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Effect of *Spirulina platensis* supplementation on growth, performance and body conformation of two Omani goat breeds

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ABSTRACT

Context. *Spirulina platensis* (SP) has been found to be an important dietary supplement for boosting animal growth performance, having a high protein content (60–70% on a dry-matter basis) with minimal toxicity. **Aims.** The effect of *Spirulina platensis* (SP) supplementation on the growth and performance of two Omani goat breeds (Jabbali and Sahrawi) was investigated. **Methods.** Thirty-six 11-month-old bucks from two Omani goat breeds were studied for 70 days at the Livestock Research Centre, Ministry of Agriculture, Fisheries and Water Resources, Oman. Each breed was divided into three groups ($n = 6$) and fed one of the following three rations: (1) control (CON): concentrate with 14% crude protein and 11.9% energy (MJ/kg DM); (2) Treatment 1 (T1): the same concentrate with 2 g/head.day SP; and (3) Treatment 2 (T2): the same concentrate with 4 g/head.day SP. Weekly growth, performance and body conformation data collected included live bodyweight (BWT), body condition score (BCS), average daily gain (ADG), chest girth (CG), wither height (WH) and body length (BL). **Key results.** The Jabbali breed had a higher feed conversion ratio for T1 and T2 than did the Sahrawi breed. During the trial, no differences in total DM intake were found between treatments for either breed. T1 and T2 SP supplementation levels significantly ($P < 0.05$) improved the BWT and ADG of the Sahrawi breed compared with the CON group. Analysis of all traits indicated a significant ($P < 0.05$) effect of feeding spirulina on all the studied traits except WH and BL. ANOVAs for fixed effects in this study (dam age and kid birth type, i.e. single, twin or triple) were not significant ($P > 0.05$) for any of the studied traits. However, the breed effect was highly significant ($P < 0.001$) on BWT, ADG, BCS and treatment effect was significant ($P < 0.05$) on CG traits. **Conclusions.** *Spirulina platensis* could be used as a supplement feed to improve growth, performance and morphological traits in Omani goat production. Feeding spirulina to kids led to increased growth, herd performance and buck selection facilitation at an earlier age. **Implications.** These findings will benefit Omani goat producers in managing productivity and product quality.

Keywords: body conformation, goats, growth, live weight, nutrition, Oman, performance, Spirulina.

Introduction

Goat breeding in Oman is constrained by the availability of quality feed, especially during the dry season. Growth rates of local goat breeds in Oman have improved through feeding concentrate supplementation at 3% of animal liveweight (MAFWR 2014). Availability of animal feed with good nutritional value at an economical price is vital for livestock production (Mahgoub *et al.* 2005). *Spirulina platensis* is a blue-green microalga with approximately 60–70% crude protein, and is a potential candidate supplement for improving goat growth and performance in Oman. It has been used in livestock feed during the past two decades, with a long history of human utilisation (Belay *et al.* 1993; Gupta *et al.* 2008). Over the past decades, cultivation of spirulina microalgae has increased because it is an easy and inexpensive management method for CO_2, which is currently a significant global problem (Póti *et al.* 2015). Spirulina grows well in alkaline waters, but mass cultivation requires infrastructure development and an appropriate climate (Mathur 2018).

Addition of spirulina microalgae with a high nutritional value to the diet of many farm animals, including pigs, goats, cattle, chickens, and pets, as well as their use in aquaculture, have resulted in increased production, health, fertility and profitability (Madeira *et al.* 2017). Use of microalgae in animal feeds has shown beneficial effects on the immunity, disease tolerance, and antibacterial activity. For example, they help with probiotic colonisation of the intestine, which may, among other things, lead to improved immune response and antiviral and antigenic action. Both factors together result in regulation of animal weight, growth promotion, an increased feed conversion ratio and reproductive efficiency (Harel *et al.* 2007).

There is a need to improve the productivity of small ruminants to satisfy an increasing demand for animal-derived protein, particularly in developing countries. Hence, researchers are being tasked to develop strategies of meeting the nutritional requirement for animals with low-cost feed. Salman *et al.* (2017) developed a new feed-block technology in the Sultanate of Oman and stated that using feed blocks as an alternative feed supplement for small ruminants showed great potential. They concluded that feed blocks could be used as a replacement for the costly imported concentrate feed.

Several microalgae, such as *Spirulina*, *Chlorella* and *Dunaliella*, can be utilised as animal-feed additives (Molino *et al.* 2018). There are several potential benefits of adding *Spirulina platensis* (SP) to animal diets. These include increasing daily gain and the feed conversion ratio (Madeira *et al.* 2017) and production of antioxidants that are proven to enhance human and animal immunity without side effects and are cheaper than are synthetically produced antioxidants (Abdel-Daim *et al.* 2013). Although the importance of spirulina as a feed supplement within protein concentrates is established, no studies have been undertaken to use it as a feed additive in Oman. Hence, this study investigates the growth and performance response of two main Omani goat breeds to different supplementation levels of SP.

This study aims to investigate the impact of feeding SP microalga as a non-conventional, usable, and rich bioactive compound on the growth rate and body conformation of two Omani goat breeds reared under an intensive system.

Materials and methods

Animal management and experimental design

The study was conducted at the Livestock Research Center, Directorate General of Agriculture and Livestock Research, Ministry of Agriculture, Fisheries and Water Resources, Muscat, Sultanate of Oman. Ethics was approved by the USYD Animal Ethics Committee (AEC) 2019/1597, following the *New South Wales (NSW) Animal Research Act 1985,* and its associated Regulations, the Australian Code for the Care and Use of Animals for Scientific Purposes 8th Edition 2013 and the Australian Code for the Responsible Conduct of Research 2007.

Thirty-six 11-month-old local Omani bucks, with an initial bodyweight of 16.44 ± 0.33 kg for two main local goat breeds, *viz.* Jabbali (n = 18) and Sahrawi (n = 18), were randomly assigined to one of three feeding treatments comprising control (CON), Treatment 1 (T1) and Treatment 2 (T2; $n = 6$; per group) in a 3 × 3 factorial design; the trial lasted for 70 days. The CON group was fed a conventional concentrate (14% crude protein (CP), and 11.97% energy, MJ/kg DM). Animals in T1 and T2 were fed the same concentrate feed with an addition of 2 g and 4 g/head.day of SP respectively. The basal diet was formulated to meet the nutrient requirements of goats, so as to achieve a bodyweight gain at a rate of 0.3 kg/day and they were fed twice a day at 08:00 hours and 15:00 hours. Commercial spirulina pellets (DXN International Australia) were fed to goats daily at 08:00 hours. All animals were housed in randomly allocated individual pens throughout the experiment, including 2 weeks of acclimatisation, during the winter season (November–February 2019–2020). Rhodes grass (*Chloris gayana*) was fed *ad libitum* to provide roughage, together with free access to fresh water during the experimental period. Feed intake was calculated as the difference between the amount of feed offered and the feed refusal, and the feed refusal was obtained and recorded in the morning of the next day.

Liveweight and body conformation measurements

Measurements of linear conformation traits were taken on Day 0 of the experiment. All sizes were recorded in centimetres (cm) with flexible tape, as described by Ford *et al.* (2009). The traits measured were chest girth (CG), calculated as the body circumference behind the buck's forelegs, the wither height (WH), measured as the distance between the highest point of the scapulae and the ground, the body length (BL), which was determined from the sternum to the aitch bone and the width of the hip.

Body condition scores (BCS) were taken at weekly intervals by the same researcher throughout the experiment to minimise variance, with the BCS range from 1 to 5, based on the fat depth estimation scale of Ghosh *et al.* (2019). Score 1 represents emaciated, depilated animal where the back section is extremely visible and the fingers will easily identify intercostal spaces. Score 2 represents an animal where individual short ribs can be detected but are not visible and intercostal spaces are smooth but can also be penetrated. Score 3 represents an animal where the spine is not so prominent, and the ribs are not easily visible, and a thin layer of fat fills them and, after applying pressure, intercostal spaces may be detected. Score 4 represents an

Table 1. Nutrient composition (g/100 g DM) and DM content (g/100 g fresh weight) of spirulina and basal diet of Rhodes grass hay and concentrate.

Nutrient (in DM)	Concentrate	Spirulina	Rhodes grass hay
Dry matter (DM)	90.0	95.1	89.70
Crude protein (CP)	14.0	62.48	7.22
Crude fibre (CF)	9.8	2.9	34.3
Ether extract (EE)	2.5	1.05	1.00
Ash	9.2	7.55	9.80
Nitrogen-free extract (NFE)	64.5	26.02	47.7
Neutral detergent fiber (NDF)	28.60	1.92	74.00
Acid detergent fiber (ADF)	11.42	0.37	46.7
Metabolisable energy (ME)[A] (MJ/kg DM)	11.97	11.63	8.30

Using the analyses expressed as g/kg DM gives ME (R) direct as MJ/kg DM energy allowances and feeding systems for ruminants. (MAFF (Ministry of Agriculture, Fisheries and Food) (1975)).
[A]ME (R) = 0.012CP + 0.031EE + 0.005CF + 0.014NFE.

animal where the backbone cannot be identified and the ribs are not visible and are covered with a distinct dense layer of fat. Score 5 represents an animal where the backbone is fully covered in fat, ribs in the pelvic and sternum areas are not visible and have excess fat deposition.

Live bodyweight (BWT) was recorded weekly by using steel load bar electronic weighing indicator (Iconix FX1, New Zealand). Average daily gain (ADG) was measured by calculating the differences between the initial and final weights of the animals in kilograms, divided by the number of days of the trial. To reduce stress, all measures were taken when bucks were held by gripping the base of the horn, and in a calm condition, with head upright and standing stably on all four legs on level ground.

Chemical analysis of spirulina and concentrate diet components

Dry matter (DM) of spirulina and the concentrate diets were determined by drying in an oven for 24 h at 80°C (Method 934.01; Table 1). For determination of ash, samples were analysed by ashing approximately 1 g of each sample in a porcelain dish in a muffle furnace at 500°C overnight, until all the carbon was oxidised to CO_2. Acid detergent fibre (ADF) was determined using cetyl trimethyl ammonium bromide (CTAB) and 1 N H_2SO_4, as described by Roberston and Van Soest (1981). Neutral detergent fibre (NDF) was determined using sodium sulfite and sodium lauryl sulfate, as described by Van Soest *et al.* (1991). Total N content was measured using the Kjeldahl procedure (AOAC 2000) and multiplied by 6.25 to determine CP values. The Soxhlet fat extraction method was used for ether extract (EE) determination (AOAC 2000). Crude fibre (CF) determination procedure was used to quantify chemical dietary components such as cellulose, hemicellulose, or lignin in the diet and excreta. An adiabatic bomb calorimeter was used to measure gross energy. It has the bomb surrounded by a water jacket and the temperature measured using a very sensitive thermometer. Approximately 0.7 g of dry powdered sample was pelleted then weighed accurately before being ignited with oxygen. The amount of gross energy in the samples was measured automatically. The chemical composition of spirulina is presented in Table 1, which shows its protein-rich content (62.5 g/100 g DM) compared with concentrate and Rhodes grass.

Statistical analyses

Descriptive statistics were conducted for each trait. ANOVA was undertaken to assess the effect of spirulina on BWT growth, ADG, BCS and body conformation measurements among groups (CON, T1 and T2). The effects of breed and spirulina on BWT and body conformation were determined using general linear model (GLM) procedure of Statistical Analysis System (SAS) Institute (2002). The data were subjected to factorial ANOVA (PROC GLM) analysis, with spirulina supplementation level, breed, and their interactions being fitted as fixed effects, and CG, WH, BL, BCS, BWT and ADG as dependent variables (Eqn 1).

$$Y_{ijkl} = \mu + A_i + B_j + C_k + D_{ijk} + e_{ijkl} \quad (1)$$

where Y_{ijkl} is the BWT, SDG, BCS and body conformation measurements of the lth kid in the ith treatment, jth breed, kth time and the interaction; μ the overall mean; A_i the effect of ith treatment, i = 1 for control, 2 for Treatments1 and 3 for Treatment 2; B_j the effect of jth breed, j = 1 for Jabbali and 2 for Sahrawi; C_k the effect of kth time, $k = 1, 2, \ldots 8$; D_{ijk} the effect of (ijk)th interaction among treatment, breed and time; e_{ijkl} the effect of random error associated with the lth individual assumed to be normally distributed $(0, I\sigma_e^2)$.

Statistical significance was set at $P < 0.05$, and differences between means were established using Duncan's multiple-range tests.

The effects of treatment, breed and time on BCS were analysed using an ordinal logistic regression (OLR) model for R studio (ver. 4.0.2; R Core Team 2021) where random effect of the animal ID and fixed factors tested were treatment, breed, time and their interactions (Eqn 2).

$$Y_{ijklm} = a + bT_i + cB_j + dM_k + fD_{ijk} + R_l + e_{ijklm} \quad (2)$$

where Y_{ijklm} is the BCS of the mth kid in the ith treatment, jth breed, kth time and the interaction and Rth animals; a the intercept; b, c, d, f the slopes; T_j the effect of ith treatment, $i = 1$ for control, 2 for Treatment 1 and 3 for Treatment 2; B_j the effect of jth breed, $j = 1$ for Jabbali and 2 for Sahrawi; M_k the effect of kth time, $k = 1, 2, \ldots 8$; D_{ijk} the effect of (ijk)th interaction among treatment, breed and time; R_l the random effect of l^{th} animal ID; e_{ijklm} the effect of random error associated with the mth individual assumed to be normally distributed $(0, I\sigma_e^2)$.

Results

The addition of SP in the concentrate feed for Jabbali goats resulted in a better feed conversion ratio (FCR, Table 2) in T1 (7.70) and T2 (7.15) than in the CON group (9.88). It was evident that there was a significant ($P = 0.03$) impact on FCR in the Sahrawi goat breed in T2 (9.79) compared with T1 (10.55) and the CON group (15.15). The daily DM intake of Jabbali and Sahrawi goats was almost constant in all three groups, indicating that spirulina had no impact on feed palatability (Table 2, Figs 1, 2).

For the Jabbali goat breed, the effect of treatment on the mean changes in CG, WH, BL, BCS, BWT and ADG was not significant ($P > 0.05$), being 0.17, 0.10, 0.40, 0.14, 0.68 and 0.69 respectively (Table 3). However, for the Sahrawi goat breed, the effect on BWT and ADG traits was significant ($P < 0.05$). At the same time, there were no significant ($P > 0.05$) effects on parameters CG, WH, BL and BCS. Moreover, adding SP to the feed showed a slight difference in the studied breeds (Fig. 3), trending towards the Jabbali breed having a higher BCS than did Sahrawi.

However, the OLR analysis indicated that there was a significant ($P < 0.001$) increase in BCS over time (Figs 4, 5). Additionally, the interaction between the treatment effect and time for BCS showed that significant overall interaction ($P < 0.001$) specifical differences between CON and T2 at Time 7, CON and T2 at Time 8 and CON and T1 at Time 8 (Fig. 6). In terms of the effect of interaction between breed and time, there was a significant ($P < 0.001$) overall interaction and specific differences between breeds at Times 5, 6, 7, and 8 (Fig. 6). In general, the Jabbali breed had a higher BCS than did Sahrawi breed at Times 5–8. There was no difference between the breeds at Times 1–4 (Table 4).

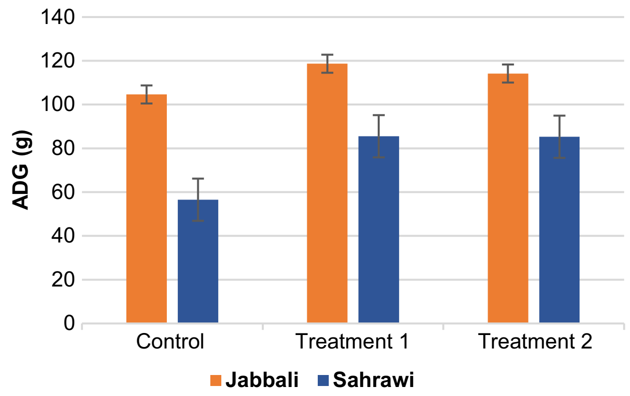

Fig. 1. Effect of spirulina supplementation on average daily gain (ADG; g/day) for Jabbali and Sahrawi bucks.

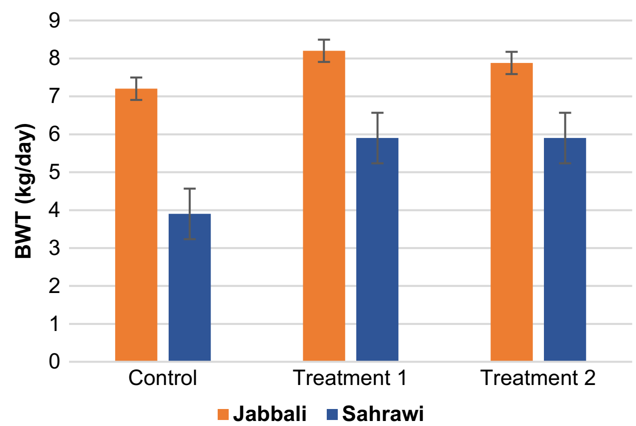

Fig. 2. Effect of spirulina supplementation on live bodyweight (kg/day) for Jabbali and Sahrawi bucks.

Table 2. Effect of spirulina supplementation on growth performance of Jabbali and Sahrawi goat breeds.

Attribute	Jabbali					Sahrawi				
	C	T1	T2	PSE	*P*-value	C	T1	T2	PSE	*P*
Initial weight (kg)	17.33 ± 1.05	16.65 ± 0.21	16.60 ± 1.05	0.47	0.80	15.75 ± 0.96	15.83 ± 0.32	16.47 ± 1.08	0.47	0.81
Final weight (kg)	24.5 ± 0.82	24.85 ± 0.58	24.48 ± 1.33	0.52	0.96	19.65 ± 0.80	21.73 ± 0.84	22.37 ± 1.24	0.60	0.15
DMI (g/day)	848.67 ± 5.08	828.79 ± 10.02	840.84 ± 2.72	5.67	0.37	814.31 ± 11.71	811.56 ± 14.03	819.86 ± 15.59	7.57	0.91
FCR	9.88 ± 2.49	7.15 ± 0.82	7.70 ± 0.52	0.88	0.43	15.15 ± 1.67a	10.50 ± 51.72b	9.79 ± 0.61b	0.96	0.03
MEI	8.98 ± 0.05	8.76 ± 0.11	8.90 ± 0.14	0.06	0.41	8.58 ± 0.13	8.56 ± 0.16	8.65 ± 0.17	0.08	0.92
CP intake	97.70 ± 0.70	96.13 ± 1.38	98.89 ± 1.74	0.78	0.37	93.19 ± 1.54	93.97 ± 1.94	95.89 ± 2.05	1.04	0.58

Means in the same row within a breed followed by the same letter or no letters are not significantly different (at $P = 0.05$).
PSE, pooled standard error of the means; FCR, feed conversion ratio (kg feed/kg weight gain); MEI, metabolisable-energy intake; CP, crude protein.

Table 3. Effect of spirulina supplementation level (mean ± s.e.) on CG, WH, BL, BCS, BWT and ADG in Jabbali and Sahrawi goat breeds.

Trait	Treatment			*P*-value		R2	CV
	C	T1	T2	Br	Trt		
CG (cm)	5.33b	6.41ab	8.08a	0.656	0.016	0.29	31.58
WH (cm)	5.58	7.67	5.83	0.485	0.210	0.11	50.83
BL (cm)	4.17	3.83	5.5	0.305	0.121	0.19	49.56
BCS (1–5)	0.54b	0.92a	1.01a	0.0001	0.014	0.49	44.83
BWT (kg)	5.56b	7.05a	6.89ab	<0.0001	0.0973	0.47	25.94
ADG (kg/day)	0.081b	0.102a	0.100ab	0.1009	<0.0001	0.47	26.00

Means in the same row followed by the same letter or no letters are not significantly different (at $P = 0.05$).
CG, chest girth; WH, withers height; BL, body length,BCS, body condition score; BWT, body weight; ADG, average daily gain; B, breed; T, treatment.

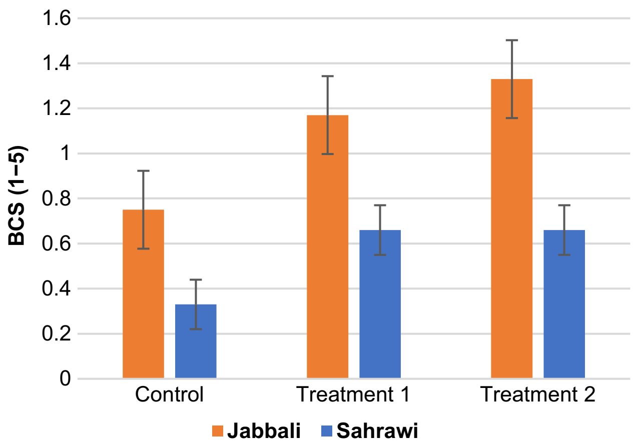

Fig. 3. Effect of spirulina supplementation on changes in BCS in Jabbali and Sahrawi bucks.

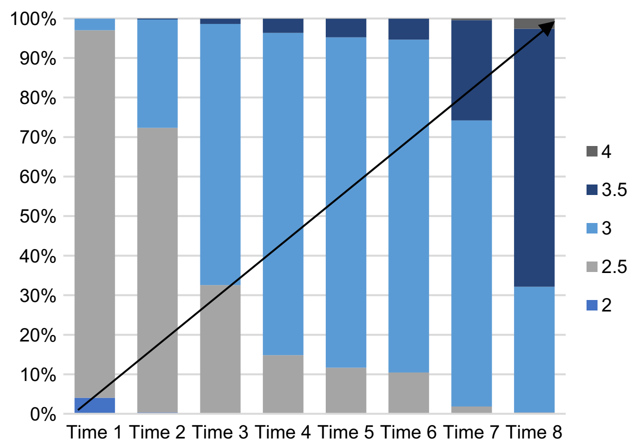

Fig. 4. Effect of time on BCS in Jabbali and Sahrawi breeds.

Discussion

The hypothesis that adding SP to the diet might improve the growth, performance and body conformation of goats was confirmed in this study. The results showed that adding spirulina improved live BWT, daily weight gain, and FCR, in comparison with the CON group, in Jabbali and Sahrawi goats. Our results also showed that there was a significant interaction between breed and time for the effect of spirulina supplementation on BCS. Prior investigation showed that protein, in particular, is an important ingredient for animal growth and performance (Hwangbo *et al.* 2009). SP contains all essential amino acids and up to 70% protein by DM (Gutiérrez-Salmeán *et al.* 2015). As a result, several studies have shown that including SP in the diet could improve animal performance (Holman and Malau-Aduli 2013; Madeira *et al.* 2017).

Our findings showed that the final weight of Sahrawi breed's was higher in T1 and T2 treatments than in the CON group. This result is consistent with a study where adding algae to the growing male lamb's diet improved final weight (Hafez *et al.* 2013). The findings of this study are also in line with the results of EL-Sabagh *et al.* (2014), who reported that spirulina supplementation increased liveweights in fattening lambs from 47.0 to 55.3 kg and in growing pigs from 12.47 to 33.60 kg (Nedeva *et al.* 2014). Also, in agreement with our results, Alazab *et al.* (2020) found that adding SP to the diet of rabbits enhanced growth and performance and the FCR.

This could be a result of spirulina being very rich in nutrients, particularly vitamins, minerals, essential fatty acids, amino acids and other nutrients that may stimulate faster growth. The better growth and performance in goats fed spirulina-supplemented diet may also be attributed to the high nutrient density of spirulina and the stimulation of the secretion of extracellular enzymes by the gut microflora (Tovar *et al.* 2002).

Nedeva *et al.* (2014) reported that the addition of SP (2 and 3 g/head.day) to the feed of growing pigs (from 12.15–12.471 kg to 30.9–33.9 kg liveweight) significantly ($P > 0.05$) increased growth, with increases of 12.50% and 14.25% respectively, and reduced the compound feed conversion and nutrients. As such, the use of the supplement is expected to proportionally enhance performance of goats. In this regard, the study demonstrated that increases in

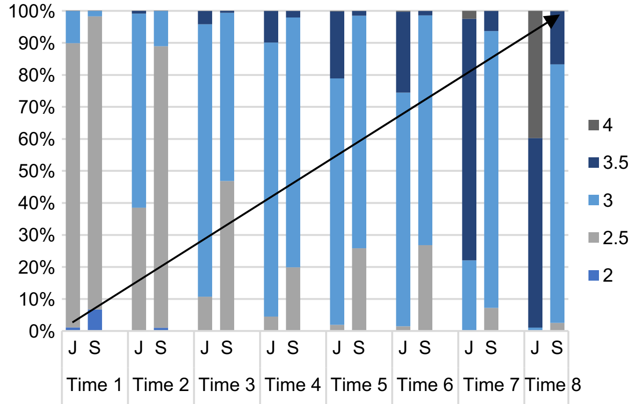

Fig. 5. Effect of interactions between time and spirulina supplementation levels on BCS in Jabbali and Sahrawi breeds.

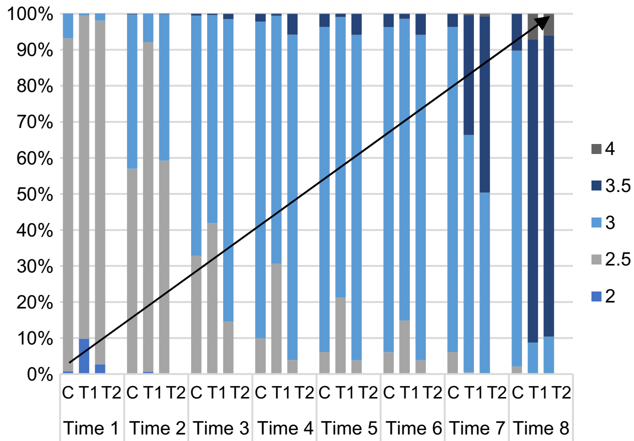

Fig. 6. Effect of goat breed (Jabbali vs Sahrawi) interactions with time on BCS.

liveweight and BCS were observed alongside spirulina supplementation. This finding is consistent with that of a study conducted by Bezerra *et al.* (2010), who found that SP at a level of 10 g increased the live bodyweight of lambs. Additionally, increased dietary protein intake is known to stimulate optimum goat growth, which may explain this finding. The difference between our results and those observed in other species might be attributable to the level of spirulina supplementation and the duration of the experiment that received this kind of alge.

It has been stated that evaluation of body conformation characteristics is linked to goat body growth and development, which would solve many of the difficulties associated with visual assessment (Okpeku *et al.* 2011). Nevertheless, the current results are consistent with those of Holman *et al.* (2012) who observed that lambs receiving spirulina showed no impact on body conformation traits.

Spirulina platensis is a microalga that contains high concentrations of essential fatty acids (Póti *et al.* 2015), which are stored as triacylglycerols in adipose tissue, explaining the rise in BCS with spirulina supplementation (Holman *et al.* 2012). In this study, liveweight, liveweight daily gain and BCS were a response to the spirulina supplementation in Jabbali and Sahrawi goat breeds, as predicted by the study hypothesis. The findings of the present study are consistent with those of the experiments reporting that spirulina has a positive impact on the BCS of lambs (Holman *et al.* 2012). Findings recorded by Gaafar *et al.* (2017) also showed an increase in Friesian cow liveweights with SP, along with an increase in BCS.

Spirulina supplementation elicits the desired results, with a slight discrepancy owing to variation in genetic composition needed for muscle growth. The study has demonstrated that both breeds have attained a higher live bodyweight and liveweight daily gain than in the CON groups. These outcomes strongly support the recommendation for the use of spirulina as an alternative source of supplementary feed for optimum growth and performance. Jabbali and Sahrawi goat breeds had a positive respond to spirulina supplementation. Typically, feed availability resulted in a superb goat performance in terms of a BCS, reflected by the goat's live bodyweight.

Improvement in the final weight may be due to the addition of SP, providing the goats an effect similar to that from providing a vitamin–mineral premix, which is often unavailable in traditional feed diets. Previous research has

Table 4. Effect of spirulina supplementation level (mean ± s.e.) on CG, WH, BL, BCS, BWT and ADG in Jabbali and Sahrawi goat breeds.

Trait	Jabbali			*P*	Sahrawi			*P*	*P*	
	C	T1	T2		C	T1	T2		B	T
CG (cm)	5.33 ± 0.80	6.33 ± 1.30	8.33 ± 0.61	0.175	5.33 ± 0.88	6.50 ± 0.56	7.83 ± 0.87	0.150	0.66	0.01
WH (cm)	6.00 ± 1.15	7.83 ± 0.60	6.50 ± 1.17	0.100	5.16 ± 1.47	7.50 ± 2.09	5.16 ± 0.98	0.451	0.48	0.21
BL (cm)	4.66 ± 0.98	4.33 ± 0.95	6.00 ± 1.29	0.440	3.66 ± 0.71	3.33 ± 1.02	5.00 ± 0.36	0.302	0.30	0.12
BCS (1–5)	0.75 ± 0.17	1.16 ± 0.16	1.33 ± 0.21	0.146	0.33 ± 0.10	0.66 ± 0.10	0.66 ± 0.10	0.131	<.0001	0.01
BWT (kg)	7.21 ± 1.08	8.20 ± 0.59	7.88 ± 0.67	0.686	3.90 ± 0.37b	5.90 ± 0.74a	5.90 ± 0.41a	0.040	<.0001	0.09
ADG (kg/day)	0.104 ± 15.78	0.119 ± 8.58	0.114 ± 9.71	0.694	0.057 ± 5.38b	0.086 ± 10.9a	0.086 ± 6.08a	0.043	<.0001	0.10

Means in the same row followed by the same letter or no letters are not significantly different (at $P = 0.05$).
CG, chest girth; WH, withers height; BL, body length; BCS, body condition score; BWT, bodyweight; ADG, average daily gain; B, breed; T, treatment; *P*, *P*-value.

shown that vitamin supplementation is normally not required when SP has been included in the feed (Venkataraman *et al.* 1994). The addition of SP to broiler feeds increased palatability, decreased toxicity, and increased digestibility, antioxidant activity, decreased hypercholesterolemia, anticancer, immune-stimulant, and antiviral effects (Rodríguez-Hernández *et al.* 2001; Colla *et al.* 2007). Hozayen *et al.* (2016) also reported that the significant effect of dietary treatments on the bodyweight of broilers fed spirulina diet may be brought through improving the efficiency of feed utilisation.

On the basis of our results, the Jabbali breed in T1 produced a better FCR than did the CON. Research on adding SP to the diets has shown similar findings, with improved FCRs in supplemented Barbari goats (Yadav *et al.* 2018), lambs (EL-Sabagh *et al.* 2014) pigs (Nedeva *et al.* 2014) and broiler chickens. The results in the present study indicated that the better FCR in goats fed spirulina resulted in increased BWT and ADG after 70 days.

On the basis of previous investigations, it is clear that the two main operations responsible for improving the FCR are fermentation and absorption in the rumen. The inclusion of SP as a feed additive, unlike plant ingredients, may improve feed efficiency by increasing gut bacterial colonisation. As suggested by Vasudevan *et al.* (2006) and Teimouri *et al.* (2013), SP enhances the intestinal flora in fish, allowing for the breakdown of indigestible feed components and boosting enzyme synthesis, which transfers lipids inside the fish for metabolism rather than storage. Riad *et al.* (2019) found that the total VFA concentration was significantly higher (17.37), whereas pH values and concentrations of NH_3-N were significantly lower (6.02, 10.27) in rumen liquor after adding SP than in the control group (12.63, 6.32 and 13.00 respectively). Also, the high concentration of SP in the diet had a significant impact on rumen function parameters.

Additionally, Choi *et al.* (2017) found that pigs fed with higher levels of *Ecklonia cava* algae had a linear rise in desirable *Lactobacillus* spp., while the population of undesired *E. coli* showed a linear decrease in microbial population, and also the population of *Clostridium* spp. tended to decrease in the algae-supplemented pigs. Choi *et al.* (2017) concluded that *E. cava* algae had beneficial effects on the expansion performance, microflora and enteric morphology (villus height) of weaned pigs.

Spirulina supplementation has been shown to increase the CP production and to significantly reduce the time needed for its maintenance inside the rumen (Quigley *et al.* 2009). Rumen fermentation activity improved with spirulina additive for cows (Zhang *et al.* 2010). Gaafar *et al.* (2017) found that the concentration of ruminal total volatile fatty acids (TVFAs) increased significantly; however, ruminal NH_3-N concentration decreased significantly with different supplementation levels of spirulina. Lactobacilli are prepared to produce sugar depolymerases and glycosidases, which may increase nutrient edibility by decomposing structural sugars in plant semipermeable membranes (Macfarlane *et al.* 1990). These positive effects of spirulina addition significantly affect digestibility because of the broad spectrum of extremely biologically valued compounds involved in spirulina algae. In terms of absorption, previous researchers have found that ~20% of dietary spirulina avoids rumen degradation and is therefore available for direct absorption at intervals in the abomasum (Quigley *et al.* 2009; Panjaitan *et al.* 2010).

Interestingly, significant interactions among the level of supplementation, goat breed, and time were remarkable, and this may provide the goat farmer with a variety of options and goat breed combinations for achieving optimal BCS and liveweights.

Also, the results of the current study confirmed the widely accepted interaction between breed and spirulina supplementatin level, which resulted in the heaviest (8.20 kg) and lightest (5.90 kg) average liveweights in Jabbali and Sahrawi respectively, when being supplemented with 2 g of spirulina.

A cost–benefit analysis of the usage of spirulina in rations should be considered to determine the actual cost of use in the field and performance gains such as body weight and condition. This further research should also compare cheap forms of plant-based products for the supplement for goats. In addition, further investigation of spirulina supplementation at different goat farming systems, such as large-scale intensive commercial systems would be benificial to establish whether the actual growth performance established in this research is transferrable to other rearing systems. This also extends to evaluating the nutritional value of the spirulina supplement.

Conclusions

The use of SP to supplement the feed of Omani goats was shown to be effective in improving growth performance. However, this improvement is dependent on the supplementation level and goat breed. Dosages of 2 g and 4 g/head of SP resulted in a significant improvement in the growth performance of Omani goats. For economic reasons, we recommend that a dose of 2 g/head of SP is the best dose for the growth performance improvement in Omani goats. A cost-based analysis of SP usage is also required, based on local prices, for the benefit of farmers.

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Data availability. The data that support this study will be shared upon reasonable request to the corresponding author.

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