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Effects of Seaweed and Organic Mineral Supplementation on Nutrient Digestibility and Milk Yield in Lactating Saanen Crossbred Goats

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ABSTRACT

Dairy goat productivity in Indonesia remains relatively low, primarily due to its suboptimal feed efficiency, affecting nutrient digestibility and milk yield. This study aimed to evaluate the effects of seaweed and organic mineral supplementation on feed intake, nutrient digestibility, and milk production performance in dairy goats. An in vivo experimental study was conducted using a completely randomized design involving 16 pregnant Saanen-Etawah crossbred ewes in their second lactation and offered treatment feeds for 4 weeks before parturition until 8 weeks postpartum. The animals divided into four dietary treatments: T0 (control diet without supplementation), T1 (control diet + rumensin), T2 (control diet + 2% seaweed), and T3 (T2 + organic minerals including Cr, Se, and Zn) with the feed offered was based on dry matter requirements of 4% of body weight, once daily at 1.30 p.m. The control diet is a mixture of concentrate, tofu dregs, and forage. The observed parameters included dry matter intake (DMI), organic matter intake (OMI), digestibility of dry matter, organic matter, crude fiber, and crude protein, as well as daily milk yield and its components. The results indicated that while feed intake did not differ significantly among treatments, the supplementation of seaweed and organic minerals significantly improved nutrient digestibility, daily milk yield, and the composition of milk, including fat, protein, lactose, and total solids. The T3 treatment yielded the most optimal outcomes in enhancing feed conversion efficiency and milk performance. These results suggest that seaweed and organic minerals may serve as effective and applicable functional feed additives to sustainably improve dairy goat productivity through optimized rumen function and metabolic utilization.

Keywords: D*airy goats, Seaweed, Organic minerals, Digestibility, Milk production*

Introduction

Milk from dairy goats is essential in fostering smallholder farmers' economic viability and advancing the livestock sector's overall growth (Ruvuga and Maleko, 2023). Nonetheless, the yield of dairy goats in Indonesia is still rather low compared to other nations, partly because of inadequate feed quality and efficiency in its usage (Sumarmono, 2022). Feed represents a significant component in ruminant production systems, and inefficiencies in nutrient absorption and digestibility frequently lead to inadequate metabolic reactions and restricted milk production during the lactation phase. Thus, enhancing feed efficiency is vital to improve the physiological and productive capabilities of dairy goats in tropical environments (Teixera et al., 2024).

Despite many improvements in feed implementations, the use of functional feed additives in goat nutrition remains under-researched, especially in tropical climate regions. Various investigations reveal ongoing issues with poor nutrient absorption and insufficient trace minerals in diets, both of which play a crucial role in affecting rumen fermentation processes and overall metabolic function (Goetsch, 2019). These obstacles underline an important void in research, especially regarding viable nutritional approaches that enhance the use of nutrients in both the rumen and after it, which in turn directly influence milk yield and quality (Clark and Garcia, 2017).

Various methods have been investigated to decrease the production of enteric methane, including the incorporation of feed additives like rumensin, a synthetic ionophore that effectively lowers methanogenic archaea levels in the rumen (Brown and Hogue, 1985; McGregor et al., 1994). Nevertheless, the ongoing application of synthetic additives has led to worries about antibiotic resistance, residual milk in products, and consumer demand for more natural options (Pinotti et al., 2008; Li et al., 2018). One promising alternative that has been highlighted is the addition of

seaweed, especially red seaweed varieties that contain bromoform and phlorotannin, substances recognized for their ability to disrupt methane production processes (Wanapat et al., 2024). Additionally, organic trace minerals such as chromium, selenium, and zinc have been noted to improve rumen fermentation and metabolic activities, which could enhance nutrient absorption and overall productivity in ruminants.

Seaweed has risen as a compelling option for a feed additive, largely due to its significant presence of bioactive elements, including polysaccharides, polyphenols, and essential micronutrients (Morais et al., 2020). These substances are recognized for their ability to influence the rumen microbial community, improve fiber breakdown, and enhance immune and metabolic processes (Reddy et al., 2024). Prior studies have indicated that *Ascophyllum nodosum* and various other brown seaweeds, can boost digestibility and increase milk production in ruminants by altering fermentation and hormonal mechanisms (Muizelaar et al., 2023); additionally, organic trace minerals (Se, Zn, and Cr), when bonded with amino acids, show enhanced bioavailability over their inorganic forms and aid important metabolic functions regarding lactation and nutrient uptake (Song et al., 2024). However, this research focused on the synergistic application of seaweed and organic minerals in the nutrition of goats remains limited and inconsistent.

The implementation of these integrative feeding approaches holds both theoretical importance and practical implications. Looking at it from a physiological perspective, maximizing the digestibility of nutrients and the absorption of trace minerals has a direct effect on the metabolic processes that facilitate milk production. In practical terms, boosting both the quantity and quality of milk through refined nutritional approaches supports higher agricultural revenue, enhanced efficiency in resource use, and sustainable practices in livestock farming. Additionally, these measures are in harmony with worldwide initiatives aimed at decreasing environmental effects by optimizing nutrient transformation and lessening waste generated from ruminant farming systems.

This study aimed to evaluate the effects of seaweed and organic mineral supplementation on feed intake, nutrient digestibility, and milk production in dairy goats. The study also sought to assess the effectiveness of combining both supplements in enhancing overall production performance, thereby contributing to developing more sustainable and nutritionally efficient feeding practices in tropical dairy goat systems.

Materials and Methods

This study experimented with sixteen, 5 months pregnant dairy ewes of Saanen-Etawah crossbred weighing 39.5 ± 2.36 kg and offered treatment feeds for 4 weeks before parturition until 8 weeks postpartum. The ethical clearance approval number is No: 1537/UN23/PT.01.02/2023. The control feed was a mixture of concentrate, tofu dregs, and forages. The feed offered was based on dry matter requirements of 4% of body weight, once daily at 1.30 p.m. The treatment feed consisted of four treatments: T_0 as a control feed, T_1 is T_0 with rumensin addition, T_2 is T_0 with 2% seaweed flour addition, and T_3 is T_2 supplemented with organic mineral (Cr, Se, Zn). Drinking water was provided ad libitum. The commercial seaweed was gathered from local traditional market with kind of seaweed limited to *Gracilaria sp.* The process of producing seaweed flour included the following steps: 1) removal of foreign materials; 2) washing the seaweed with distilled water to decrease the salt levels; 3) air-drying the seaweed, followed by drying in an oven at 105ºC; 4) grinding the dried seaweed to achieve a flour-like consistency. After that, the seaweed flour was ready to use. The experimental nutrient composition is presented in Table 1.

The research process consisted of three distinct phases. Initially, a 15 days adaptation period took place, during which the animals were solely given basic feed (control feed or T_0) in the form of concentrates and foraged material, allowing them to adjust to the subsequent treatment feed. Next, during the preliminary phase, the animals received treatment feed aimed at counteracting the influence of the initial feed while getting used to the new treatment feeds, ensuring that any observed results reflected the effectiveness of the treatment rather than the basic feed. Following that, thirty days feeding trial provided the livestock with experimental feed based on a dry matter requirement of 4% of their body weight, administered twice daily (at 7:00 a.m. and 4:00 p.m.). Finally, data were gathered utilizing the total collection method to assess the feed digestibility.

Table 1. Feed nutrient composition

Nutrient composition (%)	Treatments[1]			
	T_0	T_1	T_2	T_3
Dry matter	50.92	50.62	50.94	50.94
Organic matter	89.73	92.43	89.75	89.75
Crude protein	12.08	12.47	12.08	12.08
Extract ether	2.78	2.82	2.78	2.78
Crude fibre	36.26	37.72	36.27	36.27
Nitrogen-free extract	35.11	35.95	37.02	37.02
Total digestion nutrient	64.74	65.91	65.41	65.41

[1]T_0: control feed; T_1: T_0 + rumensin; T_2: T_0 + 2% seaweed; T_3: T_2 + organic mineral (Cr, Se, Zn)

Digestibility experiment

Digestibility experiments were carried out for 5 d. Samples of feeds, feed refusals, and faeces were weighed every day, and the feed samples and feed waste (ort) were dried at 550ºC. Exactly 10% of faecal samples were taken and composited for 5 d from 16 experimental animals. The dried samples were filtered through a 1 mm filter for further analysis for dry matter (DM), ash, crude fibre (CF), ether extract (EE), nitrogen-free extract (NFE), and crude protein (CP) (AOAC, 2016).

Milk Yield

Goats were individually housed in separate pens and were milked two times each day at 07.00 h and 15.00 h. The amount of milk produced was documented weekly for 8 w, and samples of milk (250 ml/d) were gathered during both the morning and evening milking sessions. These milk samples were preserved in the freezer before analysis for fat, protein, lactose, total solids, and non-fat solids using the Lactoscan model MCC W-V1. Initially, the frozen milk samples underwent a screening process before being analysed on the Lactoscan.

Statistical Analysis

Data were statistically analysed using analysis of variance (ANOVA), and differences among means were further examined using post hoc tests such as Duncan's multiple range tests where applicable. Before ANOVA, data were tested for normality and homogeneity of variance. All statistical analyses were performed using IBM SPSS version 25, consistent with standard practices in animal nutrition research (Allen & Ying, 2012; Tafaj et al., 2007). Statistical significance was set at $\alpha = 0.05$.

Results and Discussion

Feed intake

The results of this study revealed that supplementation with seaweed and organic minerals did not significantly affect feed intake, both in terms of dry matter intake (DMI) and organic matter intake (OMI). The maximum DMI was documented in the control group (T0) at 2,584.90 ± 77.20 g/head/d ($p = 0.400$). In a similar vein, the peak OMI was also noted in T0 (1,713.19 ± 69.73 g/head/d), and no statistically significant differences were observed among the treatment groups. These findings are consistent with earlier studies that suggest seaweed supplementation does not inherently enhance daily feed intake in ruminants (Antaya et al., 2019).

Table 2. Effects of treatment on dry matter intake (DMI), organic matter intake (OMI)

Parameters	Treatments[1]				p-value
	T_0	T_1	T_2	T_3	
DMI (g/d)	2584.90±77.20	2403.96±88.21	2326.41±63.92	2392.96±72.46	0.400
OMI (g/d)	1713.19.±69.73	1629.64±78.33	1681.23±56.35	1685.85±66.85	0.300

DMI: Dry matter; OMI: Organic matter.
[1]T0: control diet without supplementation; T1 : control diet + rumensin; T2 : control diet + 2% seaweed; and T3 : T2 + organic minerals including Cr, Se, and Zn.
[a,b]Different superscripts show significant results ($p<0.05$).

The results demonstrate that the inclusion of seaweed and organic minerals, whether administered separately or within feed mixtures, did not exert a statistically significant influence on dry matter intake (DMI) or organic matter intake (OMI). Although the control group (T0) exhibited the highest numerical value, the variations observed were not statistically relevant. This implies that the enhancements noted in milk yield and composition within the supplemented groups were not attributable to augmented feed consumption, but instead to improved digestibility and nutrient efficiency. These findings underscore the critical necessity of evaluating feed quality and nutrient bioavailability as fundamental determinants of productive performance, rather than exclusively depending on the volume of intake.

In terms of ruminant nutritional science, the consumption is modulated by factors such as palatability, rumen capacity, energy concentration, and metabolic processes. The seaweed supplementation examined in this investigation comprises intricate polysaccharides and secondary metabolites, which may have influenced rumen fermentation without markedly altering the sensory attributes that encourage voluntary consumption. Moreover, organic minerals such as chelated zinc, selenium, and chromium do not exert a direct effect on the flavor or aroma of feed, which may elucidate the lack of a significant intake response (Helmy et al., 2022). The lack of a favorable intake response aligns with earlier investigations conducted by Rey-Crespo et al. (2014), who documented a consistent dry matter intake despite the incorporation of mineral-rich seaweed in the diets of dairy cattle (Rey-Crespo et al., 2014).

A consistent feed intake coupled with augmented milk production signifies an enhancement in biological efficiency. Comparable patterns were noted by Desnoyers et al. (2009), who demonstrated that the incorporation of live yeast led to an elevation in milk yield among dairy cattle without affecting dry matter intake (Desnoyers et al., 2009). In a similar vein, El-Zaiat et al. (2024) indicated that the inclusion of a chitosan-based supplement augmented nutrient digestibility and milk output while maintaining intake levels, thereby underscoring the pivotal role of digestive processes in the responses of milk production (El-Zaiat et al., 2024). From a mechanistic perspective, bioactive compounds

derived from seaweed may modify the rumen microbiota composition to favor fibrolytic and propionate-producing microorganisms, thereby enhancing energy availability without necessitating increased intake quantities. Concurrently, organic trace minerals facilitate metabolic pathways associated with energy distribution and cellular efficacy, particularly under conditions of stress or subclinical deficiencies (Song et al., 2024).

These results possess significant practical ramifications for nutritional strategies in environments characterized by resource scarcity. Instead of augmenting the quantity of feed, which may incur substantial costs or present logistical challenges, producers may prioritize enhancing feed efficiency by incorporating functional additives that facilitate rumen fermentation and systemic metabolic processes. Within this framework, the supplementation of seaweed and organic minerals presents promising prospects for boosting productivity while simultaneously preserving feed intake at sustainable levels (El-Nile et al., 2022).

Digestibility

Nutrient digestibility parameters showed significant differences among treatments. The highest dry matter digestibility (DMD) was found in T_3, while the lowest was observed in T_0. Organic matter digestibility (OMD) significantly increased in T_1 and T_3 compared to T_0. Crude fiber digestibility (CFD) also improved significantly in T_1 and T_2 compared to T_0. Crude protein digestibility (CPD) was highest in T_1 and T_2, which were significantly higher than T_0. Theresults corroborate previous research indicating that the incorporation of seaweed can augment ruminal fermentation processes and enhance the bioavailability of nutrients (Orzuna-Orzuna et al., 2024), as well as the assertion that organic minerals contribute positively to the retention of nutrients and the functionality of the gastrointestinal system (Daniel et al., 2020).

Table 3. Effects of treatment on digestibility of dry matter (DMD), organic matter (OMD), crude fiber (CFD), and crude protein (CPD)

Parameters	Treatments[1]				p-value
	T_0	T_1	T_2	T_3	
DMD (%)	66.03±7.48[a]	76.14±3.03[b]	72.28±5.41[b]	78.84±5.94[b]	0.001
OMD (%)	61.11±0.68[c]	77.35±3.03[a]	73.14±5.06[b]	76.77±10.03[a]	0.01
CFD (%)	65.47±7.03[a]	77.53±2.57[b]	74.09±4.92[b]	74.20±3.07[b]	0.0001
CPD (%)	57.26±5.05[a]	69.70±5.87[c]	66.96±3.50[c]	64.02±5.67[b]	0.0001

DMD: Dry matter digestibility; OMD: Organic matter digestibility; CFD: Crude fiber digestibility; CPD: Crude Protein Digestibility.
[1]T0: control diet without supplementation; T1 : control diet + rumensin; T2 : control diet + 2% seaweed; and T3 : T2 + organic minerals including Cr, Se, and Zn.
[a,b]Different superscripts show significant results ($p<0.05$).

The study revealed that the incorporation of seaweed and organic minerals markedly enhanced the digestibility of dry matter (DM), organic matter (OM), crude fiber (CF), and crude protein (CP). These results suggest that the augmented production performance in the treatment groups, particularly T_3, can be primarily ascribed to improved nutrient assimilation rather than solely to increased feed consumption. Such advancements in digestibility are essential, as they have a direct impact on the availability of metabolic substrates necessary for milk synthesis, thereby aligning with the overarching aim of this research to enhance production performance through dietary modification.

From a mechanistic perspective, the improvement in digestibility can be explained by both ruminal and post-ruminal processes. Seaweed contains fermentable polysaccharides and polyphenols such as laminarin and phlorotannin, which modulate rumen microbial communities, enhancing the growth of cellulolytic bacteria and stimulating fermentation pathways that increase volatile fatty acid (VFA) production: acetate and propionate acids (Orzuna-Orzuna *et al.*, 2024). These VFAs served as energy sources for lactating goats. Furthermore, phlorotannin have been shown to reduce excessive ruminal proteolysis, allowing more bypass protein to reach the small intestine for absorption (Antaya *et al.*, 2019).

Organic minerals significantly contribute to enhancing how well nutrients are digested. When contrasted with inorganic options, organically chelated minerals like Zinc, Selenium, and Chromium exhibit greater stability within the digestive system, which promotes better absorption and minimizes interference with other dietary elements. This improvement boosts enzymatic activities that are essential for breaking down nutrients and their movement through enterocytes (Song et al., 2024). In reality, dairy goats that received organic trace minerals demonstrated a markedly greater overall digestibility of dry matter, crude protein, and fiber, reinforcing their higher effectiveness (Daniel et al., 2020).

The improvement in digestibility is also supported by other empirical studies. Rahayu *et al.* (2022) found that supplementation of organic minerals in combination with bioactive additives significantly improved fiber digestibility in lactating goats, although the degree of improvement varied depending on the specific additive used (Rahayu *et al.*, 2022). Similarly, Singh *et al.* (2017) demonstrated that the incorporation of 20% seaweed in dairy cow rations enhanced milk yield and digestibility, despite no change in nutrient intake (Singh *et al.*, 2017). These results collectively underscore the value of nutrient digestibility as a key intermediary variable that links dietary intervention with productive output.

The improved digestibility carries significant consequences for both biological performance and ecological viability. Improved breakdown of fiber fosters elevated microbial protein creation and lowers methane production for every unit of milk generated, supporting a more sustainable farming approach. Moreover, increased digestibility of crude protein leads to improved nitrogen efficiency, minimizing nitrogen waste and the potential for environmental harm. Consequently, the blend of seaweed and organic minerals offers not just a nutritionally beneficial approach but also a environmentally responsible method for enhancing the productivity of dairy goats.

Milk Production Performance

Milk yield showed a notable increase. The highest daily milk production was achieved in T_3, followed by T_2, T_1, and T0. Total solids followed a similar pattern. The highest milk fat content was T_3, although differences with T_0 and T_2 were not statistically significant. Solid-not-fat (SNF), lactose, and casein production also increased significantly in T_2 and T_3. These results are consistent with prior results that supplementation with brown macroalgae can enhance milk volume and quality (Muizelaar *et al.*, 2023).

Table 4. Effects of treatment on milk yield, milk composition, and milk efficiency

Parameters	Treatments[1]				p-value
	T_0	T_1	T_2	T_3	
Milk yield (g/d)	1620.8±20.98[a]	1830.36±9.89[b]	1923.96±22.2[b]	2330.84±73.5[b]	0.031
TS yield(g/d)	236.52±8.04[a]	237.50±0.45[a]	253.93±2.38[a]	308.12±22.64[b]	0.021
Milk fat yield (g/d)	90.68±5.66[a]	87.67±1.89[a]	91.10±3.54[a]	113.91±5.48[b]	0.021
SNF yield (g/d)	146.33±2.50[a]	149.64±1.56[a]	161.27±2.45[a]	194.91±21.67[b]	0.043
Lactose yield (g/d)	65.86±1.12[a]	84.07±0.89[a]	90.62±1.08[b]	106.79±4.55[c]	0.0001
Casein yield(g/d)	69.55±0.96[a]	70.86±0.75[a]	76.57±0.93[b]	86.66±4.02[c]	0.0001
Milk efficiency: DMI/Milk yield	1.59±0.03[a]	1.32± 0.02[b]	1.2±0.04[b]	1.03±0.02[c]	0.0001

SNF: Solid non-fat; TS: Total solid.
[1]T0: control diet without supplementation; T1 : control diet + rumensin; T2 : control diet + 2% seaweed; and T3 : T2 + organic minerals including Cr, Se, and Zn.
[a,b]Different superscripts show significant results ($p<0.05$).

The results demonstrated that supplementation with seaweed and organic minerals significantly improved daily milk yield in dairy goats compared to the control. This result directly addressed the research objective concerning the potential of nutritional interventions to enhance milk production performance. The increase in milk output observed in the T_3 group also corresponded with notable improvements in milk composition, including total solids, fat, protein, and lactose, indicating enhanced physiological function of the mammary gland and a more efficient nutrient conversion process.

From a physiological and nutritional standpoint, milk production is highly dependent on the availability of metabolic substrates such as glucose, amino acids, and fatty acids, which mammary epithelial cells utilize for synthesizing milk components. Seaweed supplementation contributes to improved rumen fermentation and microbial activity due to the presence of bioactive compounds like laminarin, fucoidan, and polyphenols. These compounds stimulate fibrolytic bacteria and increase the production of volatile fatty acids (VFAs), particularly propionate, which serves as a primary precursor for hepatic gluconeogenesis and subsequent lactose synthesis (Muizelaar *et al.*, 2023). Simultaneously, organically chelated minerals such as zinc (Zn), selenium (Se), and chromium (Cr) play critical roles in enzymatic activity, hormonal regulation, and immune function, all of which are essential for sustaining optimal lactation physiology (Song *et al.*, 2024).

The results are consistent with previous studies that reported enhanced milk yield and improved nutrient status following seaweed supplementation. For instance, Rey-Crespo *et al.* (2014) found that seaweed from the Galician coast increased iodine levels and improved milk mineral profiles in dairy cows (Rey-Crespo *et al.*, 2014). In goats, Helmy *et al.* (2022) demonstrated that humic acid and bentonite supplementation improved both nutrient digestibility and milk composition, affirming the link between enhanced digestion and milk output (Helmy *et al.*, 2022). Furthermore, Hong *et al.* (2015) observed that brown seaweed byproducts positively influenced endocrine responses associated with lactation, although the effect on milk volume was less pronounced (Hong *et al.*, 2015).

A deeper analysis of milk component synthesis reveals that the increase in milk fat content is likely driven by elevated acetate production in the rumen, a known lipogenic precursor for milk fat biosynthesis. The observed increase in crude fiber digestibility supports this hypothesis, as higher fiber degradation yields greater acetate levels (Antaya *et al.*, 2019). Similarly, the enhanced crude protein digestibility observed in T_2 and T_3 correlates with improved casein synthesis, as more amino acids become available post-ruminally. Phlorotannins in seaweed may also contribute to reduced ruminal protein degradation, allowing greater nitrogen absorption in the small intestine (Dai *et al.*, 2024).

Lactose production, being closely tied to glucose availability, benefits from increased propionate absorption from the rumen, which fuels hepatic gluconeogenesis. This mechanism underlies the observed increase in lactose concentration in the milk of supplemented groups, especially in T3 (El-Zaiat *et al.*, 2024). Meanwhile,

improvements in total solids reflect a better synchronization between energy and nitrogen availability, ensuring balanced nutrient flow toward milk biosynthesis (Schmidely & Bahloul, 2022).

On a practical level, these results suggest that enhancing milk yield and quality does not necessarily require increased feed intake, but rather, improved efficiency in nutrient utilization. The positive effects of seaweed and organic minerals on digestibility and metabolic pathways demonstrate their potential as functional feed additives to support sustainable dairy goat production, particularly under resource-constrained tropical conditions (Yakubu & Mohamed, 2019).

Feed Efficiency

Feed efficiency, measured as the ratio of dry matter intake to milk yield (DMI/milk yield), showed a significant decrease in the supplemented groups, especially in T_3 compared to T_0. The results indicate improved conversion of feed, into milk in goats with the seaweed–mineral combination. These results are supported by studies showing that bioactive feed additives can enhance biological efficiency and productivity in dairy animals (Zebeli *et al.*, 2008); (Rey-Crespo *et al.*, 2014); (Prayitno *et al.*, 2019); (Insoongnern *et al.*, 2021); (Kholif *et al.*, 2020); (Nzeyimana *et al.*, 2023).

The results of this study demonstrate that the highest milk efficiency, as indicated by the ratio of milk yield to dry matter intake, was achieved in goats receiving both seaweed and organic mineral supplementation (T_3). Although feed intake did not significantly differ among treatments, the substantial improvements in digestibility and milk yield in T_2 and T_3 led to a marked enhancement in feed conversion efficiency. This result aligned with the experiment's hypothesis that seaweed and organic minerals would improve not only production parameters but also the biological efficiency of nutrient utilization in lactating goats.

Feed efficiency represents a multifaceted characteristic shaped by various physiological factors, such as ruminal fermentation, nutrient uptake, and energy allocation. Incorporating functional feed additives like seaweed and organic minerals interacts with these factors in a combined manner. Seaweed supplies fermentable fiber along with bioactive compounds, including laminarin and fucoidan, which improve ruminal fermentation and VFA generation, leading to increased energy availability without raising intake levels (Orzuna-Orzuna et al., 2024). At the same time, organic trace minerals—particularly Zn, Se, and Cr—boost metabolic routes associated with glucose and protein synthesis, insulin sensitivity, and antioxidant defense, aiding in the effective transformation of nutrients into milk (Song et al., 2024).

Similar findings were documented by Muktiani et al. (2020), who demonstrated that adding Zn and Se to diets significantly enhanced feed efficiency and financial returns related to feed costs in Ettawa crossbred goats without increasing the amount consumed (Muktiani et al., 2020). In a similar vein, Ead et al. (2011) showed improved feed efficiency and economic gain in Friesian cows when seaweed was included at 1.5% of their diet, indicating the possibility of this feeding method being effective across different species (Ead et al., 2011). Furthermore, Newton et al. (2023) recorded an increase in mineral transfer efficiency in milk, suggesting better nutrient utilization in dairy cows fed seaweed (Newton et al., 2023).

From a mechanistic standpoint, the heightened feed efficiency in T3 could stem from improved alignment between energy and nitrogen release in the rumen, which fosters greater microbial protein production and reduces nitrogen waste. For example, organic selenium aids in maintaining redox balance and mitigates oxidative stress during high metabolic demand in the mammary gland, thereby improving energy utilization per unit of milk produced (Song et al., 2024). Enhanced microbial efficiency within the rumen also contributes to superior fiber breakdown and VFA output, lowering the feed needed for each product unit (Rahayu et al., 2022).

Practically, these findings suggest that the integration of seaweed and organic minerals presents a tactical nutritional strategy to optimize feed usage without escalating feed expenses—especially beneficial in tropical smallholder systems with restricted access to premium feed options. Increased efficiency minimizes waste, boosts profitability, and fosters environmental sustainability in dairy goat production systems (Yakubu & Mohamed, 2019).

Conclusion

This study concludes that dietary supplementation with seaweed and organic minerals, whether applied individually or in combination, exerts a positive influence on the production performance of dairy goats by enhancing nutrient digestibility, feed conversion efficiency, and milk yield along with its compositional quality, despite not significantly increasing feed intake. The combined treatment (T3), consisting of control feed supplemented with 2% seaweed and organic minerals (Cr, Se, Zn), demonstrated the most pronounced effect, indicating a synergistic interaction between the two additives. These results confirm the research hypothesis and highlight that targeted nutritional strategies involving bioactive seaweed and highly bioavailable organic minerals can be implemented as practical and sustainable interventions to improve the productivity and physiological efficiency of dairy goats under tropical farming conditions.

Conflict of interest

No potential conflict of interest relevant to this article was reported. All authors have agreed with the contents of the manuscript.

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