



Water extracts of *Fucus vesiculosus* and *Laminaria digitata* enhance male reproductive parameters via antioxidant and NO/cGMP mechanisms in rats

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Abstract

Male sexual dysfunction is increasingly prevalent, driving interest in marine algal bioactives as potential natural modulators of reproductive physiology. Brown seaweeds such as *Fucus vesiculosus* and *Laminaria digitata* contain phlorotannins, fucoidans, and antioxidant compounds of applied relevance in phycology and biotechnology. This study assessed the effects of standardized water extracts of these two species on reproductive behavior, hormonal status, sperm quality, oxidative balance, and nitric oxide (NO)/cyclic guanosine monophosphate (cGMP) signaling in male Sprague–Dawley rats. Animals received the seaweed extracts orally by gavage (300 mg kg⁻¹ day⁻¹) for 52 days. Both extracts improved male reproductive behavior by reducing the time required to initiate mounting, intromission, and ejaculation (mount latency, intromission latency, and ejaculation latency), while increasing the number of these sexual behaviors during the test period ($p < 0.05$). Serum follicle-stimulating hormone and testosterone concentrations increased, alongside higher testicular superoxide dismutase, catalase, and glutathione peroxidase activities and lower malondialdehyde levels. Sperm count and motility improved, particularly with *L. digitata* extract. Western blot analyses revealed phosphorylated phosphodiesterase-5, endothelial NO synthase, and cGMP levels, with reduced endothelin-1 in testicular and epididymal tissues ($p < 0.05$ – 0.001). These findings indicate that extracts of *F. vesiculosus* and *L. digitata*, chosen for their well-documented antioxidant and phlorotannin-rich profiles, confer protective and prosexual effects associated with enhanced antioxidant defense and upregulation of NO/cGMP-related pathways, with the *L. digitata* extract exhibiting comparatively stronger activity.

Keywords *Fucus vesiculosus* · *Laminaria digitata* · Seaweed extracts · Male reproductive function · NO/cGMP pathway · Rat model · Bioactive

Introduction

Male reproductive health is influenced by a range of physiological, environmental, and lifestyle factors, and global reports indicate a continued rise in sexual dysfunction and androgen-related disorders (Sharma et al. 2013; Anderson et al. 2022). Although pharmaceutical interventions targeting the nitric oxide (NO)/cyclic guanosine monophosphate (cGMP) pathway remain the primary treatment strategy (Dean And Lue 2005; Förstermann And Sessa 2012; Paronetto And Crescioli 2024), their efficacy varies, and side effects are common. This has stimulated interest in natural bioactive compounds as complementary or alternative options (Lee et al. 2024).

Marine environments, which cover more than 70% of the Earth's surface, offer a rich source of biologically active compounds (Rich And Maier 2015). Macroalgae

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have long been consumed as foods and used in traditional medicine due to their purported health-promoting properties. Their low toxicity, sustainability, and abundance of bioactive molecules make them attractive candidates for therapeutic development (Gupta And Abu-Ghannam 2011; Quitério et al. 2021). Red, green, and brown seaweeds all contain antioxidant and endocrine-modulating constituents with documented reproductive effects. For example, extracts of *Chondrus crispus* improved male fertility and gonadal function in rats (Ibrahim et al. 2021), while dietary supplementation with *Ulva lactuca* improved testosterone levels and sperm motility in rabbits (Okab et al. 2013). A fucoxanthin-rich fraction from the brown seaweed *Sargassum glaucescens* also ameliorated testicular injury and increased sperm count and testosterone in hamsters (Wang et al. 2020).

Brown seaweeds are particularly rich in phlorotannins, fucoidans, laminarins, alginates, fucoxanthin, and essential minerals such as iodine, which contribute to their potent antioxidant, anti-inflammatory, and metabolic activities (Catarino et al. 2018; Gomez-Zavaglia et al. 2019; André et al. 2020; Peñalver et al. 2020; Obluchinskaya et al. 2022). *Laminaria digitata* is a commercially important brown seaweed widely used in food, feed, pharmaceutical, and bio-energy applications due to its high polysaccharide content and scalable cultivation potential (Ohlsson et al. 2020; Li et al. 2024). Although several studies have examined its nutritional and health-related properties, no mammalian studies have directly evaluated the effects of *L. digitata* or *Fucus vesiculosus* on male reproductive parameters such as sperm quality or testosterone levels. In piglets, supplementation with *L. digitata* improved muscle protein profiles and meat quality but did not affect reproductive outcomes (Ribeiro et al. 2025). Transcriptomic analyses of *F. vesiculosus* revealed genes associated with gamete recognition and motility (Martins et al. 2013), underscoring the complex reproductive biology of brown macroalgae but not addressing their mammalian effects.

The nitric oxide (NO)/cyclic guanosine monophosphate (cGMP) pathway plays a central role in male sexual function, particularly erectile response. NO, produced by neuronal (nNOS) and endothelial (eNOS) nitric oxide synthases, activates guanylate cyclase in the corpus cavernosum, promoting the production of cGMP and resulting in smooth muscle relaxation and penile erection (Dean And Lue 2005; Förstermann And Sessa 2012). Disruptions to NOS activity and NO availability impair erectile function (Burnett 2004; Bivalacqua et al. 2007). cGMP is degraded by phosphodiesterase-5 (PDE5), and PDE5 inhibitors maintain elevated cGMP levels to support vasodilation (Paronetto And Crescioli 2024). Fucoidan oligosaccharides have recently been shown to improve metabolic and inflammatory status (Hamouda et al. 2025), suggesting that brown seaweed

bioactives may influence pathways also relevant to sexual function.

However, there is limited knowledge regarding the specific effects of brown seaweeds on male reproductive health. This study, therefore, aimed to investigate the potential of *F. vesiculosus* and *L. digitata* extracts to improve male sexual behavior, hormonal status, antioxidant defenses, and key molecular targets related to erectile function (eNOS, cGMP, PDE5, ET-1) in a rat model. To the best of our knowledge, this is the first study to comprehensively evaluate the effects of these brown seaweed extracts on the NO/cGMP pathway and reproductive parameters, offering novel insights into their potential use as natural therapeutic agents for managing male sexual dysfunction.

Materials and methods

Seaweed materials and preparation of extracts

Standardized dried seaweed meals of *Fucus vesiculosus* and *Laminaria digitata* were supplied by OmniActive Health Technologies (Charlottetown, Canada). Both materials were provided as freeze-dried and milled seaweed powders. The batch numbers were SW-FV-PP-01 for *F. vesiculosus* and SW-LD-PP-04 for *L. digitata*. Both batches complied with the requirement of loss on drying $\leq 10\%$, confirming acceptable moisture stability. All seaweed materials were transported under sealed, dry conditions and stored at 4 °C until extraction. Each seaweed meal was mixed with distilled water at a 1:10 (w/v) ratio and stirred at room temperature (22–24 °C) for 24 h. The mixtures were then heated to 60 °C for 2 h, allowed to cool, and filtered through sterile muslin cloth followed by Whatman No. 1 filter paper. Filtrates were concentrated using a rotary evaporator at ≤ 45 °C and dried in a ventilated oven at 40 °C to obtain solid extracts. The extraction yields were calculated gravimetrically and stored in airtight, light-protected containers at 4 °C until use. As no additional chemical characterization was performed, the extract composition reflects the standardization parameters provided by the supplier. This limitation has been acknowledged for future work.

Animals and study design

A total of 21 healthy male Sprague–Dawley rats (12 weeks old, 180–200 g) were obtained from the Experimental Animal Research Unit of Firat University (FUDAM). Animals were housed individually in polycarbonate cages under controlled environmental conditions: 22 ± 2 °C temperature, $55 \pm 5\%$ relative humidity, and a 12-h light/dark cycle. Standard laboratory chow and tap water were provided ad libitum. Prior to treatment, all rats underwent

a one-week acclimatization period to reduce stress and ensure physiological stability. After acclimation, rats were randomly divided into three groups ($n = 7$ per group): the control group received distilled water via oral gavage; the FV group was administered *F. vesiculosus* extract ($300 \text{ mg kg}^{-1} \text{ day}^{-1}$); and the LD group received *L. digitata* extract ($300 \text{ mg kg}^{-1} \text{ day}^{-1}$). The extracts were dissolved in distilled water and administered using an oral gavage once daily for 52 consecutive days. All procedures were conducted in accordance with ethical guidelines and approved by the Firat University Animal Experiments Local Ethics Committee (109/2017–217).

Assessment of sexual behavior

Sexual behavior tests were conducted on days 50–52 using standard protocols for male rat reproductive behavior. Sexually receptive female rats were prepared by estrus induction through a controlled light–dark cycle and confirmed by vaginal cytology. During each test, the following parameters were recorded: mount latency (time from female introduction to the first mount), intromission latency (time to first intromission), ejaculation latency (time from first intromission to ejaculation), as well as mount, intromission, and ejaculation frequencies. All observations were performed under dim red light and video-recorded for validation, and behavioral scoring was carried out by an investigator blinded to treatment assignments.

Sample collection and tissue processing

At the end of the 52-day treatment period, the animals were decapitated, and blood samples were collected and centrifuged at $3000 \times g$ for 10 min at 4°C and the resulting sera were aliquoted and stored at -80°C for future analyses. The reproductive organs, including testes, epididymides, seminal vesicles, and ventral prostate, were carefully excised, cleaned of any adjacent fat tissues, and then weighed. The total weights of these organs were recorded, and their relative weights were calculated using the formula: $\text{total organ weight (g)} / \text{body weight (g)} \times 100$. The caudal epididymis was longitudinally sliced while held with forceps, facilitating sperm release by dicing the cauda epididymis into segments placed in Petri dishes filled with phosphate-buffered saline (PBS) for sperm analysis. For detailed examination, the epididymis samples were prepared in duplicate: one cauda epididymis was allocated to a Petri dish containing 10 mL of 0.1 M PBS, specifically for assessing sperm count and motility; concurrently, another cauda epididymis was placed in a different Petri dish with 1 mL of 0.1 M PBS for evaluating sperm viability and morphology. This setup allowed the spermatozoa to exit the cauda epididymis naturally into the saline solution. Following this, the sperm suspensions were

left at ambient temperature for 10 min, allowing the sperm to exit the cauda epididymis lumen and facilitating analysis of sperm characteristics.

Sperm quality

Sperm analysis was conducted using previously established methodologies (Türk et al. 2008). To assess sperm count, a $10 \mu\text{L}$ sample of caudal epididymal sperm solution was applied to a coverslip placed on a hemocytometer and observed under a light microscope. This procedure was repeated with another $10 \mu\text{L}$ drop of caudal epididymal sperm for accuracy. Sperm viability analysis used samples from another cauda epididymis, placed in a Petri dish with 1 mL of 0.1 M PBS. To this, three drops of eosin were added to 1 drop of the sperm suspension and gently mixed, followed by adding one drop of 1% w/v nigrosine (Merck, Germany). After stirring, a smear was prepared and allowed to air-dry for 30 s before observation at $\times 200$ magnification. Sperm viability was assessed by membrane permeability; dead sperm exhibited a pinkish color due to eosin staining, whereas live sperm retained a whitish or colorless appearance, indicating an intact membrane.

For the examination of sperm morphology, a sperm smear analogous to that used in the viability analysis was prepared. The morphology of the sperm's head, neck, and tail was assessed under $\times 400$ magnification using an imaging microscope. Sperm were categorized as normal or abnormal based on morphology. Sperm were classified as abnormal if they exhibited structural defects such as misshapen, double, tapered, or amorphous heads, or tail abnormalities including bent, coiled, broken, or detached tails. Normal sperm were assigned a score of 100, whereas abnormal sperm received a score of "0". This scoring system was designed to facilitate the statistical analysis, allowing for straightforward processing and interpretation of the data using the Statistical Analysis System (SAS).

Biochemical analysis

Serum concentrations of blood urea nitrogen (BUN), creatinine along with the activities of alanine transaminase (ALT), and aspartate transaminase (AST), were measured using a biochemical analyzer (Samsung Electronics Co, Korea). The concentrations of serum follicle-stimulating hormone (FSH), luteinizing hormone (LH), and testosterone were measured using ELISA (Bio-Tek Instruments Inc.), through commercial kits (Cayman, USA). Activities of antioxidant enzymes (SOD, CAT, GPx) were determined using specific assay kits (Cayman). These assessments were conducted strictly in accordance with the manufacturer's instructions for the kits. Malondialdehyde (MDA) concentration was measured using an HPLC system (Shimadzu, Japan). This

system was equipped with an inertsil ODS-3 C18 column (250×4.6 mm, 5 µm), a column oven (CTO-10ASVP), a degasser unit (DGu-20A5), a pump (LC-20 AD), an autosampler (SIL-20A), an ultraviolet–visible detector (SPD-20A), and a processor system utilizing LC Solution Software.

Western blotting analysis

Protein levels of phosphorylated phosphodiesterase type 5 (p-PDE5), endothelial nitric oxide synthase (eNOS), cyclic guanosine monophosphate (cGMP), and endothelin-1 (ET-1) in testis and epididymis tissues were determined by Western blotting. The tissues were homogenized in ice-cold Tris–HCl buffer (10 mM, pH 7.4) and centrifuged at $12,000\times g$ for 15 min at 4 °C. Protein concentration was determined using the Bradford assay, and samples were denatured with SDS-PAGE buffer containing 2% β-mercaptoethanol. Subsequently, equal amounts of protein from each sample were electrophoresed in the system and then transferred to nitrocellulose membranes. These membranes were blocked with 1% albumin in PBS for 1 h before incubation with primary antibodies (p-PDE5, eNOS, cGMP, and ET-1, Abcam, UK) diluted to 1:1000 in the same buffer containing 0.05% Tween-20. After washing, the blots were incubated with a goat anti-mouse IgG antibody conjugated to HRP. To ensure equal protein loading, β-actin antibody (Sigma-Aldrich, USA) was used as a loading control. The bands were analyzed densitometrically using an image analysis system (Image J; NIH, USA).

Statistical analysis

The IBM SPSS Statistics software package (Version 22.0) was used for the analyses. The *Levene* test was used to evaluate the homogeneity of variances, which is a requirement for parametric tests. The data were then subjected to the Shapiro–Wilk test to ensure normality. A one-way ANOVA was employed to determine differences between groups. Variables are reported as mean ± standard error. For multiple comparisons, the Tukey post hoc test was used. A significance level of $p < 0.05$ was considered for statistical significance. Sample sizes represent biological replicates ($n = 7$), and technical replicates were not used for statistical comparisons.

Results

Body and reproductive organ weights

Changes in body weight, as well as the absolute and relative weights of the testis, seminal vesicles, total epididymis, right cauda epididymis, and ventral prostate, are presented

in Table 1. Although numerical differences were observed between the treatment and control groups, none of these changes reached statistical significance ($p > 0.05$).

Serum biochemical parameters

The administration of *F. vesiculosus* and *L. digitata* extracts did not produce any significant alterations in liver or kidney function markers, including serum alanine aminotransferase (ALT), aspartate aminotransferase (AST), creatinine, and blood urea nitrogen (BUN), when compared to the control group ($p > 0.05$; Fig. 1). These findings indicate that neither extract exhibited hepatotoxic or nephrotoxic effects at the administered dose.

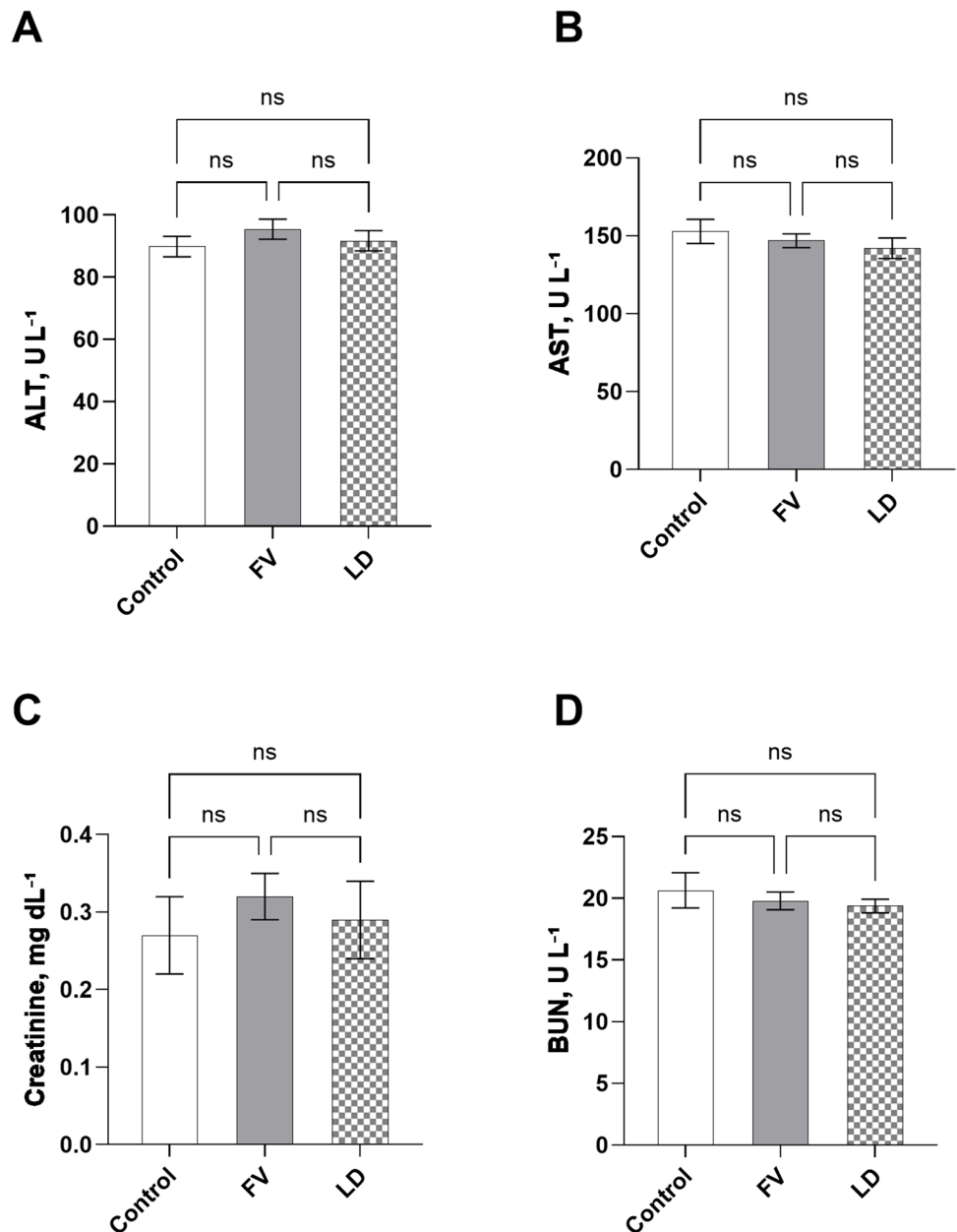
In contrast, significant improvements were observed in reproductive hormone levels (Fig. 2) and oxidative stress markers (Fig. 3). Serum FSH concentrations increased from 6.97 ± 0.21 mIU mL⁻¹ in the control group to 8.68 ± 0.21 mIU mL⁻¹ and 9.82 ± 0.18 mIU mL⁻¹ in the *F. vesiculosus* and *L. digitata* groups, respectively ($p < 0.01$). While LH levels showed no significant differences between groups ($p > 0.05$), both free and total testosterone levels were markedly elevated following seaweed treatment. Free testosterone rose from 4.41 ± 0.12 ng mL⁻¹ in controls to 6.64 ± 0.35 ng mL⁻¹ with *F. vesiculosus* extract and 8.69 ± 0.12 ng mL⁻¹ with *L. digitata* extract ($p < 0.01$ and $p < 0.001$, respectively). Similarly, total testosterone levels increased from 174.15 ± 2.13 ng mL⁻¹ in the control group to 223.76 ± 3.67 ng mL⁻¹ and 259.56 ± 5.71 ng mL⁻¹ in the FV and LD groups, respectively.

Table 1 Effects of water extracts of *Fucus vesiculosus* and *Laminaria digitata* on final body weight and absolute and relative reproductive organ weights in male rats

Item	Groups		
	Control	FV	LD
Body Weight, g	224.57 ± 9.76	237.14 ± 4.44	230.83 ± 9.93
Testis, g	1.30 ± 0.05	1.37 ± 0.02	1.39 ± 0.06
Whole Epididymis, g	0.46 ± 0.02	0.49 ± 0.01	0.46 ± 0.02
Right Cauda epididymis, g	0.19 ± 0.01	0.20 ± 0.01	0.19 ± 0.01
Seminal vesicles, g	0.64 ± 0.08	0.73 ± 0.04	0.67 ± 0.12
Ventral prostate, g	0.28 ± 0.03	0.35 ± 0.02	0.30 ± 0.05
Testis*, %	0.58 ± 0.01	0.58 ± 0.01	0.61 ± 0.01
Whole Epididymis*, %	0.21 ± 0.01	0.21 ± 0.01	0.20 ± 0.01
Right Cauda epididymis*, %	0.08 ± 0.01	0.08 ± 0.01	0.09 ± 0.01
Seminal vesicles*, %	0.28 ± 0.03	0.31 ± 0.01	0.28 ± 0.05
Ventral prostate*, %	0.13 ± 0.01	0.15 ± 0.01	0.13 ± 0.02

FV *Fucus vesiculosus* extract; LD *Laminaria digitata* extract. *Relative reproductive organ weights [organ weight (g)/final body weight (g) × 100]. Data are means ± SE ($n = 7$)

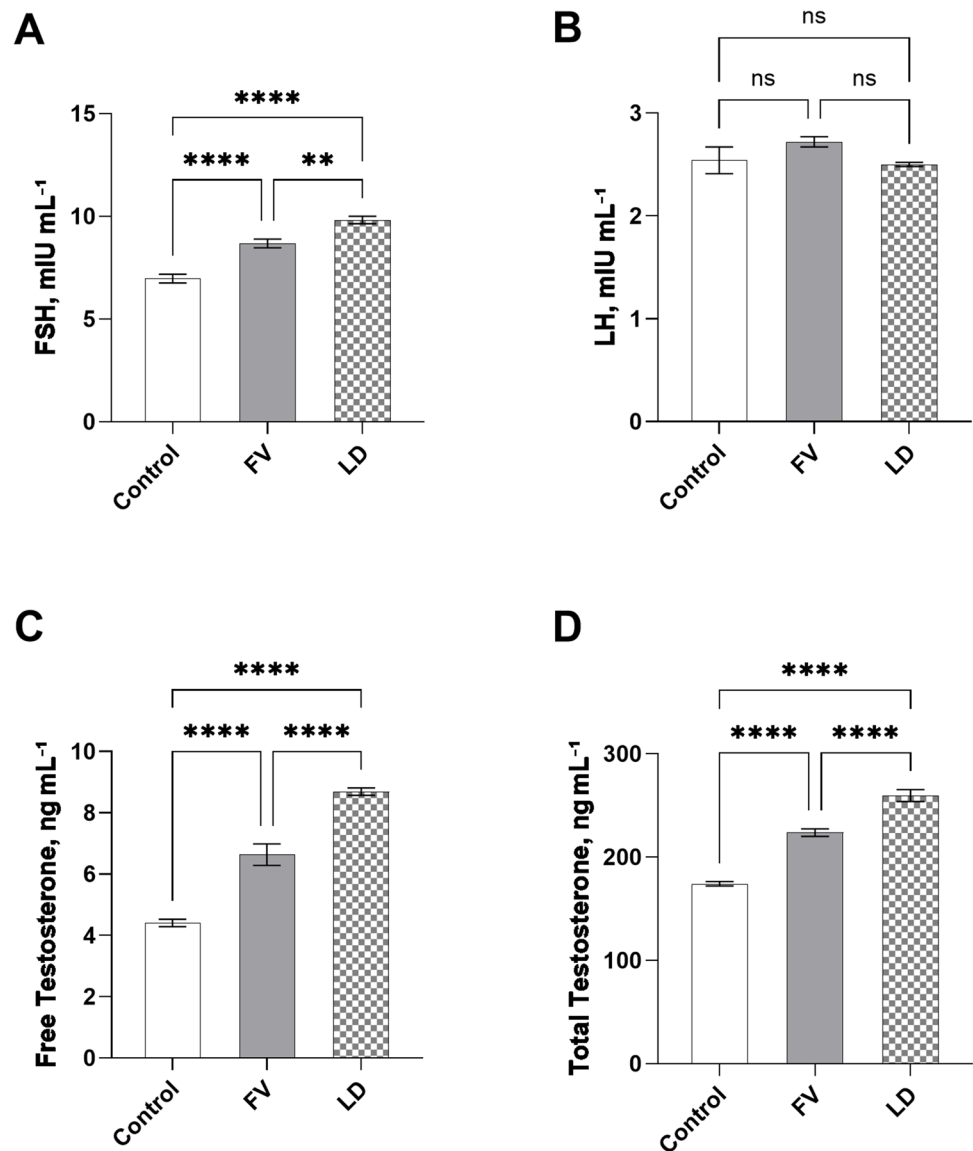
Fig. 1 Effects of *Fucus vesiculosus* (FV) and *Laminaria digitata* (LD) water extracts on serum biochemical markers. Serum (A) alanine aminotransferase (ALT), (B) aspartate aminotransferase (AST), (C) creatinine, and (D) blood urea nitrogen (BUN) levels were measured after 52 days of oral administration of FV and LD extracts. Data are presented as means $\pm$ SE ($n=7$). No statistically significant differences were detected among groups ($p>0.05$)



Serum MDA concentrations, an indicator of lipid peroxidation, declined from $0.92 \pm 0.05 \mu\text{mol L}^{-1}$ in the control group to $0.82 \pm 0.02 \mu\text{mol L}^{-1}$ with *F. vesiculosus* extract and $0.71 \pm 0.03 \mu\text{mol L}^{-1}$ with *L. digitata* extract ($p<0.05$ for LD vs. control). A similar trend was observed in testicular MDA levels, where *L. digitata* extract significantly reduced MDA to $1.19 \pm 0.04 \text{ nmol g}^{-1}$ compared to $1.68 \pm 0.04 \text{ nmol g}^{-1}$ in the control ($p<0.05$), whereas *F. vesiculosus* extract had no significant effect ($1.48 \pm 0.10 \text{ nmol g}^{-1}$). Antioxidant enzyme activities in testicular tissue were significantly enhanced by seaweed extract supplementation. SOD

activity increased from $121.00 \pm 2.15 \text{ U mg}^{-1}$ in controls to $133.57 \pm 3.96 \text{ U mg}^{-1}$ and $139.50 \pm 2.09 \text{ U mg}^{-1}$ in the *F. vesiculosus* and *L. digitata* groups, respectively ($p<0.05$). Similarly, CAT activity rose from $165.00 \pm 4.20 \text{ U mg}^{-1}$ in controls to $185.57 \pm 2.20 \text{ U mg}^{-1}$ with *F. vesiculosus* extract ($p<0.01$) and $200.50 \pm 2.23 \text{ U mg}^{-1}$ with *L. digitata* extract ($p<0.001$). GSH-Px levels also increased significantly in both treatment groups, reaching $36.43 \pm 1.54 \text{ U mg}^{-1}$ and $35.17 \pm 2.64 \text{ U mg}^{-1}$ with *F. vesiculosus* and *L. digitata* extracts, respectively, compared to $25.57 \pm 0.81 \text{ U mg}^{-1}$ in the control ($p<0.05$).

Fig. 2 Effects of *Fucus vesiculosus* (FV) and *Laminaria digitata* (LD) water extracts on serum and testicular hormone levels. (A) follicle-stimulating hormone (FSH), (B) luteinizing hormone (LH), (C) free testosterone, and (D) total testosterone levels were measured. Data are presented as means $\pm$ SE ($n = 7$). Statistical significance between groups; in comparison with the control group: ** $p < 0.01$, **** $p < 0.0001$, (Tukey post hoc test, $p < 0.05$)



Sexual behaviors

The findings indicate that *F. vesiculosus* and *L. digitata* extracts positively influenced male sexual behavior in rats, as presented in Table 2. These effects were particularly notable in mounting, intromission, and ejaculation. The administration of both seaweeds reduced latency, the time to initiate behavior (mounting, intromission, and ejaculation), with *L. digitata* extract demonstrating a greater decrease than *F. vesiculosus* extract ($p < 0.05$). Furthermore, the study observed an increase in the frequency of mounting and intromission latencies among male rats treated with these seaweed extracts, compared with the control group ($p < 0.05$), with *L. digitata* extract exhibiting a more pronounced enhancement in mounting frequency.

Sperm quality

Effects of *F. vesiculosus* and *L. digitata* extracts on sperm characteristics and abnormal sperm rates are presented in Table 3. The sperm motility findings revealed no significant difference between the *F. vesiculosus* group and the other groups, yet there was a notable difference between the Control and *L. digitata* groups ($p < 0.05$). Sperm counts indicated significant differences between the Control and *L. digitata* groups, whereas *F. vesiculosus* extract showed no significant variation in sperm count compared to either group ($p < 0.05$). The abnormal sperm rate in the control group was not significantly different from that in the groups given both types of seaweed ($p < 0.05$). However, *L. digitata* extract exhibited a significantly higher abnormal sperm rate than *F. vesiculosus* extracts ($p < 0.01$).

Fig. 3 Effects of *Fucus vesiculosus* (FV) and *Laminaria digitata* (LD) water extracts on oxidative stress markers in serum and testis. **(A)** Serum and **(B)** Testis malondialdehyde (MDA) concentrations, along with the Testis **(C)** Superoxide dismutase (SOD), **(D)** Catalase (CAT), and **(E)** Glutathione peroxidase (GSH-Px) activities are presented. Data are means $\pm$ SE ($n = 7$). Statistical significance between groups; in comparison with the control group: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, **** $p < 0.0001$, (Tukey post hoc test, $p < 0.05$)

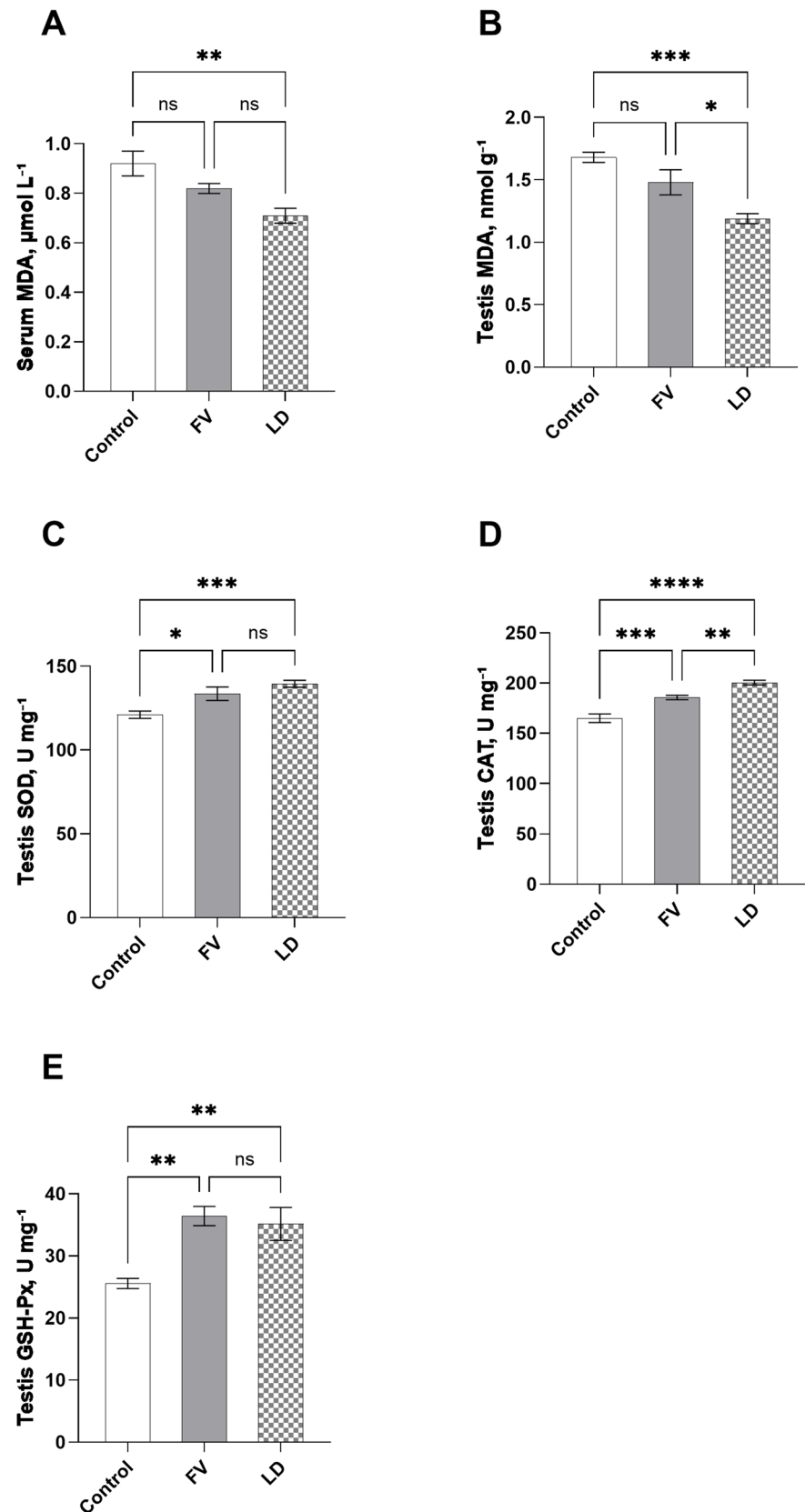


Table 2 Effects of water extracts of *Fucus vesiculosus* and *Laminaria digitata* on sexual behavior parameters in male rats

Item	Groups		
	Control	FV	LD
Mounting Latency (s)	158.43 ± 3.96 ^a	143.29 ± 2.89 ^b	138.00 ± 3.86 ^b
Mounting Frequency	9.29 ± 0.47 ^b	17.14 ± 0.40 ^a	19.33 ± 0.49 ^a
Intromission Latency (s)	279.71 ± 1.55 ^a	252.29 ± 3.14 ^b	246.17 ± 5.41 ^b
Intromission Frequency	2.29 ± 0.18 ^b	4.57 ± 0.20 ^a	5.17 ± 0.31 ^a
Ejaculation Latency (s)	445.00 ± 5.15 ^a	403.57 ± 4.14 ^b	411.67 ± 8.44 ^b

FV *Fucus vesiculosus* extract; LD *Laminaria digitata* extract. Data are means ± SE (n=7). Different superscripts (a–b) indicate significant differences among groups ($p < 0.05$)

Table 3 Effects of water extracts of *Fucus vesiculosus* and *Laminaria digitata* on sperm characteristics and abnormal sperm rate in male rats

Item	Groups		
	Control	FV	LD
Motility %	74.29 ± 2.02 ^b	77.14 ± 1.84 ^{ab}	83.33 ± 3.33 ^a
Sperm count *	94.00 ± 6.76 ^b	117.43 ± 13.11 ^{ab}	133.67 ± 11.18 ^a
<u>Abnormal sperm rate %</u>			
Head	5.14 ± 1.18	2.71 ± 0.61	5.00 ± 0.52
Tail	4.29 ± 1.23	4.00 ± 0.44	5.67 ± 0.49
Total	9.43 ± 1.48 ^{ab}	6.71 ± 0.75 ^b	10.67 ± 0.67 ^a

FV *Fucus vesiculosus* extract; LD *Laminaria digitata* extract. Data are means ± SE (n=7). Different superscripts (a–b) indicate group mean differences ($p < 0.05$). * million per right cauda epididymis. Abnormal sperm rate includes morphological defects of the head and tail that reduce sperm functional quality

Protein levels

Testicular levels of p-PDE5, eNOS, cGMP, and ET1 have been shown in Fig. 4 (A–D). The results show that PDE5 levels were significantly elevated in both groups treated with seaweed extracts compared with the control group ($p < 0.001$), with the extract from *L. digitata* proving more effective at increasing PDE5 levels than that from *F. vesiculosus* ($p < 0.01$). The group treated with *F. vesiculosus* extract showed a higher phosphodiesterase type 5 (PDE5) ratio than the control group ($p < 0.01$). Additionally, testicular levels of endothelial nitric oxide synthase (eNOS) were significantly elevated in the *L. digitata* group compared with the control group ($p < 0.001$). cGMP levels were elevated in the *F. vesiculosus* group compared to

the control group ($p < 0.05$). This improvement was even more pronounced in the *L. digitata* group, not only correlated with the control group ($p < 0.001$) but also with the *F. vesiculosus* group ($p < 0.001$). Testicular ET-1 levels decreased in both the *F. vesiculosus* ($p < 0.05$) and *L. digitata* ($p < 0.01$) groups.

Epididymis levels of p-PDE5, eNOS, cGMP, and ET1 have been presented in Fig. 5 (A–D). The p-PDE5 level in the epididymis was found to be higher in the *L. digitata* group compared to the control group ($p < 0.05$). eNOS levels significantly increased in the *L. digitata* group compared to the control group ($p < 0.001$), and there was also a notable increase in the *F. vesiculosus* group compared to the control group ($p < 0.01$). cGMP levels were higher in the *F. vesiculosus* group compared to the control group ($p < 0.05$). This increase was even more significant in the *L. digitata* group, both compared with the control group ($p < 0.001$) and with the *F. vesiculosus* group ($p < 0.01$). Epididymis ET-1 levels decreased in the *F. vesiculosus* and *L. digitata* groups in comparison to the control group ($p < 0.001$).

Among the two extracts, *L. digitata* extract demonstrated the strongest modulation of these molecular markers, showing the highest increases in eNOS and cGMP and the most pronounced decrease in ET-1. Collectively, these results indicate that the brown seaweed extracts exerted direct mechanistic effects on erectile-related proteins.

Discussion

This study has demonstrated that the water extracts of *Fucus vesiculosus* and *Laminaria digitata* produced positive effects on the male reproductive organs and their hormone levels. Specifically, untreated animals had much lower levels of both FSH and testosterone when compared to extracts at 300 mg kg⁻¹, with a proportionately greater level of hormones. Additionally, the extracts dramatically increased the latencies and frequencies of mounting, intromission, and ejaculation, without significant differences in effectiveness across the extract groups. The more general findings of this study provide evidence of significant health benefits of extracts from *F. vesiculosus* and *L. digitata*, which are endowed with bioactive compounds with antioxidant and potentially androgenic activities (El-Beltagi et al. 2022). On the other hand, the abundance and composition of bioactive compounds such as phlorotannins, fucoidans, laminarins, alginates, and fucoxanthin in *F. vesiculosus* and *L. digitata* are highly variable and depending on species, season, geographic origin, and environmental conditions, as well documented in physiological literature (Bruhn et al.

2017; Cunningham et al. 2023; Circuncisão et al. 2024). In addition to the biological relevance, particularly for *Laminaria* species, is their exceptionally high iodine content. *Laminaria* spp. are among the most efficient biological iodine accumulators, typically containing 0.1–0.5% iodine on a dry weight basis, with occasional reports of even higher concentrations (Gall et al. 2004; Verhaeghe et al. 2008; Shchukin et al. 2025). Importantly, the majority of iodine in *Laminaria* occurs in water-soluble inorganic iodide (I^-) form, and studies have shown that up to ~99% of total iodine may be extractable under aqueous conditions, particularly at elevated temperatures (Tseng et al. 1994; Hou et al. 1997). Because aqueous extraction was used, iodine was likely present in the administered extract. As an essential component of thyroid hormones, key regulators of metabolism, redox balance, and hypothalamic–pituitary–gonadal function, iodine may have contributed indirectly to the observed endocrine and reproductive effects. However, iodine was not quantified, and its relative contribution compared with other macroalgal bioactives remains unclear. Future studies should include compositional profiling, iodine quantification, and dose standardization to ensure mechanistic clarity and safety, particularly given recommended iodine levels of 0.1–0.5% in *Laminaria*-derived preparations (Shchukin et al. 2025). Similarly to our study, in male rats, red seaweed (*C. crispus*) extract improved sperm motility and testicular function, with a modest increase in testosterone, supporting gonadal function and fertility, and even increasing genital organ weight (Ibrahim et al. 2021). Support of gonadal function and fertility is increased, and genital organ weight is similarly enhanced by red seaweed compounds, according to prior studies. For example, in rams, supplementation with *Gracilaria parvispora* (a red seaweed) increased testicular size and scrotal circumference, improved semen quality (higher sperm concentration, motility, and viability), and enhanced testicular histology, indicating improved spermatogenesis and gonadal function (Hoque et al. 2024). This serves to exemplify the value found within these seaweeds for use in treating and managing a wide range of conditions due to their antioxidant and androgenic potentials, among other benefits to reproductive health. *F. vesiculosus* and *L. digitata* contain various dietary components that can improve physiological processes in humans. These include carbohydrates, dietary fiber, polysaccharides, proteins, amino acids, lipids, fatty acids, and minerals (Obluchinskaya et al. 2022). Furthermore, seaweeds are rich in micronutrients, providing both fat-soluble vitamins (A, D, E, and K) and water-soluble vitamins (C and B complex) (Leandro et al. 2020; Xu et al. 2023). The primary pigment component, fucoxanthin, has been shown to have anti-obesity

benefits by reducing the expression of adipocyte marker proteins (Gammone and D’Orazio 2015). Furthermore, it decreased oxidative stress due to lipid peroxidation (Ye et al. 2022). However, phlorotannins, a specific type of phenolic compound found exclusively in marine environments, are noted for their anti-inflammatory properties (Catarino et al. 2017, 2018). Most of the literature on *F. vesiculosus* and *L. digitata* has highlighted their attractive nutritional and bioactive profiles, with significant potential for health benefits (Catarino et al. 2017, 2018). Together, these data support the possibility that multiple classes of macroalgal bioactives may interact to produce the reproductive and endocrine effects observed in this study, while also underscoring the need for future work to chemically profile the specific constituents present in the water-based extracts used here.

We observed in male rats that both sperm motility and count improved significantly after administration of extracts of *F. vesiculosus* and *L. digitata*, with *L. digitata* extract demonstrating superior outcomes. In addition, the abnormal sperm percentage was significantly lower in the *F. vesiculosus* group than in the *L. digitata* group. This study has also unveiled positive effects of the extracts on the sexual behavior of male rats, that is, decreasing the mount, intromission, and ejaculation latencies. There was greater potency in the *L. digitata* group, with both mounting and penetration frequency significantly increased, demonstrating greater variability than in the control group of male rats. Moreover, treatment with extracts from *F. vesiculosus* and *L. digitata* increased levels of the sexual hormones FSH, free testosterone, and total testosterone. The increased levels of sexual hormones have been linked to heightened sexual activity, making them more responsive to sexual stimuli. However, our search did not yield any previous research comparing the impact of *F. vesiculosus* and *L. digitata* extracts on FSH, LH, and testosterone levels similar to those observed in our experiment. In a previous investigation, fucoxanthin was found to restore sperm motility, reduce the percentage of defective sperm, and reduce lipid peroxidation as well (Kong et al. 2019). A significant increase in serum testosterone levels was observed after four weeks of treatment with fucoxanthin extracts. Similar protective effects were observed in hamsters with cisplatin-induced testicular damage, in which fucoxanthin-rich extracts improved sperm count, reduced sperm abnormalities, and decreased markers of oxidative stress, such as malondialdehyde (Wang et al. 2020). It also upregulated the expressions of hypothalamic GPR54 and SOCS-3 to normal levels at the mRNA level. Rats treated with the fucoxanthin extract for 4 weeks showed significantly improved sperm motility and a reduced percentage of abnormal sperm morphology (Kong et al. 2019).

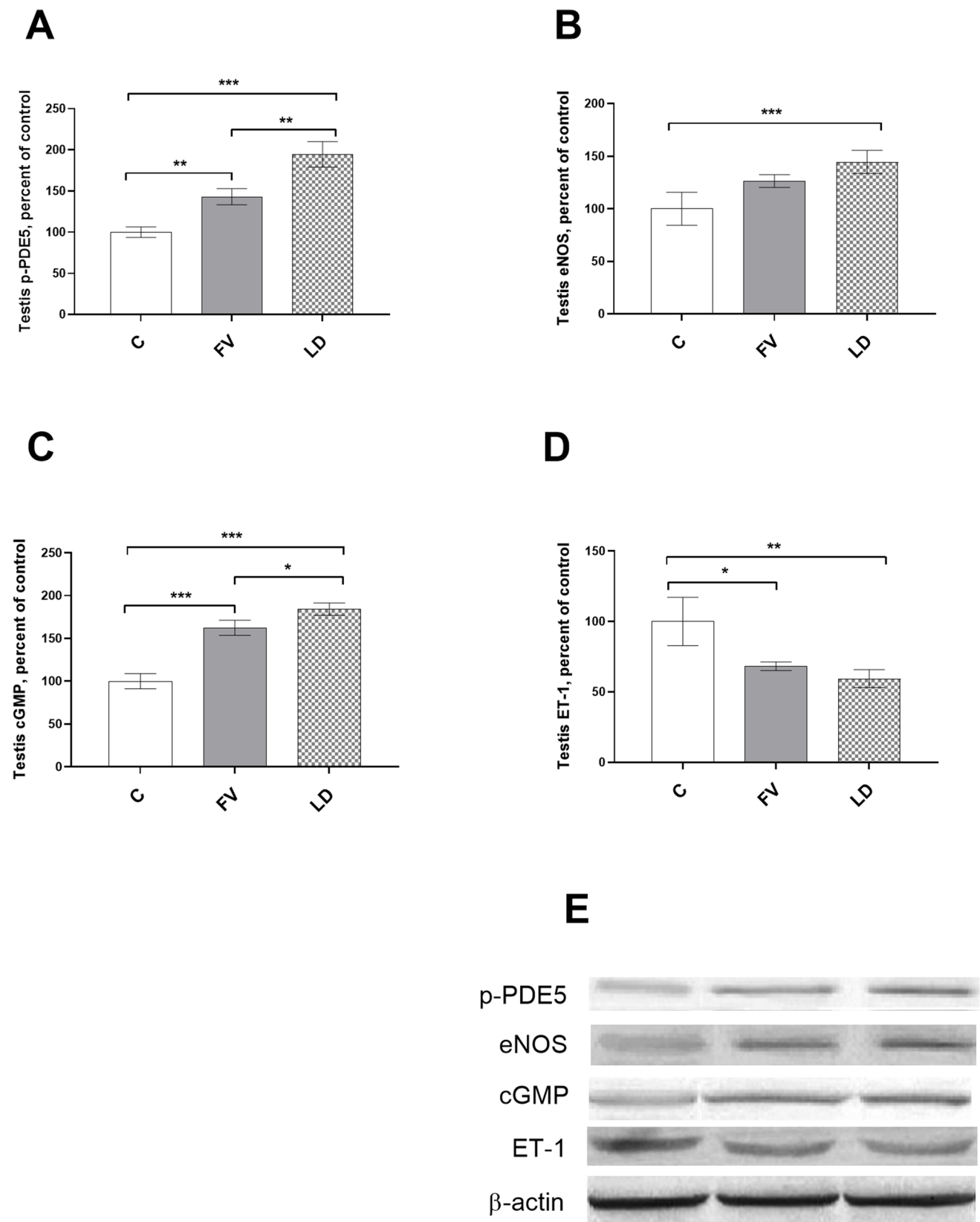


Fig. 4 Effects of *Fucus vesiculosus* (FV) and *Laminaria digitata* (LD) water extracts on erectile-related proteins in testicular tissue. (A) Effect on phosphodiesterase type 5 (p-PDE5), (B) endothelial nitric oxide synthase (eNOS), (C) Cyclic guanosine monophosphate (cGMP), (D) Endothelin-1 (ET-1) Protein levels, and Western blot band images (E). Data were calculated as a percentage of the control relative to band density. For parameters measured by the western blot technique, blots were repeated 3 times and analyzed with β -actin to ensure equal protein loading. Statistical significance between groups; in comparison with the control group: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, (Tukey post hoc test, $p < 0.05$)

Due to the lack of antioxidant enzymes and the production of reactive oxygen radicals by enzymes such as NADPH oxidase, xanthine oxidase, and the mitochondrial electron transport chain, the testes' antioxidant defense mechanisms are notably weaker (Alharbi et al. 2022). Although antioxidant mechanisms contribute to testicular protection, these effects cannot be attributed to generic antioxidant activity alone. In line with previous findings, our results suggest that specific brown seaweed constituents, particularly fucoidans, phlorotannins, and other sulfated polysaccharides, may support endogenous defense systems. For example, D-galactose-treated mice displayed increased activities of SOD, CAT, and GSH in liver, brain, and kidney tissues following administration of *L. digitata* extract, indicating that bioactive components unique to this species can enhance antioxidant pathways in vivo (Kong et al. 2019; Wang et al. 2020). Although agar is typically obtained from red algae, Reshma et al. (2022) demonstrated that agar can also be successfully extracted from *L. digitata*. Their in vitro analyses showed a clear concentration-dependent antioxidant effect, with the 200 μ L extract exhibiting markedly higher radical-scavenging activity ($83.70 \pm 3.83\%$) than the 50 μ L extract ($32.68 \pm 1.21\%$) (Reshma et al. 2022). In addition, rats treated with a phlorotannin-rich extract from *Ascophyllum nodosum* and *F. vesiculosus* reduced levels of IL-6 and TNF- α , along with increased activities of SOD and GPx (Tung et al. 2022). Treatment with fucoxanthin for four weeks significantly increased the CAT, SOD, and GPx activities in the plasma of rats, particularly at high doses; it also significantly improved SOD activity in the testis of rats, and, importantly, significantly reduced the levels of MDA in the plasma, testis, and sperm in a dose-dependent manner (Kong et al. 2019).

Extracts that increase eNOS and cGMP in testicular tissues promote NO-mediated vasodilation, directly supporting the physiological processes necessary for erection. This mechanism underlies both pharmaceutical and natural approaches to improving erectile function, especially in conditions where NO-cGMP signaling is

compromised (Kaltsas et al. 2024). The physiological process of penile erection is regulated by the nitric oxide/cyclic guanosine monophosphate (NO/cGMP) signaling pathway (Burnett 2006). Sexual stimulation triggers NO release, which activates guanylate cyclase (GC) in the smooth muscle cells, converting guanosine triphosphate (GTP) into cGMP. cGMP then activates protein kinase G (PKG), reducing Ca^{2+} influx into smooth muscle cells, causing them to relax and allowing increased blood flow into the cavernous bodies, resulting in an erection (Francis et al. 2010). Phosphodiesterase-5 (PDE5) can break down cGMP, thus inhibiting the erection process by increasing Ca^{2+} flow back into the cells. The primary pharmacological treatment for erectile dysfunction (ED) is PDE5 inhibitors (PDE5-i), such as avanafil, sildenafil, tadalafil, and vardenafil, which work by inhibiting PDE5 and therefore promoting erection (Nemr et al. 2025). However, the effectiveness of these treatments is limited. Given the limited efficacy and potential side effects of current therapies, there is an identified need for the development of new treatment options for ED (Anand Ganapathy et al. 2021). The current study found that *F. vesiculosus* and *L. digitata* extracts elevated p-PDE5, eNOS, and cGMP levels while reducing ET-1 levels. These results are corroborated by observations that these extracts markedly enhanced sexual behaviors and sexual hormones, encompassing aspects such as fertility, intromission, ejaculation, and mating frequency in male rats. However, since there are no studies on the effects of these extracts on these protein levels, a comparison could not be done.

Conclusion

The present study demonstrates that the water extracts of the brown seaweeds *Fucus vesiculosus* and *Laminaria digitata* exert measurable beneficial effects on male reproductive physiology in rats. Both extracts improved sexual behavior by reducing mount, intromission, and ejaculation latencies and increasing the corresponding behavioral frequencies. They also elevated serum FSH and testosterone levels, indicating a modulatory influence on endocrine function. Improvements in sperm motility were observed as well, suggesting supportive effects on spermatogenic activity, although direct fertility outcomes were not assessed in this study. At the molecular level, decreases in ET-1 alongside increases in p-PDE5, eNOS, and cGMP expression in reproductive tissues are consistent with modulation of pathways relevant to erectile physiology. Among the two brown seaweeds, *L. digitata* extract generally produced more pronounced behavioral

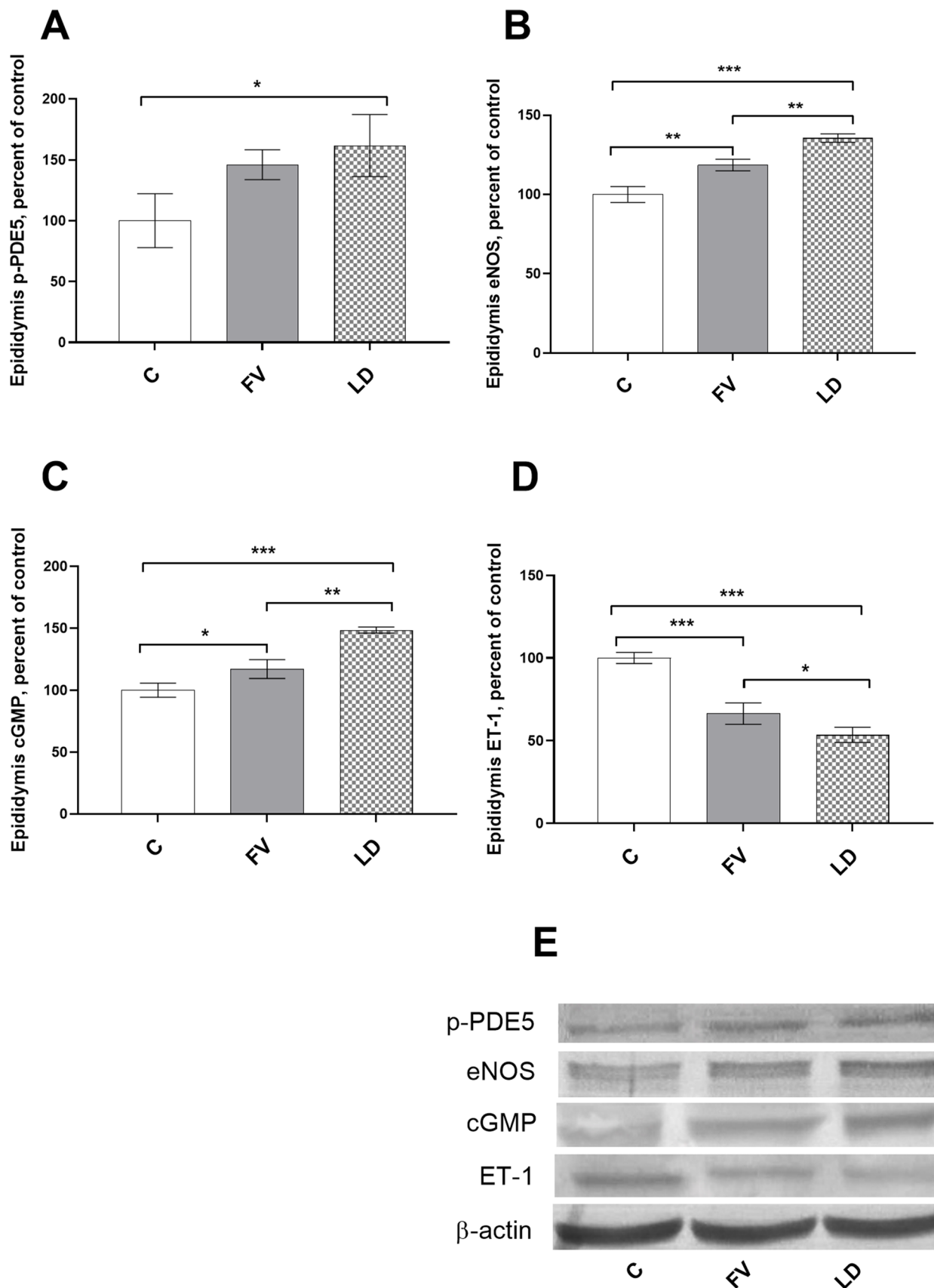


Fig. 5 Effects of *Fucus vesiculosus* (FV) and *Laminaria digitata* (LD) water extracts on erectile-related proteins in epididymal tissue. (A) Effect on phosphodiesterase type 5 (p-PDE5), (B) endothelial nitric oxide synthase (eNOS), (C) Cyclic guanosine monophosphate (cGMP), (D) Endothelin-1 (ET-1) Protein levels and Western blot band images (E). Data were calculated as a percent of control relative to the density of the bands. For parameters measured by the western blot technique, blots were repeated 3 times, analyzed with β -actin to ensure equal protein loading. Statistical significance between groups; in comparison with the control group: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, (Tukey post hoc test, $p < 0.05$)

and molecular changes. These findings should be interpreted within the scope of an exploratory study, as no pharmaceutical positive control was included and chemical profiling of the extracts was not performed. Nevertheless, the results provide preliminary evidence that *F. vesiculosus* and *L. digitata* possess bioactive properties worthy of further investigation. Future work should include comprehensive characterization of the extracts, dose–response studies, toxicity assessments, and functional fertility trials to evaluate their potential as natural agents for supporting male reproductive health.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

Ethical statement This study was approved by the Firat University Animal Experiments Ethics Committee (Approval No: 109/2017–217). All protocols were carried out in accordance with the European Union Directive 2010/63/EU.

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