal; BSM2 = a standard grower diet containing 20 g/kg seaweed meal; BSM4 = a standard grower diet containing 40 g/kg seaweed meal; BSM6 = a standard grower diet containing 60 g/kg seaweed meal; BSM8 = a standard grower diet containing 80 g/kg seaweed meal.
[2]Parameters: HCW, hot carcass weight; CCW, cold carcass weight.

DISCUSSION

Apparent Nutrient Digestibility

Nutrient digestibility refers to the extent to which dietary nutrients are absorbed and assimilated as they pass through the bird's gastrointestinal tract (Nhlane et al., 2020). The inclusion of dietary BSM had no effect on the digestibility of dry matter, crude protein, organic matter, and fiber. An increase in nutrient digestibility was expected because the BSM contains bioactive compounds with growth-stimulating and antimicrobial properties that aid feed utilization (Schiener et al., 2015). Nonetheless, these results corroborate the findings of Nhlane et al. (2020), who reported that the incorporation of green seaweed (*Ulva* spp.) meal between 20 and 35 g/kg in Boschveld hen diets, did not alter apparent nutrient digestibility. However, Balasubramanian et al. (2021) reported an improvement in DM digestibility of broilers fed with diets containing (0, 0.5, 0.1, 1.5, and 2.5 g/kg) red seaweed (*Halymenia palmata*). These

Table 6. Breast meat quality parameters of 16-wk-old Boschveld cockerels ($n = 175$) fed with diets containing graded levels of brown seaweed meal.

	[1]Experimental diets						Significance	
[2]Parameters	BSM0	BSM2	BSM4	BSM6	BSM8	SEM	Linear	Quadratic
pH_1	5.85	5.90	5.892	5.942	6.00	0.037	0.051	0.849
L^*_1	61.02	59.25	62.23	62.66	61.71	1.24	0.335	0.989
a^*_1	0.711	1.10	0.86	0.692	0.740	0.162	0.640	0.250
b^*_1	1.921	2.60	2.240	2.08	2.69	0.403	0.526	0.861
$Chroma_1$	2.08	2.83	2.419	2.300	2.79	0.389	0.561	0.966
Hue $angle_1$	1.18	1.16	1.19	1.19	1.30	0.087	0.429	0.352
pH_{24}	6.05	6.02	6.00	6.06	6.06	0.061	0.189	0.975
L^*_{24}	57.63	61.44	63.05	59.39	62.16	2.15	0.291	0.339
a^*_{24}	0.596	0.922	0.828	0.687	0.941	0.152	0.431	0.813
b^*_{24}	2.05	1.69	2.28	1.50	2.49	0.402	0.736	0.301
$Chroma_{24}$	2.16	1.94	2.46	1.67	2.67	0.405	0.707	0.364
Hue $angle_{24}$	1.22	1.07	1.18	1.09	1.23	0.075	0.956	0.183
WHC (%)	88.60	86.68	89.37	85.80	87.09	1.19	0.623	0.348
Drip loss (%)	4.98	5.41	5.42	6.46	6.41	0.68	0.242	0.623
Cooking loss (%)	28.98	29.49	27.92	30.24	29.94	1.542	0.602	0.884

[1]Experimental diets: BSM0 = a standard grower diet without brown seaweed meal; BSM2 = a standard grower diet containing 20 g/kg brown seaweed meal; BSM4 = a standard grower diet containing 40 g/kg brown seaweed meal; BSM6 = a standard grower diet containing 60 g/kg brown seaweed meal; BSM8 = a standard grower diet containing 80 g/kg brown seaweed meal.
[2]Parameters: L^*, lightness; a^*, redness; b^*, yellowness; WHC, water holding capacity.

contradictory findings could be attributed to the use of different seaweed species. Indeed, Ortiz et al. (2006) and Schiener et al. (2015) reported that seaweeds have a different chemical composition, which is due to different harvesting stages, water temperatures, growing sites, and environmental conditions. Future research should, therefore, investigate the use of seaweed extracts to improve nutrient digestibility in Boschveld chickens.

Growth Performance and Blood Parameters

Repeated measures analysis showed no significant interaction effects between diet and week (cockerel age) on average weekly FI, BWG, and FCR, which demonstrates that the relative dietary effect was independent of the cockerels' age. In this study, a linear increase was observed for overall FI as dietary BSM levels were increased. Similarly, Nhlane et al. (2020) observed an increase in feed intake of Boschveld hens fed with diets containing up to 35 g/kg of green seaweed meal. The authors attributed these findings to the extra dietary fiber in the seaweed-containing diets, which could have reduced blood sugar levels and thus causing the birds to consume more feed. Further, the presence of other secondary metabolites in BSM like phlorotannins could have resulted in compensatory feed intake. The current findings corroborated those of Cañedo-Castro et al. (2019), who found that the addition of green seaweed (*Ulva rigida*) at different levels (40 and 60 g/kg) in Arbor Acres broiler diets increased the feed intake of the birds.

Despite their much-touted bioactive substances that are reported to have growth-stimulating activities, the inclusion of BSM up to 80 g/kg did not have any significant effect on overall BWG and FCR of the Boschveld cockerels. The lack of dietary effects on these parameters suggests, therefore, a need to investigate inclusion levels higher than 80 g/kg to generate quadratic responses that would allow the determination of an optimum inclusion level. Contrary to the current findings, Matshogo et al. (2020) reported that inclusion levels of dietary green seaweed meal between 20 and 35 g/kg compromise feed conversion efficiency in Cobb 500 broilers. However, the results agree with the findings of other researchers (El-Deek and Brikaa, 2009; Abudabos et al., 2013; Karu et al., 2018), who found that the inclusion of seaweeds in poultry diets had no influence on growth performance parameters. These contradictory findings suggest a need for more research studies to fully understand seaweed utilization in poultry and, as a result, close the existing gaps in literature.

Blood parameters are the most efficient and reliable indicators for examining the birds' health and pathophysiological status (Minias, 2015; Onasanya et al., 2015). Doyle (2006) stated that blood analysis allows for the clinical investigation of various metabolites present in animal bodies, and can be used to measure the nutritional, pathological and physiological statuses (Etim et al., 2014; Onasanya et al., 2015). Feeding graded levels of dietary BSM had no influence on the measured hematological values. These findings support those of Lokaewmanee et al. (2012) and Matshogo et al. (2020), who reported that the use of dietary seaweeds in broiler diets does not affect the birds' health status. The recorded hematological values were within the normal ranges reported for healthy chickens (Nhlane et al., 2020; Matshogo et al., 2021). The enzymes, alanine transaminase (ALT) and aspartate aminotransferase (**AST**), are standard biomarkers for diagnosing hepatocellular injury. In cases where there is hepatocellular damage, the ALT and AST enzymes, which are present in the cytoplasm of hepatocytes, are released into the bloodstream (Schomaker et al., 2020). According to Bona et al. (2018), high concentrations of ALT and AST in the blood indicate hepatocellular disease. Thus, the quadratic effect observed for ALT in response to dietary BSM indicates the potential of moderate seaweed levels to protect the birds from liver injuries. However, levels beyond 44 g/kg of dietary BSM could compromise the hepatocellular membrane integrity of the birds.

Carcass Characteristics, Internal Organs, and Meat Quality

Including BSM in the diets of Boschveld cockerels did not induce any changes on the carcass characteristics of the birds. The current results were consistent with those of Cañedo-Castro et al. (2019), who reported no dietary influences on dressing percentage and carcass weights of Arbor Acres broilers reared on diets containing various levels (20, 40, and 60 g/kg) of green seaweed (*Ulva rigida*). However, Abudabos et al. (2013) reported that the incorporation of green seaweed (*Ulva lactuca*) up to 30 g/kg enhanced dressing percentage and breast yield of broiler chickens. Moreover,Qadri (2019) observed that including up to 15 g/kg of red algae (*Kappaphycus alvarezi*) in broiler chicken diets enhanced dressing percentage as well as liver, heart, and gizzard weights of the birds. Kulshreshtha et al. (2020) reported that the inconsistencies in seaweed feeding trials could be attributed to seaweed dietary levels, seaweed purity, particle size, drying methods and processing, and species differences. The caecum weights of the birds were increased by the increase in dietary BSM levels. These findings supported the observation of Kulshreshtha et al. (2014) and Nhlane et al. (2021), who reported an increase in cecum weights when red and green seaweed were supplemented into laying hens and indigenous chicken diets. The increase in caecum weights was expected because high dietary fiber levels cause intestinal enlargements as an adaptive mechanism by the birds to utilize extra dietary fiber (Sarbaz et al., 2018). Indeed, positive quadratic responses were observed for cecum weights as well as the lengths of small intestines as BSM levels increased. However, the weights of the gizzard, gizzard fats, liver, spleen, duodenum, and jejunum were not affected, suggesting that brown seaweed has low antinutrients that can compromise the GIT and internal organs of the birds (Matshogo et al., 2020).

The appearance, odor, color, texture, tenderness, flavor, juiciness, and water-holding capacity are a set of sensory properties that are used to define meat quality (Purslow, 2017). These properties are used to assess the biological, chemical, and physical characteristics of meat (Van Laack et al., 2000). Feeding graded levels of dietary BSM did not induce any influences on meat quality parameters, which indicates that the inclusion of dietary BSM does not compromise product quality. The current findings were consistent with those of Nhlane et al. (2020), who recorded no dietary influences on breast meat pH and color in Boschveld hens reared on seaweed-containing diets. Nonetheless, the meat pH (5.9−6.1) reported in the current study was within the normal meat pH range (5.7−6.1) reported by Zhang and Barbut (2005) for poultry meat. Further, there were no dietary effects observed on WHC, cooking loss and drip loss, which suggests that the addition of brown seaweed does not interfere with normal oxidative stability levels of the meat. According to Wang et al. (2017) and Chen et al. (2018), oxidative stress is a biological phenomenon that adversely affects meat quality by speeding up the rate at which meat pH declines, and consequently reduces the WHC of the meat. Moreover, Bowker and Zhuang (2015) reported that postmortem metabolism causes a drop in muscle pH, which, ultimately, lowers the net charges of the muscle proteins resulting in the denaturation of sarcoplasmic proteins and thus poor meat WHC. Similar to the current findings, Matshogo et al. (2020) reported that seaweed supplementation does not alter the WHC, cooking loss, and drip loss of broiler meat. The lack of dietary differences on these parameters could be explained by the similar pH values across the treatment groups since there is a significant correlation between muscle pH and these quality parameters (Fletcher, 2002). The presence of biocompounds such as polyphenols, antioxidants, protein, minerals, and vitamins in BSM (Rajauria et al., 2017), was anticipated to positively influence the overall quality of the meat. This further suggests a need for future studies to investigate the physicochemical characteristics of chicken reared on seaweed-containing diets.

CONCLUSIONS

Dietary inclusion of brown seaweed meal improved feed intake and some internal organ sizes, and altered alanine transaminase levels, but had no effect on apparent nutrient digestibility, growth performance, and meat quality attributes of Boschveld indigenous cockerels. The inability to generate an optimum inclusion level on the growth performance data suggests a need for further research with inclusion levels higher than 80 g/kg.

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DISCLOSURES

The authors declare that there are no conflicts of interest.

REFERENCES

Abudabos, A. M., A. B. Okab, R. Aljumaah, E. Samara, K. A. Abdoun, and A. A. Al-Haidary. 2013. Nutritional value of green seaweed (*Ulva lactuca*) for broiler chickens. Ital. J. Anim. Sci. 2:28.

AgriLASA. 1998. Feed and Plant. Analysis Methods. Agri Laboratory Association of Southern Africa, Pretoria, South Africa.

AOAC. 2005. Official Methods of Analysis of Association of Official Analytical Chemists International. 16th ed. AOAC, Arlington, VA.

Atela, J., V. Mlambo, and C. M. Mnisi. 2019. A multi-strain probiotic administered via drinking water enhances feed conversion efficiency and meat quality traits in indigenous chickens. Anim. Nutr. 5:179–184.

Balasubramanian, B., S. Shanmugam, S. Park, N. Recharla, J. S. Koo, I. Andretta, and I. H. Kim. 2021. Supplemental impact of marine red seaweed (*Halymenia palmata*) on the growth performance, total tract nutrient digestibility, blood profiles, intestine histomorphology, meat quality, fecal gas emission, and microbial counts in broilers. Animals 11:1244.

Bona, L., N. van Staaveren, B. B. Pokharel, M. van Krimpen, and A. Harlander-Matauschek. 2018. The effect of low protein energy-rich diets on plasma hepatic markers, hepatic damage, and discrimination reversal learning in young female chicks. Front. Vet. Sci. 5:107.

Bowker, B., and H. Zhuang. 2015. Relationship between water-holding capacity and protein denaturation in broiler breast meat. Poult. Sci. 94:1657–1664.

Cañedo-Castro, B., A. Piñón-Gimate, S. Carrillo, D. Ramos, and M. Casas-Valdez. 2019. Prebiotic effect of *Ulva rigida* meal on the intestinal integrity and serum cholesterol and triglyceride content in broilers. J. Appl. Phycol. 31:3265–3273.

Carpenter, K. J., and K. M. Clegg. 1956. The metabolizable energy of poultry feeding stuffs in relation to their chemical composition. J. Sci. Food Agri. 7:45–51.

Chen, X., R. Gu, L. Zhang, J. Li, Y. Jiang, G. Zhou, and F. Gao. 2018. Induction of nuclear factor-kappa B signal-mediated apoptosis and autophagy by reactive oxygen species is associated with hydrogen peroxide-impaired growth performance of broilers. Animal 12:2561–2570.

CIE. 1976. Recommendations on Uniform Color Spaces-Color Difference Equations, Psychometric Color Terms. Commission Internationale de l'Eclairage, Paris, France. Supplement No. 2 to CIE Publication No. 15 (E-1.3.1.) 1978, 1971/(TC-1-3).

Dessie, T., T. Taye, N. Dana, W. Ayalew, and O. Hanotte. 2011. Current state of knowledge on phenotypic characteristics of indigenous chickens in the tropics. Worlds Poult. Sci. J. 67:507–516.

Doyle, D. 2006. William Hewson (1739-74): the father of haematology. Br. J. Haematol. 133:375–381.

El-Deek, A., and M. A. Brikaa. 2009. Nutritional and biological evaluation of marine seaweed as a feedstuff and as a pellet binder in poultry diet. Int. J. Poult. Sci. 8:875–881.

Etim, N. N., M. E. Williams, U. Akpabio, and E. E. Offiong. 2014. Haematological parameters and factors affecting their values. Agric. Sci. 2:37–47.

Fletcher, D. L. 2002. Poultry meat quality. Worlds Poult. Sci. J. 58:131–145.

González-Esquerra, R., and S. Leeson. 2001. Alternatives for enrichment of eggs and chicken meat with omega-3 fatty acids. Can. J. Anim. Sci. 81:295–305.

Honikel, K. O. 1987. How to measure the water-holding capacity of meat? Recommendation of standardized methods. Pages 129−142 in Evaluation and Control of Meat Quality in Pigs. P. V. Tarrant, G. Eikelenboom, and G, Monin, eds. Springer; Dordrecht, Netherlands.

Honikel, K. O. 1998. Reference methods for the assessment of physical characteristics of meat. Meat Sci 49:447–457.

Hussain, M., A. Mahmud, J. Hussain, S. N. Qaisrani, S. Mehmood, and A. Rehman. 2018. Subsequent effect of dietary lysine regimens fed in the starter phase on the growth performance, carcass traits and meat chemical composition of Aseel chicken in the grower phase. Rev. Bras. Cienc. Avic. 20:455–462.

Karu, P., S. Selvan, H. Gopi, and M. Manobhavan. 2018. Effect of macroalgae supplementation on growth performance of Japanese quails. Int. J. Curr. Microbiol. Appl. Sci. 7:1039–1041.

Kulshreshtha, G., M. T. Hincke, B. Prithiviraj, and A. Critchley. 2020. A Review of the varied uses of macroalgae as dietary supplements in selected poultry with special reference to laying hen and broiler chickens. J. Mar. Sci. Eng. 8:536.

Kulshreshtha, G., B. Rathgeber, G. Stratton, N. Thomas, F. Evans, A. Critchley, J. Hafting, and B. Prithiviraj. 2014. Feed supplementation with red seaweeds, *Chondrus crispus* and *Sarcodiotheca gaudichaudii*, affects performance, egg quality, and gut microbiota of layer hens. Poult. Sci. J. 933:2991–3001.

Larbi, A., P. Rymkiewicz, A. Vasudev, I. Low, N. B. Shadan, S. Mustafah, S. Ayyadhury, and T. Fulop. 2013. The immune system in the elderly: A fair fight against diseases? Aging Health 9:35–47.

Lokaewmanee, K., P. K. Yamauchi, and N. Thongwittaya. 2012. Effects of fermented plant product on growth performance, some blood variables, carcase characteristics, and intestinal histology in broilers. Br. Poult. Sci. 53:215–223.

Magothe, T. M., T. O. Okeno, W. B. Muhuyi, and A. K. Kahi. 2012. Indigenous chicken production in Kenya: II. Prospects for research and development. Worlds Poult. Sci. J. 68:133–144.

Manyelo, T. G., L. Selaledi, Z. M. Hassan, and M. Mabelebele. 2020. Local chicken breeds of Africa: their description, uses and conservation methods. Animals 10:2257.

Matshogo, T. B., C. M. Mnisi, and V. Mlambo. 2020. Dietary green seaweed compromises overall feed conversion efficiency but not blood parameters and meat quality and stability in broiler chickens. Agriculture 10:547.

Matshogo, T. B., C. M. Mnisi, and V. Mlambo. 2021. Effect of pretreating dietary green seaweed with proteolytic and fibrolytic enzymes on physiological and meat quality parameters of broiler chickens. Foods 10:1862.

Michalak, I., K. Chojnacka, Z. Dobrzański, H. Górecki, A. Zielińska, M. Korczyński, and S. Opaliński. 2010. Effect of macroalgae enriched with microelements on egg quality parameters and mineral content of eggs, eggshell, blood, feathers and droppings. J. Anim. Physiol. Anim. Nutr. 95:374–387.

Michalak, I., and K. Mahrose. 2020. Seaweeds, intact and processed, as a valuable component of poultry feeds. J. Mar. Sci. Eng. 8:620.

Michalak, I., R. Tiwari, M. Dhawan, M. Alagawany, M. R. Farag, K. Sharun, T. B. Emran, and K. Dhama. 2022. Antioxidant effects of seaweeds and their active compounds on animal health and production − a review. Vet. Q. 42:48–67.

Minias, P. 2015. The use of haemoglobin concentrations to assess physiological condition in birds: a review. Conserv. Physiol. 3: cov007.

Nhlane, L. T., C. M. Mnisi, M. J. Madibana, and V. Mlambo. 2020. Nutrient digestibility, growth performance and blood indices of Boschveld chickens fed seaweed-containing diets. Animals 10:1296.

Nhlane, L. T., C. M. Mnisi, V. Mlambo, and M. J. Madibana. 2021. Effect of seaweed-containing diets on visceral organ sizes, carcass characteristics, and meat quality and stability of Boschveld indigenous hens. Poult. Sci. 100:949–956.

Onasanya, G. O., F. O. Oke, T. M. Sanni, and A. I. Muhammad. 2015. Parameters influencing haematological, serum and bio-chemical references in livestock animals under different management systems. Open J. Vet. Med. 5:181.

Ortiz, J., N. Romero, P. Robert, J. Araya, J. Lopez-Hernández, C. Bozzo, E. Navarrete, A. Osorio, and A. Rios. 2006. Dietary fiber, amino acid, fatty acid and tocopherol contents of the edible seaweeds *Ulva lactuca* and *Durvillaea Antarctica*. Food. Chem. 99:98–104.

Priolo, A., D. Micol, J. Agabriel, S. Prache, and E. Dransfield. 2002. Effect of grass or concentrate feeding systems on lamb carcass and meat quality. Meat Sci 62:179–185.

Purslow, P. P. 2017. New Aspects of Meat Quality: Pages 1−9 From Genes to Ethics. Woodhead Publishing, Cambridge, United Kingdom.

Qadri, S. S., A. Biswas, A. B. Mandal, M. Kumawat, R. Saxena, and A. M. Nasir. 2019. Production performance, immune response and carcass traits of broiler chickens fed diet incorporated with *Kappaphycus alvarezii*. J. Appl. Phycol. 31:753–760.

Rajauria, G., B. Foley, and N. Abu-Ghannam. 2017. Characterization of dietary fucoxanthin from *Himanthalia elongata* brown seaweed. Food Res. Int. 99:995–1001.

Resiere, D., H. Mehdaoui, J. Florentin, P. Gueye, T. Lebrun, A. Blateau, J. Viguier, R. Valentino, Y. Brouste, H. Kallel, B. Megarbane, A. Cabie, R. Banydeen, and R. Neviere. 2020. *Sargassum* seaweed health menace in the Caribbean: clinical characteristics of a population exposed to hydrogen sulfide during the 2018 massive stranding. Clin. Toxicol. Phila. 59:215–223.

SAPA. 2020. South African Poultry Association 2020 industry profile. https://www.sapoultry.co.za/wp-content/uploads/2022/03/SAPA-INDUSTRY-PROFILE-2020.pdf (accessed Jul. 2022).

Sarbaz, E., B. Navidshad, and F. M. Aghjegheshlagh. 2018. The effect of peanut pod on performance, small intestine pH and ileum bacteria population in broiler chickens. S. Afr. J. Anim. Sci. 48:435–444.

Schiener, P., K. D. Black, M. S. Stanley, and D. H. Green. 2015. The seasonal variation in the chemical composition of the kelp species *Laminaria digitata, Laminaria hyperborea, Saccharina latissima* and *Alaria esculenta*. J. Appl. Phycol. 27:363–373.

Schomaker, S., D. Potter, R. Warner, J. Larkindale, N. King, A. C. Porter, J. Owens, L. Tomlinson, J. M. Sauer, K. Johnson, and J. Aubrecht. 2020. Serum glutamate dehydrogenase activity enables early detection of liver injury in subjects with underlying muscle impairments. PLoS One 15:e0229753.

Van Laack, R. L., C. H. Liu, M. O. Smith, and H. D. Loveday. 2000. Characteristics of pale, soft, exudative broiler breast meat. Poult. Sci. 79:1057–1061.

Van Soest, P. J., J. B. Robertson, and B. A. Lewis. 1991. Methods for dietary fibre, neutral detergent fibre and non-starch polysaccharides in relation to animal nutrition. J. Dairy. Sci. 74:3583–3597.

Wang, R. H., R. R. Liang, H. Lin, L. X. Zhu, Y. M. Zhang, Y. W. Mao, P. C. Dong, L. B. Niu, M. H. Zhang, and X. Luo. 2017. Effect of acute heat stress and slaughter processing on poultry meat quality and postmortem carbohydrate metabolism. Poult. Sci. 96:738–746.

Washington, I. M., and G. van Hoosier. 2012. Clinical Biochemistry and Hematology. Univ. Washington, Seattle, WA.

Zhang, L., and S. Barbut. 2005. Rheological characteristics of fresh and frozen PSE, normal and DFD chicken breast meat. Br. Poult. Sci. 46:687–693.