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Some Physiological and Immunological Responses of Growing Barki Lambs Fed on Biologically Treated Trimming Waste of Mandarin Trees in Siwa Oasis

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ABSTRACT

This study aimed to evaluate the effects of replacing traditional roughage with trimming waste of mandarin trees (TWMT), either untreated or biologically treated with Bio-Magic (BM), on thermo-respiratory responses, hematological, biochemical, thyroid hormonal profiles, and immunological status of growing Barki lambs under the environmental conditions of Siwa Oasis. Thirty-three weaned Barki lambs (aged 5 months, average weight 31.56 ± 0.48 kg) were randomly assigned to three experimental groups (11 lambs per group) for a 4-month trial. The control group (CR) received Berseem Hay (BH) + Concentrate Feed Mixture (CFM). The untreated group (UR) was fed TWMT + CFM. The treated group (TR) received TWMT + CFM biologically treated with Bio-Magic at a rate of 10 kg fresh matter/ton CFM. Feed was offered as 70% CFM of total requirements, with roughage provided *ad libitum*. The results showed that biological treatment (TR) significantly reduced skin temperature, respiration rate, and heart rate compared to the control group, indicating improved thermal comfort and heat adaptability in Siwa Oasis conditions. Lambs in the TR group showed a significant increase in RBC count (8.24×10^6 / mm^3), Hemoglobin (11.15 g dL^{-1}), and PCV% (30.37%), as well as total WBCs count (11.59×10^3/ cells / mm^3) compared to UR and CR groups. TR significantly elevated Total Protein (8.55 g dL^{-1}) and Albumin (4.19 g dL^{-1}), while maintaining normal globulin levels. Thyroid hormones (T3 and T4) were significantly higher in the TR group (5.89 ng mL^{-1} and 98.70 ng mL^{-1}) respectively, indicating enhanced metabolic rate and nutrient utilization. Liver enzymes (ALT, AST, GGT, Alk. Ph) and kidney markers (Creatinine and Urea) remained within healthy physiological ranges, showing a slight decrease in blood urea, which reflects improved ruminal nitrogen utilization efficiency without any systemic toxicity. TR significantly enhanced Immunoglobulin G (IgG: 2.33 ng mL^{-1}), Total Antioxidant Capacity (TAC: 0.90 nmol mL^{-1}), and Interleukins (IL-2 and IL-6) compared to untreated and control rations. Lipid parameters (Total Lipids, Total Cholesterol, HDL, and LDL) were significantly decreased in TWMT-fed groups (TR and UR), likely due to the active phytochemicals (flavonoids and tannins) present in mandarin residues. Conclusion: Utilizing biologically treated trimming waste of mandarin trees (TWMT + Bio-Magic) as a non-conventional roughage source can successfully replace traditional roughages. It improves growth performance, metabolic efficiency, antioxidant activity, and immune response without adverse effects on liver or kidney functions, offering an eco-friendly and cost-effective feeding strategy in arid region oasis conditions.

Keywords: Trimming mandarin trees, Bio-Magic, Barki Lambs, Thermo-respiratory Responses, Physiological and Immunological Responses, T3 and T4.

1. Introduction

In arid and semi-arid regions such as the Siwa Oasis in Egypt, small ruminant production plays a vital role in food security and rural livelihoods. However, sheep farming in these harsh environments faces severe challenges, including intense solar radiation, high ambient temperatures, and acute

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shortages of traditional forage resources. Under such conditions, animals experience heat stress and nutritional deficits that impair thermo-respiratory regulation, compromise metabolic status, weaken immune function, and depress overall growth performance (Khidr, 2022).

To sustain livestock productivity in remote oases, animal nutritionists (Khidr *et al.,* 2021) have increasingly focused on utilizing non-conventional feedstuffs and agro-industrial by-products (Abo Bakr *et al.*, 2020a). In Siwa Oasis, substantial quantities of agricultural residues such as discarded dates and trimming waste from fruit trees are generated annually. Trimming waste of mandarin trees (TWMT) represents a promising, underutilized roughage source. Rich in digestible carbohydrates, organic fiber, and natural bioactive compounds (including flavonoids, essential oils, and ascorbic acid), citrus residues offer beneficial antioxidant and anti-inflammatory properties. However, their raw utilization in ruminant diets is often constrained by high lignocellulosic fiber content and anti-nutritional factors, notably tannins, which can reduce nutrient digestibility and intake if left untreated (Kewan *et al.*, 2021).

Biological treatment of crop residues using multi-enzyme preparations and beneficial microbial inoculants (such as Bio-Magic) has emerged as an effective eco-friendly technology (Abo Bakr *et al.,* 2020b). Supplementing low-quality roughages with exogenous enzymes (e.g., cellulase, protease, amylase) and probiotic microorganisms enhances fiber degradation, disrupts lignocellulosic complexes, neutralizes anti-nutritional compounds, and improves nitrogen retention in the rumen (Abo Bakr *et al.,* 2020a). Consequently, biological processing enhances feed intake, nutrient availability, and overall metabolic efficiency in growing animals (Khidr *et al.,* 2024).

While extensive research exists on the general use of citrus by-products in animal nutrition, limited systematic work has evaluated the biological treatment of mandarin tree trimming waste under the hot, dry climate of Siwa Oasis. Specifically, the physiological mechanisms by which biologically treated TWMT affects heat tolerance, blood parameters, hormonal regulation, and systemic immunocompetence in Barki lambs remain to be fully elucidated.

Therefore, the main objective of this study was to evaluate the potential of replacing traditional roughage (Berseem hay) with untreated or biologically treated trimming waste of mandarin trees (TWMT + Bio-Magic). The investigation focused on assessing the impacts of these dietary regimens on thermo-respiratory parameters under ambient heat load, hematological indices, serum biochemical parameters, liver and kidney function markers, and metabolic lipid profiles, thyroid hormone concentrations (T3 and T4) as indicators of basal metabolic activity, immunological response and systemic antioxidant status.

2. Materials and Methods

2.1. Experimental location and meteorological data

The present trial was conducted at the Siwa Research Station (Tegzerti), affiliated with the Desert Research Center, located in Siwa Oasis, Matrouh Governorate, Egypt (approximately 300 km from Matrouh City). The Siwa Oasis lies up to 18 meters below sea level.

Ambient temperature (AT, ◦C) and relative humidity (RH, %) were monitored throughout the experimental period using a hygro-thermometer. The daily mean Temperature-Humidity Index (THI) was calculated according to the standard formula (Table 1 A):

Table 1 A: Variations in air temperature, relative humidity, and THI during the experimental period.

Items	Air Temperature, (°C)		Relative humidity, (%)		THI	
	Min	Max	Min	Max	Min	Max
April	15.4	23.5	65.1	71.8	15.3	22.5
May	27.5	37.0	38.4	64.3	26.1	32.7
June	28.2	37.7	34.4	69.1	26.9	33.0
July	29.4	37.0	48.5	59.9	27.5	33.4
Overall means	23.2	31.7	50.3	67.4	22.2	28.8

THI = The daily mean Temperature-Humidity Index

Ambient temperature and relative humidity values were recorded twice a day at 8:00 am and 13.30 pm during the experimental period to estimate temperature humidity index (THI) according to LPHSI (1990) modified by Marai *et al.* (2001). Using this formula: THI = T- [(0.31 -0.31 *RH) (T-14.4)] Where: T= dry bulb temperature in Celsius. RH= relative humidity (percentage)/100 THI values obtained were then classified as follow (Marai *et al.*, 2001): Less than 27.8= absence of heat stress, 27.8 ≤ 28.9 = moderate heat stress, 28.9-≤ 30.0= severe heat stress and 30.0 and more = very severe heat stress.

2.2. Experimental animals, housing, and dietary regimens

Thirty-three weaned male Barki lambs, aged 5 months with an average initial live body weight of 31.56 ± 0.48 kg, were used in a 4-month feeding trial during the period from April and lasted for July. Lambs were housed in freely ventilated semi-closed pens under similar hygienic and management conditions.

Animals were stratified by weight and randomly allocated into three equal experimental groups (11 lambs each) to receive one of three dietary regimens: Control Ration Group (CR): Lambs were fed berseem hay (BH) as roughage plus a concentrate feed mixture (CFM) without additives. Untreated Ration Group (UR): Lambs received trimming waste of mandarin trees (TWMT) as roughage plus CFM. Treated Ration Group (TR): Lambs received TWMT as roughage plus CFM supplemented with the biological additive Bio-Magic (BM) at an inclusion level of 10 kg fresh matter per ton of CFM.

Feed was offered to meet the animals' requirements, with CFM supplied at 70% of the total energy requirements based on periodic updates of body weight, while roughage sources were offered *ad libitum*. Freshwater was accessible to animals at all times.

2.3. Feed additive and experimental diets composition

The Bio-Magic (BM) feed additive is a multi-compound commercial formula composed of amino acids (301.6 g/kg), vitamins (4.7 g/kg), mineral complex (145.0 g/kg), enzymes (Pepsin, Amylase, Protease, Lipase, and Hemi-cellulase), and beneficial bacterial strains (aerobic Gram-positive and anaerobic Gram-negative bacteria). Proximate analysis of Bio-Magic revealed: 33.60% DM, 62.03% OM, 37.97% Ash, 36.34% CP, 1.99% CF, 6.19% EE, and 17.51% NFE.

The standard CFM was formulated from: corn 50.5%, wheat bran 20.0%, soybean meal 16.0%, discarded dates 10.0%, limestone 1.6%, common salt 1.6%, vitamin and mineral premix 0.1%, feed yeast 0.1%, and mycotoxin binder 0.1%. The proximate chemical compositions of dietary ingredients and full experimental rations are presented in Table 1 B.

Table 1B: Chemical composition of the concentrate feed mixtures, roughages, feed additive and the experimental rations

Item	Concentrate mixtures		Roughages		Feed Additive	Experimental rations		
	CFM	CFM+BM	BH	TWMT	BM	CR	UR	TR
DM %	91.33	91.44	89.67	93.08	33.60	90.83	91.87	91.92
OM %	94.02	92.83	85.79	84.94	62.03	91.48	91.20	90.03
CP %	14.43	14.97	12.98	13.36	36.34	14.00	14.18	14.50
CF %	3.59	3.41	27.50	20.74	1.99	10.58	8.90	9.54
EE %	4.09	4.38	3.79	5.32	6.19	4.00	4.47	4.71
NFE %	71.91	70.07	41.52	45.52	17.51	62.90	63.65	61.28
Ash %	5.98	7.17	14.21	15.06	37.97	8.52	8.80	9.97
GE,MJ/kg DM	17.05	15.39	16.49	15.85	12.88	16.87	16.86	15.54

DM: dry matter, CP: crude protein, CF: crude fiber, EE: ether extract, NFE: non-fat extract, GE: Gross energy

2.4. Thermo-respiratory parameters and physiological measurements

Thermo-respiratory responses and cardiovascular parameters were measured routinely: Rectal temperature (RT, ◦C), recorded to the nearest 0.1 ◦C using a standard veterinary clinical thermometer inserted into the rectum. Respiration rate (RR, resp./min), counted by observing flank movements per minute. Heart rate (HR, bpm), measured using a clinical stethoscope over the cardiac region. Blood pressure and oxygen saturation, systolic/diastolic blood pressure was monitored using a veterinary digital blood pressure monitor (Model Contec 08A Vit). Peripheral blood oxygen concentration (O_2%) was evaluated using an OLED display pulse oximeter attached to the central ear vein. Skin and coat temperatures, measured across designated body areas to monitor physiological heat exchange between the skin surface and the surrounding microclimate.

2.5. Blood sampling and hematological analyses

Blood samples were collected monthly from all experimental lambs via jugular venipuncture. Each blood sample was divided into two portions.

Anticoagulated Portion, collected into tube containing *K*2EDTA. A fresh sample was immediately analyzed for Complete Blood Count (CBC). Red blood cell (RBCs, 10^6/mm^3) and white blood cell (WBCs, 10^3/mm^3) counts were performed manually using a Neubauer hemocytometer. Hemoglobin concentration (Hb, g dl^{-1}) was measured calorimetrically using commercial kits. Packed cell volume (PCV, %) was determined using Wintrobe tubes following standard centrifugation. Standard erythrocyte indices (MCV, MCH, and MCHC) were calculated.

The second portion (without anticoagulant) was allowed to clot at 6◦C for two hours and centrifuged at 3000 rpm for 20 minutes. Separated plasma and serum were stored at −20◦C for biochemical assays.

2.6. Plasma biochemistry and hormonal Assays

Biochemical determinations were performed calorimetrically using commercial diagnostic kits (Biodiagnostic Co., Egypt). Total Protein (TP, g dL^{-1}) and Albumin (Alb, g dL^{-1}) were determined. Globulin (Glb, g dL^{-1}) was calculated by subtracting Albumin from Total Protein, and the Albumin/Globulin (A/G) ratio was established. Liver Enzymes: Alanine aminotransferase (ALT, *IU L^{-1}*), aspartate aminotransferase (AST, *IU L^{-1}*), gamma-glutamyl transferase (GGT, *IU L^{-1}*), and alkaline phosphatase (Alk.Ph, U L^{-1}) were assayed. Kidney Function & Metabolites: Serum Creatinine (mg dL^{-1}), Urea (mg dL^{-1}), and Glucose (mg dL^{-1}) concentrations were evaluated. Lipid Profile: Total Lipids (TL), Total Cholesterol (TC), High-Density Lipoprotein (HDL), and Low-Density Lipoprotein (LDL) were evaluated. Thyroid Hormones: Plasma Triiodothyronine (T3, ng mL^{-1}) and Thyroxine (T4, ng mL^{-1}) levels were quantified using radioimmunoassay/enzyme diagnostic techniques.

2.7. Immunological profile and antioxidant Status

Immunoglobulins and Cytokines: Plasma Immunoglobulin G (IgG, ng mL^{-1}) subsets, Interleukin-1 (IL-1), Interleukin-2 (IL-2), Interleukin-6 (IL-6), and Tumor Necrosis Factor-alpha (TNF-α) were quantified using specific ELISA kits according to the manufacturer's protocol. Total Antioxidant Capacity (TAC,nmol mL^{-1}) level was determined colorimetrically using diagnostic kits.

2.8. Statistical analysis

Data were subjected to statistical analysis using the General Linear Model (GLM) procedure of SAS (2004). Thermo-respiratory parameters were analyzed using a three-way analysis of variance (ANOVA) with repeated measurements. Other blood indices, metabolic parameters, and hormone concentrations were analyzed using two-way ANOVA with repeated measures over time. Significant differences between treatment means were separated using Duncan's Multiple Range Test, with statistical significance established at $P<0.05$.

3. Results and Discussion

3.1. Thermo-respiratory and heart rate responses

The least square means of thermo-respiratory parameters (rectal temperature [RT], skin temperature [ST], coat temperature [CT], and respiration rate [RR]) as well as heart rate (HR) in growing Barki lambs are presented in table 2**.**

Table 2: Least Square mean values of thermos-respiratory and heart rate responses in growing Barki lambs fed a basic diet supplemented with biologically treated Trimming Waste of Mandarin Trees

	Durations	Groups (G)			Overall (D)	Sig. ± Standard Error				
		Control	Untreated ration	Treated ration		G	D	M	G*M	G*D*M
Rectal Temperature, (ºC)	Am	39.60	38.68	39.04	39.11 ^{b}			Sig.		
	Pm	40.23	38.97	39.36	39.52 ^{a}	**	**	(NS)	(NS)	(NS)
						± Standard Error				
	Overall	39.92 ^{A}	38.83 ^{C}	39.92 ^{B}		0.11	0.09	0.14	0.25	0.35
Skin Temperature, (ºC)	Am	35.98	34.80	34.80	35.20 ^{b}			Sig.		
	Pm	37.36	35.91	36.43	36.66 a	**	**	**	**	*
						± Standard Error				
	Overall	36.81 ^{A}	35.36 ^{B}	35.63 ^{B}		0.19	0.16	0.25	0.42	0.60
Coat Temperature, (ºC)	Am	31.20	30.78	29.20	30.50 ^{b}			Sig.		
	Pm	35.85	33.99	33.67	34.51 ^{a}	**	**	**	**	**
						± Standard Error				
	Overall	33.53 ^{A}	32.39 ^{B}	31.59 ^{C}		0.23	0.19	0.29	0.51	0.72
Respiration Rate, (resp./min)	Am	50.80	38.13	36.13	41.69 ^{b}			Sig.		
	Pm	59.47	51.80	45.40	52.22 ^{a}	**	**	**	**	**
						± Standard Error				
	Overall	55.13 ^{A}	44.97 ^{B}	40.77 ^{C}		1.01	0.83	1.31	2.26	3.20
Heart Rate, (beats./min)	Am	82.03	72.53	73.07	75.88 ^{b}			Sig.		
	Pm	92.67	80.37	83.67	85.57 ^{a}	**	**	**	*	(NS)
						± Standard Error				
	Overall	87.35 ^{A}	76.45 ^{B}	78.37 ^{B}		1.50	1.23	1.94	3.36	4.75

Means with different letters are statistically different (P<0.05). A, B, C= Values with different letters on the same row differ at (P<0.05), a, b = Values with different letters on the same column differ at (P<0.05). NS: Non-significant. * Significant. DV: Diurnal variation (am and pm).

The overall mean rectal temperature showed significant differences ($P<0.05$) among the experimental groups. The control group (CR) recorded the highest value (39.92 °C), followed by the treated ration (TR; 39.92 °C) and the untreated ration (UR; 38.83 °C).

Significant differences ($P<0.01$) were observed in skin and coat temperatures in favor of the biological treatment. Lambs fed the biologically treated mandarin trimming waste (TR) displayed the lowest skin (35.63 °C) and coat (31.59 °C) temperatures compared to the untreated group (35.36 °C and 32.39 °C) and control group (36.81 °C and 33.53 °C), respectively.

Respiration rate was significantly reduced ($P<0.05$) in lambs receiving TR (40.77 resp./min) compared to UR (44.97 resp./min) and CR (55.13 resp./min). Similarly, heart rate was significantly lowered in the TR (78.37 bpm) and UR (76.45 bpm) groups relative to the control group (87.35 bpm).

The marked reduction in skin temperature, respiration rate, and heart rate in lambs fed biologically treated trimming waste of mandarin trees (TWMT) suggests a positive physiological impact on heat dissipation and body temperature regulation. The lower skin temperature facilitates rapid heat exchange between the skin surface and the surrounding microclimate, assisting the animal to maintain thermal comfort under the arid environmental conditions of Siwa Oasis. The presence of bioactive compounds and Vitamin C in TWMT acts as a dietary antioxidant that mitigates thermal and metabolic stress. Vitamin C limits metabolic stress signs, improves growth performance, and reduces physiological distress under high environmental temperature (El-Senousey *et al.*, 2018). Furthermore, citrus compounds and essential oils influence cardiovascular and autonomic nervous system activity (Sattayakhom *et al.*, 2023; Al-Ghamdi *et al.*, 2025). Citrus essential oil inhalation or ingestion modulates hemodynamics, lowering heart rate and stabilizing breathing patterns via central nervous system pathways (Kosiara and Harrison, 2021; Sattayakhom *et al.*, 2023).

3.2. Erythrocyte indices (hematological profile)

The effect of feeding biologically treated TWMT on red blood cell parameters over time is detailed in table 3. Red blood cell counts (RBCs), Hemoglobin (Hb), and packed cell volume %: Inclusion of biologically treated TWMT in the TR diet significantly improved erythrocyte parameters. Red blood cell counts ($8.24\times10^6/mm^3$), Hb levels (11.15 g dL^{-1}), and percentage PCV: (30.37 %) were significantly higher ($P<0.05$) in the TR group than in both UR ($6.94\times10^6/mm^3$, 10.00 g dL^{-1}, 26.85%) and CR ($6.53\times10^6/mm^3$, 9.92 g dL^{-1}, 25.77%).

Mean corpuscular volume (MCV) and mean corpuscular hemoglobin concentration (MCHC) did not show significant overall group variations ($P>0.05$). However, mean corpuscular hemoglobin (MCH) significantly decreased ($P<0.05$) in the TR group (13.73 pg) compared to the CR group (15.45 pg). Over time, prolonged feeding significantly influenced MCV, MCH, and MCHC values.

Blood composition is an established indicator of long-term nutritional status and health in livestock (Akinmutimi, 2004). The observed lower RBC and Hb levels in untreated mandarin waste compared to control can be attributed to tannin content, which aligns with El-Hawy (2013), who noted decreases in erythrocytic values when feeding tanniniferous plants without treatment. Conversely, biological treatment using Bio-Magic (containing multi-enzymes, beneficial bacteria, and essential amino acids) enhanced nutrient digestibility and fiber degradation, overcoming anti-nutritional factors like tannins. Enzymes improve the nutritive value of low-quality roughages and enhance iron absorption and protein utilization (Abo Bakr, 2012). The cumulative positive effect on RBCs, Hb, and PCV confirms that TR provided superior nutritional support, stimulating erythropoiesis and maintaining optimal systemic oxygen transportation without causing physiological anemia or stress.

Table 3: Least Square mean values of erythrocyte indices in growing Barki lambs fed a basic diet supplemented with biologically treated Trimming Waste of Mandarin Trees

Item	Time	Groups			Overall	Sig. ± Standard Error		
		Control	Untreated ration	Treated ration		G	M	G×M
RBC, 10^6 /mm^3	Zero time	6.62	6.22	6.97	6.60 ^{b}			
	One months	5.67	6.82	7.61	6.70 ^{b}		Sig.	
	Two months	6.44	6.99	8.98	7.47 ^{ab}	**	**	(NS)
	Three months	7.29	8.07	9.37	8.24 ^{a}	± Standard Error		
	Four months	6.66	6.62	8.28	7.19 ^{b}	0.22	0.28	0.49
	Overall	6.53 ^{B}	6.94 ^{B}	8.24 ^{A}				
Hb, g dL^{-1}	Zero Time	10.27	9.72	10.73	10.24			
	One months	9.05	11.00	10.88	10.31		Sig.	
	Two months	10.02	9.90	10.97	10.30	**	(NS)	(NS)
	Three months	9.63	9.53	11.03	10.07	± Standard Error		
	Four months	10.63	9.87	12.12	10.87	0.33	0.43	0.74
	Overall	9.92 ^{B}	10.00 ^{B}	11.15 ^{A}				
PCV %	Zero Time	26.23	28.30	31.62	28.72			
	One months	24.23	26.57	27.85	26.22		Sig.	
	Two months	25.83	27.00	29.73	27.52	**	(NS)	(NS)
	Three months	26.33	26.72	32.90	28.65	± Standard Error		
	Four months	26.23	25.68	29.75	27.22	0.68	0.87	1.51
	Overall	25.77 ^{B}	26.85 ^{B}	30.37 ^{A}				
MCV Fl=liter× 10^{-15}	Zero Time	39.77	46.06	45.52	43.78 ^{a}			
	One months	42.80	39.56	36.79	39.72 ^{b}		Sig.	
	Two months	40.27	39.75	33.89	37.97 ^{c}	(NS)	**	(NS)
	Three months	36.65	34.29	35.56	35.50 ^{c}	± Standard Error		
	Four months	39.61	39.09	36.00	38.23 ^{bc}	1.02	1.32	2.28
	Overall	39.82	39.75	37.55				
MCH pg=10^{-12} g	Zero Time	15.57	17.79	15.47	16.28 ^{a}			
	One months	16.46	16.04	14.37	15.62 ^{a}		Sig.	
	Two months	15.62	14.58	12.27	14.16 ^{ab}	*	**	(NS)
	Three months	13.47	12.16	11.87	12.50 ^{b}	± Standard Error		
	Four months	16.14	14.85	14.67	15.22 ^{a}	0.54	0.69	1.20
	Overall	15.45 ^{A}	15.08 ^{AB}	13.73 ^{B}				
MCHC %	Zero time	39.07	34.67	34.83	36.19 ^{b}			
	One months	38.32	40.55	39.04	39.30 ^{a}		Sig.	
	Two months	38.67	36.57	36.72	37.32 ^{ab}	(NS)	*	(NS)
	Three months	36.61	35.51	33.70	35.27 ^{b}	± Standard Error		
	Four months	40.62	37.95	40.50	39.68 ^{a}	0.71	0.92	1.59
	Overall	38.65	37.05	36.95				

Means with different letters are statistically different (P<0.05). A, B, C= Values with different letters on the same row differ at (P<0.05), a, b = Values with different letters on the same column differ at (P<0.05). NS: Non-significant. * Significant RBCs: erythrocytes cells, PCV: packed cell volume, Hb: hemoglobin, MCV: mean corpuscular volume, MCH: mean corpuscular hemoglobin, MCHC: mean corpuscular hemoglobin concentration.

3.3. Leukocyte profile and immune-cytokine indices

Leukocyte counts and immunologic parameters are summarized in table 4. White Blood Cells (WBCs) and Differential Counts: Total WBCs count was significantly elevated (P<0.05) in TR (11.59×10^3/mm^3) relative to CR (8.35×10^3/mm^3), while UR showed intermediate values

($10.33\times10^3/mm^3$). Lymphocyte, monocyte, and granulocyte percentages showed no significant differences among the three dietary groups overall (P>0.05), although they varied significantly across duration intervals.

Table 4: Least Square mean values of leucocyte and some cytokine indices in growing Barki lambs fed a basic diet supplemented with biologically treated Trimming Waste of Mandarin Trees

Item	Time	Groups			Overall Time	Sig. ± Standard Error		
		Control	Untreated ration	Treated ration		G	M	G×M
WBCs, 10^3 Cells / mm^3	Zero time	07.72	12.46	13.55	11.24 ^{ab}			
	One months	10.69	17.10	08.43	12.08 ^{a}		Sig.	
	Two months	07.46	08.14	16.45	10.68^{abc}	**	*	(NS)
	Three months	07.67	06.68	09.63	07.99 ^{c}		± Standard Error	
	Four months	08.19	07.28	09.89	08.45^{bc}	0.79	1.02	1.76
	Overall	8.35 ^{B}	10.33 ^{AB}	11.59 ^{A}				
Lymphocytes, %	Zero time	56.10	60.88	59.97	58.98^{ab}			
	One months	67.66	63.69	60.74	64.03^{a}		Sig.	
	Two months	59.88	61.13	56.38	59.13^{ab}	(NS)	**	*
	Three months	56.96	52.66	51.33	53.65^{b}		± Standard Error	
	Four months	59.50	52.10	52.59	54.73^{b}	1.46	1.89	3.27
	Overall	60.02	58.09	56.20				
Monocytes, %	Zero time	13.26	31.58	27.74	24.19 ^{a}			
	One months	21.33	28.59	31.44	27.12 ^{a}		Sig.	
	Two months	07.34	11.34	14.57	11.08 ^{c}	(NS)	**	**
	Three months	35.39	07.70	06.34	16.48 ^{b}		± Standard Error	
	Four months	09.14	06.12	10.91	08.72 ^{c}	1.28	1.65	2.86
	Overall	17.29	17.07	18.20				
Granulocytes, %	Zero time	30.64	07.55	12.30	16.83 ^{c}			
	One months	11.01	07.72	07.82	08.85 ^{d}		Sig.	
	Two months	32.78	27.53	29.06	29.79 ^{b}	(NS)	**	**
	Three months	07.66	39.64	42.33	29.87 ^{b}		± Standard Error	
	Four months	31.36	41.78	36.50	36.55 ^{a}	1.02	2.25	3.89
	Overall	22.69	24.84	25.60				
C3, mg mL^{-1}	Zero time	01.27	01.12	01.19	01.19			
	One months	00.70	01.02	01.70	01.14		Sig.	
	Two months	00.83	01.11	01.55	01.17	**	(NS)	(NS)
	Three months	00.90	01.06	01.63	01.20		± Standard Error	
	Four months	00.89	01.24	01.90	01.34	0.11	0.14	0.23
	Overall	0.92 ^{B}	1.11 ^{B}	1.59 ^{A}				
C4, mg mL^{-1}	Zero time	00.34	00.41	00.42	00.39			
	One months	00.29	00.34	00.42	00.35		Sig.	
	Two months	00.28	00.34	00.44	00.36	*	(NS)	(NS)
	Three months	00.32	00.31	00.38	00.34		± Standard Error	
	Four months	00.34	00.34	00.40	00.36	0.02	0.03	0.05
	Overall	0.32 ^{B}	0.35 ^{B}	0.41 ^{A}				

Means with different letters are statistically different (P<0.05). A, B, C= Values with different letters on the same row differ at (P<0.05), a, b = Values with different letters on the same column differ at (P<0.05). NS: Non-significant. * Significant WBCs: White blood cells.

Complementary immunologic markers demonstrated distinct responses. Interleukin-1 (IL-1) levels remained comparable across all groups (62.34−63.56 pg mL^{-1}). However, Interleukin-2 (IL-2) was significantly higher ($P<0.05$) in TR (36.04 pg mL^{-1}) and CR (40.03 pg mL^{-1}) than in UR (30.15 pg mL^{-1}). Interleukin-6 (IL-6) and Tumor Necrosis Factor-alpha (TNF-α) were significantly elevated in CR (76.64 and 49.63 pg mL^{-1}) compared to UR (63.94 and 35.26 pg mL^{-1}), with TR occupying an intermediate, balanced level (71.11 and 43.31 pg mL^{-1}).

Leukocyte responses reflect the animal's immunocompetence and capacity to mounting cell-mediated immunity (Banji *et al.*, 2012). The significant elevation of WBCs in lambs fed biologically treated TWMT highlights an enhanced cellular defense mechanism. The probiotic bacterial strains and enzymatic complexes in Bio-Magic interact with the gut-associated lymphoid tissue (GALT), converting secondary bacterial metabolites into systemic immunological signals (Thaiss *et al.*, 2016).

This immunomodulatory effect enhances lymphocyte activation and cytokine production without triggering systemic inflammatory disorders. Balanced secretion of IL-2 and IL-6 plays a pivotal role in regulating B-lymphocyte proliferation and adaptive immune response orchestration (Buckwalter and Albert, 2009; Zhou *et al.*, 2018).

3.4. Plasma proteins and thyroid hormones

Data regarding plasma protein fractions and thyroid hormone activity (T3 and T4) are illustrated in table 5.

Total protein (TP) and albumin (Alb) were significantly elevated ($P<0.05$) in the TR group (8.55 g dL^{-1} and 4.19 g dL^{-1}, respectively) compared to UR (7.61 g dL^{-1} and 3.39 g dL^{-1}) and CR (7.79 g dL^{-1} and 3.43 g dL^{-1}). Globulin values did not differ significantly among groups (4.22−4.37 g dL^{-1}), while the Albumin/Globulin (A/G) ratio was significantly higher ($P<0.05$) in TR (0.98) than in CR (0.80) and UR (0.88).

Triiodothyronine (T3) and Thyroxine (T4) concentrations were significantly highest ($P<0.05$) in TR (5.89 ng mL^{-1} and 98.70 ng mL^{-1}), followed by CR (5.22 ng mL^{-1} and 86.73 ng mL^{-1}), and lowest in UR (4.35 ng mL^{-1} and 76.92 ng mL^{-1}).

Circulating total protein and albumin levels reflect dietary protein intake, hepatic synthetic capacity, and systemic protein status (Saro *et al.,* 2020). Albumin provides amino acid reserves to support tissue growth when crude protein requirements are met (Saro *et al.*, 2020). The inclusion of Bio-Magic (enzymes and probiotics) enhanced protein digestibility and nitrogen retention in the rumen and may be led to increasing amino acid availability for absorption (Abo Bakr *et al.,* 2020b).

The concurrent stimulation of T3 and T4 in TR indicates heightened metabolic activity and efficiency (Jiao *et al.*, 2025). Citrus compounds and pectin in mandarin residues facilitate hepatic detoxification, indirectly supporting thyroid gland function. Increased thyroid hormone production accelerates basal metabolic rates, enhancing cellular nutrient utilization and growth rate in Barki lambs.

3.5. Liver and kidney functions

The effects of dietary treatments on liver enzymes, blood creatinine, and urea levels are presented in table 6.

Alanine aminotransferase (ALT), aspartate aminotransferase (AST), gamma-glutamyl transferase (GGT), and alkaline phosphatase (Alk.Ph) levels showed no adverse elevations in TR. ALT was significantly lower ($P<0.05$) in UR (71.58 *IU* mL^{-1}) and TR (77.85 *IU* mL^{-1}) than in CR (84.04 *IU* mL^{-1}). AST was significantly reduced in TR (63.86 *IU* mL^{-1}) compared to CR (74.65 *IU* mL^{-1}). Alk.Ph activity was lower in TR (66.91 *IU* mL^{-1}) than in CR (82.36 *IU* mL^{-1}) and UR (83.16 *IU* mL^{-1}).

Serum creatinine was significantly lower ($P<0.05$) in both UR (1.41 mg dL^{-1}) and TR (1.54 mg dL^{-1}) compared to CR (1.88 mg dL^{-1}). Similarly, blood urea concentration was significantly lower in TR (31.81 mg dL^{-1}) and UR (41.52 mg dL^{-1}) than in CR (48.54 mg dL^{-1}).

Transaminases (ALT and AST) are primary diagnostic indicators of hepatocellular injury and muscle deterioration (Malla *et al.,* 2015). Comparable or reduced activities of ALT, AST, GGT, and Alk.Ph in treated groups confirm the safety of TWMT incorporation without inducing hepatotoxicity or muscle breakdown (Kour *et al.,* 2016). Decreased liver enzyme activity in non-traditional feeding regimens also correlates with reduced thermal heat load during hot seasons (Alnaimy *et al.,* 2017).

The reduction in blood urea nitrogen in TR reflects superior ruminal microbial nitrogen capture and utilization (Nousiainen *et al.*, 2004; Papi *et al.,* 2022). Biological treatment increased carbohydrate

availability in the rumen, allowing ruminal bacteria to incorporate ammonia nitrogen more efficiently into microbial protein, thus lowering blood urea levels (Beizaei *et al.,* 2014). All evaluated liver and kidney parameters fell within normal physiological standards for healthy sheep as reported by Kaneko *et al.* (1997).

Table 5: Least Square mean values of protein indices and some thyroid hormone in growing Barki lambs fed a basic diet supplanted with biologically treated Trimming Waste of Mandarin Trees

Item	Time	Groups			Overall	Sig. ± Standard Error		
		Control	Untreated ration	Treated ration		G	M	G×M
Total Protein, g dL^{-1}	Zero Time	7.54	7.01	8.16	7.57^{bc}			
	One months	7.39	6.63	8.70	7.57^{bc}		Sig.	
	Two months	8.79	9.01	9.54	9.11 ^{a}	**	**	(NS)
	Three months	7.69	6.69	7.78	7.38 ^{c}	± Standard Error		
	Four months	7.55	8.71	8.55	8.27 ^{b}	0.20	0.26	0.44
	Overall	7.79 ^{B}	7.61 ^{B}	8.55 ^{A}				
Albumin, g dL^{-1}	Zero time	3.43	3.63	4.07	3.71^{ab}			
	One months	3.20	3.37	4.38	3.65 ^{b}		Sig.	
	Two months	4.08	3.65	4.68	4.14 ^{a}	**	*	(NS)
	Three months	3.16	3.15	3.74	3.35 ^{b}	± Standard Error		
	Four months	3.26	3.14	4.07	3.49 ^{b}	0.13	0.16	0.28
	Overall	3.43 ^{B}	3.39 ^{B}	4.19 ^{A}				
Globulins, g dL^{-1}	Zero time	4.11	3.38	4.10	3.86 ^{b}			
	One months	4.19	3.26	4.32	3.92 ^{b}		Sig.	
	Two months	4.71	5.35	4.86	4.97 ^{a}	(NS)	**	**
	Three months	4.53	3.54	4.04	4.03 ^{b}	± Standard Error		
	Four months	4.29	5.57	4.48	4.78 ^{a}	0.15	0.19	0.33
	Overall	4.37	4.22	4.36				
A/G ratio, %	Zero Time	0.87	1.11	1.01	0.99 ^{a}			
	One months	0.78	1.05	1.03	0.95 ^{ab}		Sig.	
	Two months	0.90	0.74	0.99	0.87 ^{ab}	**	**	*
	Three months	0.71	0.92	0.93	0.85 ^{b}	± Standard Error		
	Four months	0.77	0.61	0.92	0.77 ^{b}	0.04	0.05	0.08
	Overall	0.80 ^{B}	0.88 ^{B}	0.98 ^{A}				
T3, ng mL^{-1}	Zero time	5.02	4.57	5.68	5.09 ^{b}			
	One months	4.63	4.10	5.45	4.73 ^{b}		Sig.	
	Two months	5.32	3.97	6.33	5.21 ^{b}	**	**	(NS)
	Three months	5.17	4.12	4.82	4.70 ^{b}	± Standard Error		
	Four months	5.97	5.00	7.17	6.04 ^{a}	0.23	3.30	0.51
	Overall	5.22 ^{B}	4.35 ^{C}	5.89 ^{A}				
T4, ng mL^{-1}	Zero Time	93.85	88.87	98.70	93.81 ^{a}			
	One months	78.27	71.65	88.33	79.42 ^{b}		Sig.	
	Two months	88.32	74.88	96.82	86.67 ^{ab}	**	**	(NS)
	Three months	77.55	68.12	80.18	75.28 ^{b}	± Standard Error		
	Four months	95.68	81.08	103.75	93.51 ^{a}	3.09	3.99	6.90
	Overall	86.73 ^{B}	76.92 ^{B}	93.56 ^{A}				

Means with different letters are statistically different (P<0.05). A, B, C= Values with different letters on the same row differ at (P<0.05), a, b = Values with different letters on the same column differ at (P<0.05). NS: Non-significant. * Significant.

Table 6: Least Square mean values of liver and kidney functions indices in growing Barki lambs fed a basic diet supplanted with biologically treated Trimming Waste of Mandarin Trees

Item	Time	Groups			Overall	Sig. ± Standard Error		
		Control	Untreated ration	Treated ration		G	M	G×M
ALT *IU L-1*	Zero Time	86.88	80.12	73.88	80.31 ^{ab}			
	One months	88.43	82.27	96.08	88.93 ^{a}		Sig.	
	Two months	87.70	61.22	76.42	75.11^{bc}	**	**	(NS)
	Three months	80.15	74.37	76.17	76.89^{bc}		± Standard Error	
	Four months	77.03	59.90	66.70	67.88 ^{c}	2.79	3.60	6.24
	Overall	84.04 ^{A}	71.58 ^{B}	77.85 ^{AB}				
AST IU *L-1*	Zero time	69.75	69.12	63.43	67.43			
	One months	71.65	66.18	62.33	66.72		Sig.	
	Two months	79.93	72.77	65.32	72.67	*	(NS)	(NS)
	Three months	77.95	71.18	65.77	71.63		± Standard Error	
	Four months	73.98	66.57	62.45	67.67	2.83	3.65	6.33
	Overall	74.65 ^{A}	69.16 ^{AB}	63.86 ^{B}				
GGT *IU L-1*	Zero time	48.68	51.52	41.97	47.39 ^{a}			
	One months	44.43	47.77	42.27	44.82 ^{ab}		Sig.	
	Two months	45.33	48.32	40.07	44.57 ^{ab}	**	**	(NS)
	Three months	42.17	45.20	33.07	40.14 ^{b}		± Standard Error	
	Four months	42.77	44.27	35.77	40.93 ^{b}	1.20	1.55	2.68
	Overall	44.68 ^{A}	47.41 ^{A}	38.63 ^{B}				
Alkaline phosphatase U L-1	Zero time	86.23	86.65	84.90	85.93			
	One months	72.92	70.07	52.35	65.11		Sig.	
	Two months	84.52	91.62	67.80	81.31	*	(NS)	(NS)
	Three months	81.15	77.12	58.65	72.31		± Standard Error	
	Four months	87.00	90.37	70.87	82.74	5.41	6.99	12.10
	Overall	82.36 ^{A}	83.16 ^{A}	66.91 ^{B}				
Creatinine, mg dL-1	Zero Time	2.10	1.12	1.61	1.61			
	One months	1.72	1.31	1.42	1.48		Sig.	
	Two months	1.72	1.54	1.35	1.54	**	(NS)	(NS)
	Three Months	1.85	1.32	1.53	1.57		± Standard Error	
	Four months	2.03	1.74	1.82	1.86	0.08	0.10	0.18
	Overall	1.88 ^{A}	1.41 ^{B}	1.54 ^{B}				
Urea, mg dL-1	Zero time	46.45	45.07	35.20	42.24			
	One months	48.38	44.58	24.48	39.15		Sig.	
	Two months	49.77	39.27	36.42	41.82	**	(NS)	(NS)
	Three months	49.72	44.82	37.77	44.10		± Standard Error	
	Four months	43.08	37.50	27.80	36.13	2.33	3.01	5.22
	Overall	47.48 ^{A}	42.25 ^{A}	32.33 ^{B}				

Means with different letters are statistically different (P<0.05). A, B, C= Values with different letters on the same row differ at (P<0.05), a, b = Values with different letters on the same column differ at (P<0.05). NS: Non-significant. * Significant.

3.6. Immunoglobulin G (IgG) and total antioxidant capacity (TAC)

Immunologic protection and antioxidative status parameters are detailed in table 7. Plasma IgG concentration was significantly higher (P<0.05) in the TR group (2.33 ng mL^{-1}) than in the CR group

(1.50 ng mL^{-1}), while UR was intermediate (2.07 ng mL^{-1}). TAC was significantly increased (P<0.05) in TR (0.90 nmol mL^{-1}) and UR (0.79 nmol mL^{-1}) compared to CR (0.60 nmol mL^{-1}).

Table 7: Least Square mean values immunoglobulin G, some immuno-cytokines indices and antioxidant capacity in growing Barki lambs fed a basic diet supplanted with biologically treated Trimming Waste of Mandarin Trees

Item	Time	Groups			Overall	Sig. ± Standard Error		
		Control	Untreated ration	Treated ration		G	M	G×M
Interleukin (1), pg mL^{-1}	Zero Time	67.84	63.44	69.36	66.88			
	One months	55.21	53.92	67.98	59.04		Sig.	
	Two Months	63.70	73.63	71.18	69.50	(NS)	(NS)	(NS)
	Three onths	64.57	60.06	52.64	59.09	± Standard Error		
	Four months	60.40	66.74	52.04	59.73	3.37	5.64	9.76
	Overall	62.34	63.56	62.64				
Interleukin (2), pg mL^{-1}	Zero Time	40.67	31.05	35.23	35.65			
	One months	39.05	29.40	36.65	35.03		Sig.	
	Two months	40.52	29.47	36.50	35.49	**	(NS)	(NS)
	Three Months	40.78	32.75	34.15	35.89	± Standard Error		
	Four months	39.13	28.08	37.67	34.96	1.41	1.82	3.15
	Overall	40.03 ^{A}	30.15 ^{C}	36.04 ^{B}				
Interleukin (6), pg mL^{-1}	Zero Time	80.63	72.03	77.17	76.61 ^{a}			
	One months	68.58	60.95	69.72	66.42 ^{ab}		Sig.	
	Two months	67.95	59.85	65.80	64.53 ^{b}	**	(NS)	(NS)
	Three months	76.65	63.95	70.58	70.39 ^{ab}	± Standard Error		
	Four months	89.40	62.92	72.27	74.86 ^{ab}	2.75	3.55	6.15
	Overall	76.64 ^{A}	63.94 ^{B}	71.11 ^{AB}				
Tumor necrosis factor alfa, pg mL^{-1}	Zero Time	45.30	39.66	46.82	43.93			
	One months	48.65	34.03	47.62	43.43		Sig.	
	Two months	60.20	36.40	42.36	46.32	**	(NS)	(NS)
	Three months	50.37	28.84	39.01	39.41	± Standard Error		
	Four months	43.64	37.34	40.72	40.56	2.56	3.30	5.72
	Overall	49.63 ^{A}	35.26 ^{B}	43.31 ^{A}				
IgG, ng mL^{-1}	Zero time	1.92	1.78	1.87	1.86 ^{bc}			
	One months	1.92	3.52	3.06	2.83 ^{a}		Sig.	
	Two months	1.66	2.16	3.26	2.36 ^{ab}	*	**	(NS)
	Three months	0.93	1.49	1.62	1.35 ^{c}	± Standard Error		
	Four months	1.05	1.37	1.86	1.43 ^{bc}	0.25	0.32	0.55
	Overall	1.50 ^{B}	2.07 ^{AB}	2.33 ^{A}				
Total antioxidant capacity, nmol mL^{-1}	Zero Time	0.57	0.58	0.53	0.56 ^{b}			
	One months	0.58	0.73	0.85	0.72 ^{ab}		Sig.	
	Two months	0.67	1.09	1.08	0.95 ^{a}	*	**	(NS)
	Three months	0.58	0.65	1.00	0.74 ^{ab}	± Standard Error		
	Four months	0.59	0.89	1.04	0.84 ^{a}	0.07	0.08	0.15
	Overall	0.60 ^{B}	0.79 ^{A}	0.90 ^{A}				

Means with different letters are statistically different (P<0.05). A, B, C= Values with different letters on the same row differ at (P<0.05), a, b = Values with different letters on the same column differ at (P<0.05). NS: Non-significant. * Significant.

Higher IgG levels provide humoral protection, reducing susceptibility to infectious pathogens and diarrhea (Teleb *et al.,* 2009). The parallel increases in total protein, globulin, and IgG demonstrate robust immune status passive support in lambs fed biologically treated waste.

The elevation in total antioxidant capacity in TWMT-fed groups is attributed to the rich phytochemical profile of mandarin pruning residues, including polyphenols, bioflavonoids, and essential oils (Wadhwa *et al.*, 2015; Saini *et al.*, 2019). These bioactive compounds neutralize free radicals, suppress lipid peroxidation, and bolster the endogenous antioxidant defense system, maintaining cellular integrity under environment-induced oxidative stress.

3.7. Blood glucose and lipid profile

Metabolic energy substrates and serum lipid fractions are presented in table 8. Glucose concentration was significantly lower (P<0.05) in the TR group (55.65 mg dL^{-1}) compared to the control group (70.92 mg dL^{-1}), while UR was intermediate (63.56 mg dL^{-1}). All values remained within the physiological norm for growing lambs (50−80 mg dL^{-1}).

Table 8: Least Square mean values blood glucose and lipid profile in growing Barki lambs fed a basic diet supplanted with biologically treated Trimming Waste of Mandarin Trees

	Time	Groups			Overall	Sig. ± Standard Error		
		Control	Untreated ration	Treated ration		G	M	G×M
Glucose, mg dL^{-1}	Zero Time	63.94	55.98	45.10	55.00			
	One months	69.98	63.35	53.51	62.28		Sig.	
	Two months	74.01	67.92	59.61	67.18	**	(NS)	(NS)
	Three months	76.67	69.70	67.52	71.30		± Standard Error	
	Four months	69.99	60.87	52.51	61.12	3.70	4.78	2.28
	Overall	70.92 ^{A}	63.56 ^{AB}	55.65 ^{B}				
Total Lipids mg dL^{-1}	Zero Time	205.88	175.92	193.42	191.74			
	One months	212.30	211.22	210.42	211.33		Sig.	
	Two Months	241.55	151.48	163.12	185.38	**	(NS)	(NS)
	Three Months	209.10	160.25	190.00	186.45		± Standard Error	
	Four Months	215.66	177.75	190.60	194.67	5.90	8.88	14.66
	Overall	216.90 ^{A}	175.32 ^{C}	189.51 ^{B}				
Total Cholesterol mg dL^{-1}	Zero Time	127.89	118.40	101.22	115.84 ^{b}			
	One months	125.91	121.01	115.25	120.72 ^{a}		Sig.	
	Two Months	126.23	119.61	109.41	118.42 ^{ab}	**	*	(NS)
	Three Months	125.95	120.52	110.36	118.94 ^{ab}		± Standard Error	
	Four Months	127.97	124.12	116.49	122.86 ^{a}	1.60	1.78	2.86
	Overall	126.79 ^{A}	120.73 ^{B}	110.55 ^{C}				
HDL mg dL^{-1}	Zero Time	68.11	68.17	66.08	67.45^{ab}			
	One months	76.82	70.42	62.04	69.76^{a}		Sig.	
	Two Months	65.12	63.97	54.85	61.31^{c}	*	**	*
	Three Months	71.40	65.02	63.27	66.56^{b}		± Standard Error	
	Four Months	63.34	62.87	61.24	62.48c	1.33	1.62	2.99
	Overall	68.96 ^{A}	66.09 ^{B}	61.50 ^{C}				
LDL mg dL^{-1}	Zero Time	27.24	23.65	17.41	22.77^{b}			
	One months	28.32	22.88	20.90	24.03^{b}		Sig.	
	Two Months	31.52	29.08	25.78	28.79^{a}	**	**	(NS)
	Three Months	34.11	29.08	21.48	28.22^{a}		± Standard Error	
	Four Months	30.14	23.54	25.45	26.38^{ab}	0.99	1.24	2.00
	Overall	30.27 ^{A}	25.65 ^{B}	22.20 ^{C}				

Means with different letters are statistically different (P<0.05). A, B, C= Values with different letters on the same row differ at (P<0.05), a, b = Values with different letters on the same column differ at (P<0.05). NS: Non-significant. * Significant WBCs: White blood cells.

Feeding TWMT led to a significant overall hypolipidemic effect (P<0.05). Total lipids (TL) were significantly lower in UR (175.32 mg dL^{-1}) and TR (189.51 mg dL^{-1}) than in CR (216.90 mg dL^{-1}). Total cholesterol (TC) decreased significantly in TR (110.55 mg dL^{-1}) compared to UR (120.73 mg dL^{-1}) and CR (126.79 mg dL^{-1}). High-density lipoprotein (HDL) and low-density lipoprotein (LDL) fractions also showed significant reductions in the TR group (61.50 and 22.20 mg dL^{-1}) compared to control (68.96 and 30.27 mg dL^{-1}), respectively.

Blood glucose in ruminants is regulated primarily by propionate production via ruminal fermentation of carbohydrates (Busquet *et al.*, 2006). The observed glucose levels reflect stable dry matter intake and normal gluconeogenic activity within physiological ranges (Kaneko, 1989).

The hypolipidemic and hypocholesterolemic effects of TWMT diets are mediated by several bioactive secondary metabolites: Tannins: Form complexes along the intestinal mucosa, inhibiting dietary cholesterol absorption (Oluremi *et al.*, 2007). Saponins: Bind gastrointestinal cholesterol into insoluble complexes, increasing fecal excretion (Malinow *et al.*, 1987). Flavonoids: Suppress intestinal micelle formation, upregulate hepatic LDL receptor expression, and modulate lipid oxidation and adipocyte function (Brusq *et al.,* 2006; Gropper *et al.,* 2009*;* Galleano *et al.,* 2012). These combined mechanisms improve overall lipid metabolism, protect cardiovascular function, and reduce fat accumulation, confirming the nutritional value of citrus by-products in small ruminant feeding regimens (Alabi *et al.*, 2021; Assar *et al.*, 2023).

4. Conclusion

Utilizing biologically treated trimming waste of mandarin trees (TWMT + Bio-Magic) as a non-conventional roughage source can successfully replace traditional roughages. It improves growth performance, metabolic efficiency, antioxidant activity, and immune response without adverse effects on liver or kidney functions, offering an eco-friendly and cost-effective feeding strategy in arid region oasis conditions.

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