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Leverage of Curcumin Nanoliposome against Heat Stress in New Zealand Male Rabbits

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Abstract

CLIMATE change has increased the frequency of heat waves, thereby exacerbating heat stress a critical factor affecting livestock productivity with rabbits being particularly susceptible to elevated temperatures. This study evaluated the efficacy of curcumin and curcumin nanoliposomes in mitigating heat stress in growing male rabbits. Ninety 35-day-old male rabbits were randomly assigned to six experimental groups (n = 15 per group) and maintained under thermoneutral conditions (18.2 ± 2.6°C; 38.8 ± 2.8% relative humidity) or heat stress conditions (36.4 ± 1.1°C; 70.3 ± 5.8% relative humidity). Treatment effects were assessed by measuring serum thyroid hormones, testosterone, oxidative and antioxidant biomarkers, liver and kidney function parameters, serum interleukin-4 (IL-4) levels, heat shock protein 70 (HSP70) expression, and meat quality indices. The results indicate that both curcumin and its nanoliposome formulation significantly enhanced serum thyroid hormone and testosterone levels, particularly under heat stress conditions. Although curcumin alone exhibited minimal effects on IL-4 levels, curcumin nanoliposomes markedly reduced these levels during heat stress, underscoring their anti-inflammatory potential. Additionally, dietary supplementation with curcumin formulations effectively maintains meat quality by mitigating oxidative stress and preserving the nutritional composition of breast muscle tissue. These findings suggest that incorporating curcumin, particularly in its nanoliposome form, into rabbit diets can be a promising strategy to alleviate heat stress, improve physiological and metabolic functions, reduce inflammation, and sustain meat quality under elevated temperature conditions.

Keywords: Curcumin, curcumin nanoliposome, rabbits, climatic changes, reproduction, immunity, meat quality.

Introduction

Rabbit production is a significant aspect of farm animal husbandry due to its high nutritional value. Rabbits are well-regarded for their rapid reproduction rates and economic efficiency [1]. They serve as a primary source of white meat, known for its high-quality protein, low-fat content, and low cholesterol levels [2].

Recently, there has been increased attention on enhancing the growth performance of rabbits to

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maximize meat production through dietary supplements [3]. In tropical regions like Egypt, rabbits experience heat stress due to non-functional sweat glands and dense fur. This hampers their ability to dissipate heat, resulting in higher production costs and reduced efficiency. Additionally, oxygen-derived free radicals worsen oxidative stress [4].

The use of eco-friendly food additives to counteract the adverse effects of heat stress is gaining importance [5]. Fortifying diets with natural antioxidants from herbal sources, known as phytogenic additives, is recommended to improve the health and production of heat-stressed rabbits [6]**.**

Curcumin, derived from the turmeric plant (Curcuma longa), has shown promising therapeutic effects. As a natural antioxidant and growth promoter, curcumin is a xanthophyll carotenoid isolated from turmeric [7]. This compound possesses primary antioxidant properties that neutralize oxygen free radicals. Its conjugated structure disrupts the oxidant chain reaction [8]. Moreover, curcumin exhibits antibacterial, immunomodulatory, anti-inflammatory, antimutagenic, and anticancer properties [9]**.** However, challenges such as poor absorption, rapid metabolism, and quick systemic elimination hinder its biological stability and bioavailability [10].

Nanotechnology offers a potential solution by enhancing the bioavailability and solubility of curcumin through nanoparticles [11]. In vivo studies indicate that nano-curcumin has a higher tissue distribution and longer biological half-life compared to standard curcumin [12].

This study aims to investigate the effects of nano-curcumin on alleviating heat stress in male New Zealand rabbits. The goal is to develop a novel approach to managing heat stress, ultimately improving the health and productivity of rabbits in regions with high ambient temperatures.

Material and Methods

Reagents

Curcumin (product number: NIST3300; Sigma-Aldrich) and curcumin nanoliposomes were prepared according to Homayoonfal et al. [13].

Preparation and characterization of curcumin nanoliposomes

The preparation of curcumin nanoliposomes, as outlined by Homayoonfal et al. [13], involves key ingredients: curcumin, soy lecithin, cholesterol, and phosphate-buffered saline (PBS). First, soy lecithin and cholesterol are dissolved in a 4:1 ratio, while curcumin is mixed in a 2:1 solution of chloroform and methanol. This mixture is placed in a flask with glass beads and processed with a rotary evaporator to create a thin lipid layer. The layer is then hydrated with PBS (pH 6.5) at 60°C, and after three hours, a lipid vesicular suspension forms.

For Characterization, the shape of the prepared nanoparticles was investigated by Transmission Electron Microscope (TEM) (EM-2100 High-Resolution at Magnification). The hydrodynamic particle size was examined via dynamic light scattering techniques (NICOMP 380 ZLS, Dynamic light scattering (DLS) instrument. The zeta potential of the prepared nanoparticle was measured using the Malvern device. 2D and 3D surface geographical images of curcumin nanoliposomes were produced by an atomic force microscope (AFM) instrument (Agilent, model 5600LS, USA).

Animals and experimental design:

This experiment was conducted by the Animal Health Research Institute at the Agriculture Research Center in Egypt. New Zealand weaned male rabbits (n= 90) aged 5-wk and weighing 691± 10.8 g were obtained from a private rabbit farm, in Giza Governorate. Rabbits were distributed into six equal groups (15 rabbits in each). The experimental design was tabulated (Table 1).

All rabbits were individually housed in galvanized wire cages measuring 35 × 35 × 60 cm. Each cage was equipped with a feeder and a nipple providing fresh water, and the rabbits were given free access to food. The rabbits in all groups were subjected to the same management, hygiene, and environmental conditions. The control diet provided all the necessary nutrients for growing rabbits [14]. The curcumin and curcumin nanoliposomes were thoroughly mixed according to their dosage. Feed amounts were formulated and adjusted every week. During an eight-week growing period, we documented the ambient temperature, relative humidity, and temperature-humidity index [15].

The protocol of this study was approved by the Animal Health Research Institute (AHRI), Agriculture Research Centre (ARC), Giza, Egypt with the approved code: (AHRI;12/2020).

Samples collection

At the end of the experiment, at 13 wk. of age, blood samples were obtained from the rabbits. The collected samples were allowed to coagulate within a test tube for 30 minutes. Subsequently, they were centrifuged at 4000 revolutions per minute (rpm) for 15 minutes. Finally, the processed samples were stored at a temperature of -70°C. These blood samples were the basis for assessing various parameters, including testosterone levels, T3 and T4 hormones, oxidant/antioxidant indicators, Hsp70 levels, and liver and kidney enzyme activity.

Determination of serum thyroid hormones and testosterone

Serum concentrations of triiodothyronine (T3), thyroxine (T4), and testosterone were quantified using HPLC-UV, following the method outlined by El-Sheshtawy et al. [16]. The detection limits for T3, T4, and testosterone were 0.0013 ng/mL, 0.003 ng/mL, and 0.27 ng/mL, respectively. Moreover, the separation of these hormones was completed in under 10 minutes with high linearity (Figure 1 and 2).

Determination of serum oxidants/antioxidants

The spectrophotometric determination of malondialdehyde (MDA), an indicator of oxidative stress, and glutathione (GSH), a biomarker of antioxidant parameters, total antioxidant capacity (TAC), and superoxide dismutase (SOD) were reported by Ohkawa et al. [17], Beutler [18], Miller and Rice-Evans [19], and Sun et al. [20].

Determination of liver and kidney function

Serum alanine aminotransferase (ALT), aspartate aminotransferase (AST) activities, and total protein concentrations were determined using commercial kits, following the protocols described by Reitman and Frankel [21] and Doumas et al. [22], respectively. Additionally, serum creatinine and urea concentrations were quantified using spectrophotometric methods as outlined by Perakis and Wolff [23] and Searcy [24], respectively.

Determination of serum IL-4

Serum interleukin-4 (IL-4) concentrations were quantified using the Rabbit Interleukin-4 (IL-4) ELISA Kit (Cat. No. MBS2508855; MyBioSource Co.). The assay demonstrated a detection range of 15.63–1000 pg/mL and a sensitivity of 9.38 pg/mL.

Determination of serum HSP70

The concentration of HSP70 was determined using the Rabbit Heat Shock Protein 70 ELISA Kit (Cat. No. MBS727268; MyBioSource Co.). A standard curve was generated over a range of 0–50 ng/mL.

Determination of meat quality

A Jenway 3505 pH meter (Jenway, Staffordshire, United Kingdom) was employed to determine the pH of rabbit breast meat samples. The probe was calibrated using two standard buffer solutions (pH 4 and pH 7), with calibrations repeated between each measurement to ensure consistent accuracy. The chemical composition of breast meat, including protein, fat, and ash, was subsequently analyzed following the methods outlined by the AOAC [25].

Results

Characterization

Figure 3 represented the results of the characterization techniques employed for the curcumin nanoliposomes. Transmission electron microscopy (TEM) revealed that the particles are predominantly spherical to subspherical, with diameters ranging from 40 to 60 nm, and they exhibit minimal aggregation. Atomic force microscopy (AFM) corroborated these observations by demonstrating the spherical morphology and homogeneous dispersion of the nanoliposome matrix. Dynamic light scattering measurements using a Zetasizer determined that the average particle size was 55.4 ± 0.01 nm, with a zeta potential of +29.25 ± 0.01 mV. This high zeta potential significantly contributes to the colloidal stability of the nanoliposome in water, which is likely associated with the enhanced bioactivity of the curcumin nanoliposomes.

Serum thyroid hormones and testosterone

Curcumin and its nanoliposome formulation significantly elevate serum thyroid hormone and testosterone levels in male rabbits under both thermoneutral and heat-stressed conditions; notably, after curcumin nanoliposome supplementation, the hormone levels in heat-stressed rabbits approach those observed under thermoneutral conditions (Table 2).

Serum oxidants/antioxidants

Under thermoneutral conditions, curcumin alone does not significantly alter serum oxidant or antioxidant markers in rabbits. In contrast, curcumin nanoliposomes reduce malondialdehyde (MDA) levels and increase both superoxide dismutase (SOD) activity and total antioxidant capacity (TAC). Heat stress markedly elevates serum MDA while decreasing SOD and TAC; however, supplementation with curcumin nanoliposomes significantly improves the oxidative status of male rabbits under both thermoneutral and heat-stressed conditions (Table 3).

Liver and kidney function

In thermoneutral rabbits, curcumin does not impact the parameters of hepatorenal function. However, curcumin nanoliposome significantly reduces all of these parameters, except for total protein levels. Under heat stress, levels of ALT, AST, urea, and creatinine increase significantly, while total protein levels decrease. Supplementation with curcumin nanoliposome is more effective than curcumin alone in improving these levels, helping to restore them to normal (Table 4).

Serum IL-4

Figure 4 illustrates that curcumin administration does not significantly affect serum IL-4 levels in rabbits under either thermoneutral or heat-stressed conditions. Notably, although heat stress significantly elevates serum IL-4 concentrations, treatment with curcumin nanoliposomes markedly reduces these levels.

Serum HSP70

During heat stress, rabbits receiving curcumin or curcumin nanoliposome supplementation exhibited significantly higher serum HSP70 levels compared to control groups. During heat stress, rabbits receiving curcumin or curcumin nanoliposome supplementation exhibited significantly higher serum HSP70 levels compared to control groups (Figure 5).

The physicochemical characteristics of breast muscle

Heat stress has been shown to elevate the pH levels of rabbit breast muscle while reducing its chemical composition percentages. In thermoneutral conditions, the inclusion of curcumin and curcumin nanoliposomes in the diet does not influence the pH of breast muscle. However, their administration contributes to pH stabilization. Furthermore, the chemical composition analysis reveals that the supplementation of curcumin and curcumin nanoliposomes under thermoneutral conditions results in a significant increase in the protein percentage of breast muscle. Additionally, this supplementation enhances the percentages of protein, fat, and ash, as outlined in Table 5.

Discussion

Heat stress exerts detrimental effects on serum thyroid hormones and testosterone through several mechanisms. One principal impact involves the disruption of the hypothalamic-pituitary-gonadal (HPG) axis, which impairs the secretion of gonadotropin-releasing hormone (GnRH). This disruption subsequently decreases luteinizing hormone (LH) and follicle-stimulating hormone (FSH) levels, both of which are essential for testosterone synthesis and spermatogenesis, ultimately compromising reproductive health [26].

Additionally, heat stress increases testicular temperature, a critical factor since the testes require a temperature 2–6°C lower than the core body temperature for optimal function. Elevated temperatures can damage testicular tissue and reduce testosterone synthesis, potentially leading to long-term reproductive issues [27]. Furthermore, heat stress enhances aromatase activity in Leydig cells, promoting the conversion of testosterone into oestradiol and thereby contributing to hormonal imbalances that may reduce fertility [28]. Prolonged exposure to high temperatures also decreases plasma levels of thyroxine (T4) and triiodothyronine (T3), which are critical for metabolic regulation, further exacerbating the negative consequences of heat stress [29].

The physiological ramifications of reduced thyroid hormones and testosterone are extensive. In male adolescents, low testosterone can lead to delayed puberty, incomplete sexual maturation, reduced lean body mass, increased fat deposition, and compromised bone mineral density [30]. Conversely, curcumin and its nanoliposome formulation have demonstrated the capacity to significantly enhance serum thyroid hormone and testosterone levels in male rabbits, particularly under heat stress conditions. The improved bioavailability of curcumin nanoliposomes, which facilitates greater absorption and utilization of their beneficial properties, underscores their potential as a promising intervention for managing heat-induced hormonal imbalances [31].

In our study, curcumin exhibited minimal effects on serum oxidant and antioxidant levels in rabbits maintained under thermoneutral conditions. Under these conditions, rabbits display a balanced production of reactive oxygen species (ROS) and antioxidant enzymes, thereby reducing the need for supplemental antioxidant protection [32]. Conversely, when the equilibrium between ROS production and natural antioxidant defences is disrupted under heat stress, curcumin markedly enhances the antioxidant defence system, mitigating oxidative damage.

The beneficial effects of curcumin are especially apparent under stressful conditions. In the absence of stressors, the demand for additional exogenous antioxidant support diminishes [33]. Furthermore, Wu et al. [34] demonstrated that curcumin treatment significantly attenuates heatstroke-induced lung injury, as evidenced by improved lung histopathology, reduced inflammatory responses, and enhanced activation of the PI3K/AKT pathway. This finding suggests that the PI3K/AKT pathway plays a key role in mediating curcumin’s protective effects under heat stress.

Heat stress serves as a significant instigator of oxidative stress in animals, including rabbits, by disrupting the balance between ROS production and the body’s inherent antioxidant defenses. Akbarian et al. [35] reported that such an imbalance leads to increased oxidative damage, as indicated by elevated levels of malondialdehyde (MDA), a marker of lipid peroxidation. Additionally, heat stress results in decreased levels of critical antioxidant enzymes such as superoxide dismutase (SOD) and a concomitant reduction in total antioxidant capacity (TAC), thereby compromising the overall antioxidant defense system [36].

Recent evidence indicates that curcumin nanoliposomes offer significant potential in combating oxidative stress. These formulations, with their enhanced solubility, stability, and bioavailability, exert more pronounced antioxidant effects than conventional curcumin [37]. Notably, nano-curcumin supplementation significantly reduces serum MDA levels while increasing SOD concentrations, thereby elevating the TAC. These observations are in agreement with the findings of Karimi et al. [38], who reported that nano-curcumin markedly decreases MDA levels and simultaneously elevates SOD and TAC in serum. Overall, these results suggest that while curcumin may have limited antioxidant effects under thermoneutral conditions, its nanoliposome formulation effectively reinforces the oxidative defense system during heat stress, offering a promising therapeutic strategy for managing oxidative damage.

Interleukin-4 (IL-4) is a crucial cytokine involved in the regulation of immune responses, particularly in modulating inflammation and allergic reactions [39]. Research indicates that curcumin alone does not significantly influence serum IL-4 levels in rabbits, whether maintained under thermoneutral conditions or exposed to heat stress, suggesting that curcumin by itself may be insufficient to modulate this specific aspect of the immune response [40]. In contrast, exposure to high temperatures elevates oxidative stress and inflammation, which is reflected in a significant increase in serum IL-4 levels, an indicator of an enhanced inflammatory response that may adversely affect animal health [41]. Notably, curcumin nanoliposomes, owing to their improved bioavailability and enhanced efficacy, have demonstrated superior anti-inflammatory effects by effectively modulating serum IL-4 levels. These findings concur with El-Ratel et al. [42] and Dutta et al. [43], who reported that curcumin nanoliposomes are more effective than conventional curcumin in reducing the inflammatory response induced by heat stress.

Heat shock protein 70 (HSP70) plays a critical role in cellular homeostasis by facilitating protein folding, preventing protein aggregation, and assisting in the refolding or degradation of damaged proteins [44]. Under stress conditions, such as thermal insult, the expression of HSP70 is markedly upregulated as a protective mechanism against cellular damage [45].

In studies involving rabbits, supplementation with curcumin or curcumin nanoliposomes under thermoneutral conditions resulted in elevated serum HSP70 levels. This observation suggests that these supplements may be prime cellular defense mechanisms, thereby enhancing the ability of the cells to cope with future stressors such as heat or oxidative challenges [46]. During heat stress, rabbits receiving these dietary interventions exhibited significantly higher serum HSP70 levels compared to control groups, a response that contributed to the maintenance of cellular integrity by mitigating the adverse effects of protein denaturation and aggregation [45].

The underlying mechanism appears to involve the activation of the Nrf2 pathway by curcumin, which in turn upregulates not only HSP70 but also a range of antioxidative enzymes that collectively bolster cellular defenses against oxidative stress [47]. Supporting these findings, studies in other species have demonstrated that curcumin supplementation can enhance heat stress tolerance by increasing the expression of HSP70 and related antioxidative enzymes [48].

Notably, curcumin nanoliposomes owing to their enhanced bioavailability have exhibited superior efficacy in upregulating HSP70 compared to conventional curcumin. Research using heat stroke models has shown that nanoliposome formulations, such as poly(amidoamine) nanoparticles loaded with curcumin, provide greater neuroprotection against heat-induced damage than curcumin alone [49]. Similarly, nanovesicles loaded with curcumin have been found to mitigate neuroferroptosis and reduce oxidative stress more effectively, thereby preserving neural cell integrity in the context of heat stroke [50]. Collectively, these findings underscore the potential of curcumin, particularly in its nanoliposome form, to enhance stress resilience by modulating HSP70 expression and activating key antioxidative pathways.

Under thermoneutral conditions, where ambient temperatures remain within the rabbits' comfort zone, the administration of curcumin and its nanoliposome formulation does not significantly alter the pH of the breast muscle, indicating that the physiological state remains stable and meat quality is preserved [51,52]. In contrast, heat stress generally elevates muscle pH due to glycogen depletion and the consequent reduction in lactic acid production [53,54]**.** Elevated temperatures also negatively impact the chemical composition of rabbit breast muscle by decreasing protein content through the activation of catabolic processes [55], reducing fat content as increased energy demands mobilize lipid reserves [56], and diminishing ash content as minerals are reallocated to sustain critical physiological functions such as electrolyte balance and thermoregulation—a situation further exacerbated by disrupted feed intake [4, 57]. Notably, supplementation with curcumin and its nanoliposome formulation during heat stress mitigates these deleterious effects by enhancing antioxidant defenses and reducing oxidative damage, thereby stabilizing protein, fat, and ash levels [58]. Collectively, these findings underscore the potential of curcumin nanoformulations to maintain both the pH and chemical composition of rabbit breast muscle under varying thermal conditions, ultimately ensuring meat quality and animal welfare.

Conclusion:

Our study demonstrates that heat stress negatively impacts endocrine function and muscle integrity in rabbits by disrupting the hypothalamic-pituitary–gonadal axis, reducing serum thyroid hormones and testosterone, and altering muscle chemical composition through enhanced catabolic activity and oxidative damage. Elevated ambient temperatures lead to glycogen depletion, increased muscle pH, and diminished levels of protein, fat, and ash due to mobilization of reserves and impaired nutrient absorption. Notably, the administration of curcumin especially in its nanoliposome formulation mitigates these effects by enhancing antioxidant defenses, reducing oxidative stress, and stabilizing both hormonal levels and muscle composition. The improved bioavailability of curcumin nanoliposomes facilitates better absorption and targeted delivery, thereby preserving protein content, maintaining a balanced lipid profile, and stabilizing mineral composition even under thermal stress. and underscore the potential of curcumin nanoliposomes as a promising intervention to alleviate heat-induced physiological disruptions, ultimately contributing to improved animal welfare and production outcomes.

Recommendation

Rabbit producers operating in heat-stressed environments should consider incorporating curcumin nanoliposomes into the diet. Their enhanced bioavailability helps mitigate heat-induced hormonal disruptions, protein degradation, and oxidative damage, thereby preserving meat quality. Future research should focus on optimizing dosages and exploring synergies with other nutraceuticals.

Funding statement

This study didn't receive any funding support

Declaration of Conflict of Interest

The authors declare that there is no conflict of interest.

Ethical approval

The protocol of this study was approved by the Animal Health Research Institute (AHRI), Agriculture Research Centre (ARC), Giza, Egypt with the approved code: (AHRI;12/2020).

Data availability

Data is provided within the manuscript file.

Author ‘contributions

Maha S. Abd Elhafeez, Mohammed A. M. Saleh, Sahar Hagag, and Fady Sayed Youssef focused on preparing curcumin nanoliposomes and assessing serum thyroid hormones, testosterone levels, oxidative and antioxidant biomarkers, liver and kidney function indicators, as well as IL-4 and HSP70 levels. Meanwhile, Fadel Abdel-Fattah Mohammed, Eman Elkhawaga, Eman Shukry, and Gamilat A. Elsaid examined the physicochemical properties of breast muscle. All authors collaboratively designed the experiment, conducted data analysis and evaluation, and contributed to the manuscript preparation.

TABLE 1. Experimental design for leverage of curcumin nanoliposome against heat stress in New Zealand male rabbits.

Groups		Temperature	Humidity	Curcumin	Curcumin nanoliposome
Thermoneutral	TN	$18.2 \pm 2.6\ ^{o}C$	38.8 ± 2.8 %	-	-
Thermoneutral with curcumin	TNC			+	-
Thermoneutral with curcumin nanoliposome	TNCN			-	+
Heat shock	HS	$36.4 \pm 1.1\ ^{o}C$	70.3 ± 5.8 %	-	-
Heat shock with curcumin	HSC			+	-
Heat shock with curcumin nanoliposome	HSCN			-	+

TABLE 2. Effect of curcumin and curcumin nanoliposome on serum thyroid hormones and testosterone of male rabbits under heat stress.

	T3	T4	Testosterone
TN	0.87 ± 0.03^{a}	24.5 ± 1.74^{a}	1.55 ± 0.06^{a}
TNC	0.89 ± 0.03^{a}	31.7 ± 1.07^{b}	1.81 ± 0.09^{b}
TNCN	1.9 ± 0.1^{b}	44.9 ± 2.32^{c}	2.1 ± 0.22^{b}
HS	0.54 ± 0.05^{c}	9.54 ± 1.32^{d}	0.47 ± 0.08^{c}
HSC	0.68 ± 0.04^{d}	15.2 ± 0.83^{e}	0.86 ± 0.06^{d}
HSCN	1.38 ± 0.13^{e}	29.5 ± 1.88^{b}	1.61 ± 0.14^{ab}

Values were expressed as mean ± standard deviation (n= 15).
The different uppercase alphabetical letters in the same column mean significance (p-value < 0.05).

TABLE 3. Effect of curcumin and curcumin nanoliposome on serum oxidant/antioxidant levels of male rabbits under heat stress.

	MDA (U/mL)	TAC (mmol/mL)	SOD (U/mL)
TN	5.86 ± 0.18[a]	1062.2 ± 73.7[a]	19.1 ± 0.95[a]
TNC	5.78 ± 0.53[a]	1142.8 ± 83.8[a]	19.9 ± 1.6[a]
TNCN	3.86 ± 0.29[b]	1439.6 ± 62.5[b]	23.6 ± 0.78[b]
HS	10.1 ± 0.51[c]	623.4 ± 50.1[c]	5.52 ± 0.51[c]
HSC	8.74 ± 0.72[d]	890.4 ± 20.9[d]	7.2 ± 0.39[c]
HSCN	4.48 ± 0.28[e]	1149.8 ± 90.2[a]	15.1 ± 0.84[d]

Values were expressed as mean ± standard deviation (n= 15).

The different uppercase alphabetical letters in the same column mean significance (p-value < 0.05).

TABLE 4. Effect of curcumin and curcumin nanoliposome on serum Liver and kidney functions of male rabbits under heat stress.

	ALT (U/mL)	AST (U/mL)	Total protein (g/dl)	Urea (mg/dl)	Creatinine (mg/dl)
TN	49.04 ± 1.04[a]	23.68 ± 0.47[a]	8.04 ± 0.48[a]	91.76 ± 1.26[a]	0.71 ± 0.02[a]
TNC	48.68 ± 1.5[a]	23.62 ± 0.51[a]	8.08 ± 0.66[ab]	89.2 ± 1.64[a]	0.7 ± 0.01[a]
TNCN	44 ± 1.41[b]	20.36 ± 0.73[b]	7.38 ± 0.58[abc]	80.7 ± 0.84[b]	0.51 ± 0.02[b]
HS	55.8 ± 0.84[c]	35.4 ± 1.14[c]	5.62 ± 0.43[d]	176.4 ± 8.7[c]	1.01 ± 0.05[c]
HSC	55.4 ± 0.89[c]	29.66 ± 1.11[d]	6.5 ± 0.43[cd]	127.8 ± 8.3[d]	0.78 ± 0.03[d]
HSCN	49.42 ± 0.91[a]	23.3 ± 1.4[a]	7.3 ± 0.36[bc]	98.8 ± 4.27[e]	0.59 ± 0.03[e]

Values were expressed as mean ± standard deviation (n= 15).

The different uppercase alphabetical letters in the same column mean significance (p-value < 0.05).

TABLE 5. Effect of curcumin and curcumin nanoliposome on physicochemical characteristics of breast muscle in male rabbits under heat stress

	pH	Protein %	Fat %	Ash %
TN	5.86 ± 0.1[a]	23.4 ± 0.1a	3.5 ± 0.07[a]	1.2 ± 0.04[a]
TNC	5.85 ± 0.1[a]	23.6 ± 0.07[b]	3.6± 0.06[b]	1.2 ± 0.06[a]
TNCN	5.77 ± 0.1[a]	24.2 ± 0.08[b]	3.4 ± 0.1[a]	1.2 ± 0.07[a]
HS	6.47 ± 0.08[b]	21.8 ± 0.07[c]	2.7 ± 0.1[c]	1.1 ± 0.05[b]
HSC	6.05 ± 0.05[c]	22.4 ± 0.05[d]	2.9 ± 0.06[d]	1.2 ± 0.05[a]
HSCN	5.84 ± 0.1[a]	23.3 ± 0.2[a]	3.0 ± 0.1[e]	1.3 ± 0.07[c]

Data was expressed as mean ± standard error (n=15). Different small letters indicate significance between groups at p < 0.05

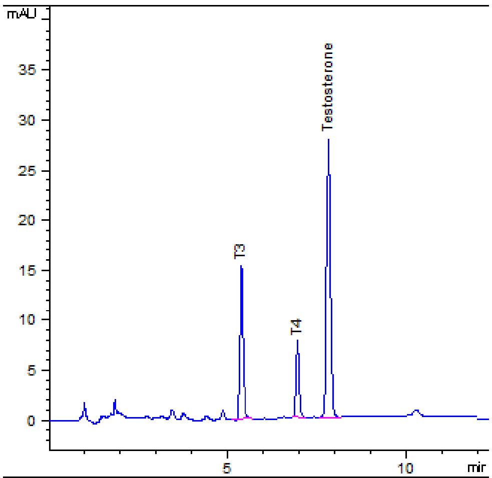


Fig. 1. Chromatogram displays the separation of 0.2 ng/mL of T3, T4, and testosterone hormones at retention times of 5.3, 6.7, and 7.88 minutes, respectively.

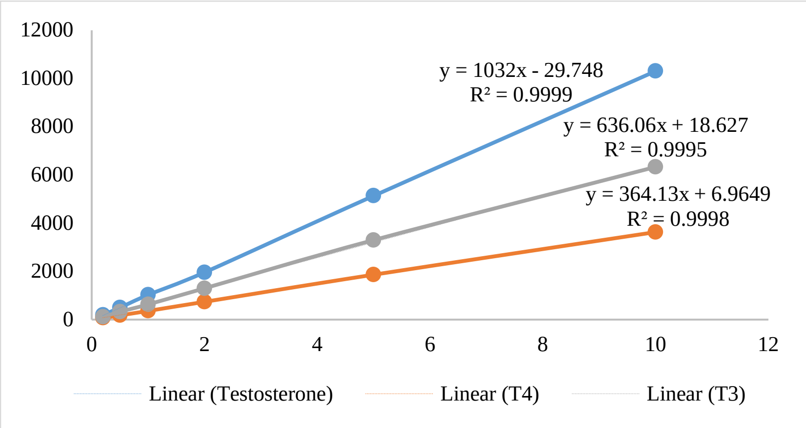


Fig. 2. Standard curves for testosterone, T3, and T4 by HPLC with regression equations.

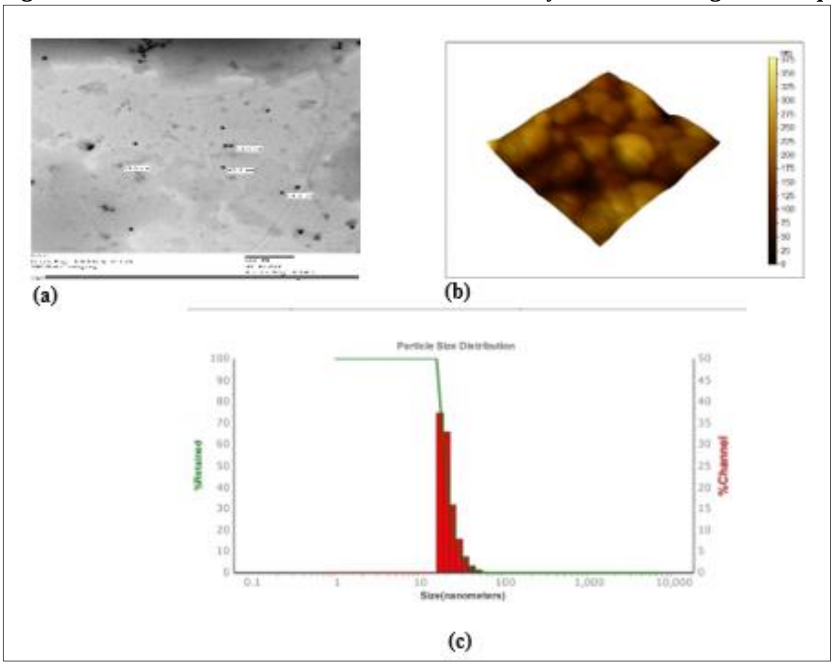
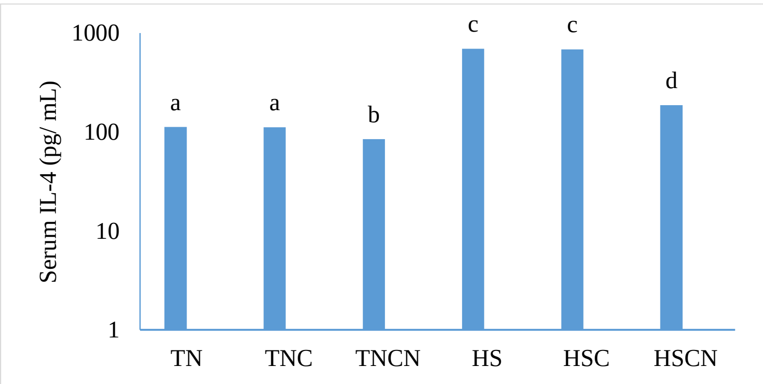
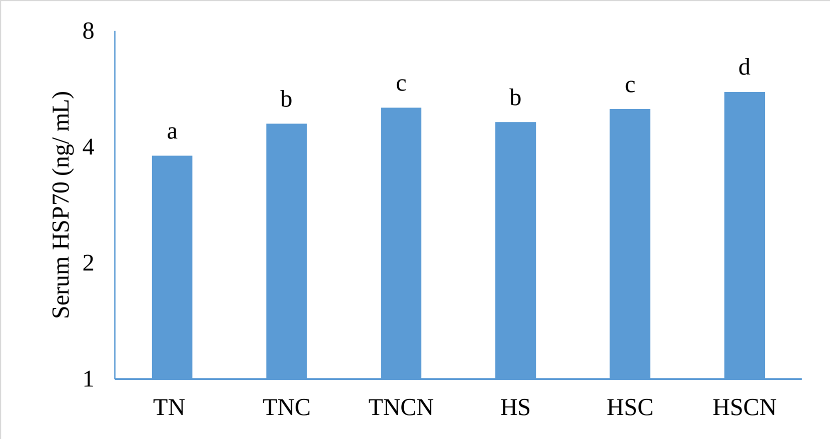


Fig. 3. Characterization (a) TEM. (b) AFM. (c) DLS of Curcumin Nanoliposome.



Data was expressed as mean ± standard error (n=15). Different small letters indicate significance between groups at $p < 0.05$.

Fig. 4. Effect of curcumin and curcumin nanoliposome on serum IL4 in male rabbits under heat stress.



Data was expressed as mean ± standard error (n=15). Different small letters indicate significance between groups at $p < 0.05$.

Fig. 5. Effect of curcumin and curcumin nanoliposome on serum HSP70 in male rabbits under heat stress.

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الاستفادة من نانوليبوزوم الكركمين في مواجهة الإجهاد الحراري لدى ذكور الأرانب النيوزيلندية

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الملخص

أدى تغير المناخ إلى زيادة وتيرة موجات الحر، مما أدى إلى تفاقم الإجهاد الحراري، وهو عامل حاسم يؤثر على إنتاجية القطعان، حيث تكون الأرانب أكثر عرضة لدرجات الحرارة المرتفعة. قيّمت هذه الدراسة فعالية الكركمين ونانوليبوزومات الكركمين في تخفيف الإجهاد الحراري لدى ذكور الأرانب النامية. تم توزيع تسعين أرنبًا ذكرًا بعمر 35 يومًا بشكل عشوائي على ست مجموعات تجريبية (15 لكل مجموعة) وحُفظت في ظروف محايدة حرارياً (18.2 ± 2.6 درجة مئوية؛ 38.8 ± 2.8٪ رطوبة نسبية) أو ظروف إجهاد حراري (36.4 ± 1.1 درجة مئوية؛ 70.3 ± 5.8٪ رطوبة نسبية). تم تقييم آثار العلاج عن طريق قياس هرمونات الغدة الدرقية في المصل، والتستوستيرون، والمؤشرات الحيوية المؤكسدة ومضادات الأكسدة، ومعايير وظائف الكبد والكلى، ومستويات إنترلوكين-4 (IL-4) في المصل، وتعبير بروتين الصدمة الحرارية 70(HSP70) ، ومؤشرات جودة اللحوم. تشير النتائج إلى أن كلاً من الكركمين وتركيبته النانوليبوزومية قد عززا بشكل ملحوظ مستويات هرمون الغدة الدرقية والتستوستيرون في المصل، وخاصةً في ظل ظروف الإجهاد الحراري. على الرغم من أن الكركمين وحده أظهر تأثيرات طفيفة على مستوياتIL-4 ، إلا أن نانوليبوزومات الكركمين خفضت هذه المستويات بشكل ملحوظ خلال الإجهاد الحراري، مما يؤكد قدرتها المضادة للالتهابات. بالإضافة إلى ذلك، تحافظ المكملات الغذائية التي تحتوي على تركيبات الكركمين بفعالية على جودة اللحوم من خلال تخفيف الإجهاد التأكسدي والحفاظ على التركيب الغذائي لأنسجة عضلات الصدر. تشير هذه النتائج إلى أن دمج الكركمين، وخاصةً في شكله النانوليبوزومي، في أنظمة الأرانب الغذائية يمكن أن يكون استراتيجية واعدة لتخفيف الإجهاد الحراري، وتحسين الوظائف الفسيولوجية والأيضية، وتقليل الالتهابات، والحفاظ على جودة اللحوم في ظل ظروف درجات الحرارة المرتفعة.

الكلمات الدالة: الكركمين، نانوليبوسوم الكركمين، الأرانب، التغيرات المناخية، التكاثر، المناعة، جودة اللحوم.