Tikrit Journal of Veterinary Sciences (2026) 5(1): 215-222
DOI : 10.25130/tjvs.5.1.23

IRAQI Academic Scientific Journals

TJVS Tikrit Journal of Veterinary Sciences

Tikrit Journal of Veterinary Science

Effects of Omega-3 Supplementation on Renal Function in D-Galactose-Induced Aging Male Rabbits

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ARTICLE INFO.

Article history:
-Received: 5/4/2026
-Received in Revised Form: 15/5/2026
-Accepted: 20/5/2026
-Available online: 30/6/2026

Keywords:
Aging, D-galactose, omega-3 fatty acids, oxidative stress, renal dysfunction.

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ABSTRACT

Background and Objective: Aging is associated with progressive deterioration of renal function through glomerulosclerosis and tubular atrophy. Experimental administration of D-galactose accelerates the aging process by inducing oxidative stress and inflammatory responses, leading to renal dysfunction. The present study aimed to investigate the protective effects of omega-3 polyunsaturated fatty acids against D-galactose-induced renal damage in adult male New Zealand White rabbits.

Methods: Sixteen adult male New Zealand White rabbits were randomly divided into four experimental groups: control (T1), D-galactose-treated (T3B), concurrent treatment with D-galactose and omega-3 (T2), and delayed omega-3 treatment following D-galactose administration (T3A). The experimental period lasted 90 days. Serum samples were analyzed for advanced glycation end products (carboxymethyl lysine [CML] and pentosidine), oxidative stress markers (Malondialdehyde [MDA], protein carbonyl, superoxide dismutase [SOD], and catalase), inflammatory cytokines (tumor necrosis factor-alpha [TNF-α] and interleukin-1 beta [IL-1β]), and kidney function parameters, including blood urea nitrogen (BUN), creatinine, albumin, and cystatin C.

Results: Administration of D-galactose significantly increased the concentrations of advanced glycation end products, oxidative stress markers, and inflammatory cytokines, while significantly impairing kidney function compared with the control group. Omega-3 supplementation significantly reduced the levels of advanced glycation end products, oxidative stress markers, and inflammatory cytokines, and improved kidney function parameters. Furthermore, concurrent administration of omega-3 with D-galactose (T2) produced greater protective effects than delayed omega-3 treatment (T3A).

Conclusion: D-galactose-induced aging resulted in marked oxidative stress, inflammation, and renal dysfunction in rabbits. Omega-3 polyunsaturated fatty acids effectively attenuated these adverse effects through their antioxidant and anti-inflammatory properties, with concurrent supplementation providing greater protection than delayed treatment. These findings suggest that omega-3 supplementation may represent a promising preventive strategy against age-related renal dysfunction.

Introduction

Aging is a constant biological process characterized by continuing deterioration in fundamental physiological functions across all organ systems leading to an increased susceptibility to age-related disease and elevation in mortality rates [1]. The kidneys as vital organs responsible for filtration electrolyte homeostasis, acid base balance and waste elimination particularly vulnerable to age-related dysfunction. Age-related renal changes include glomerulosclerosis, tubular atrophy, reduced in glomerular filtration rate and impaired renal hemodynamics, all of which compromised kidney function and increase the risk of chronic kidney disease [2,3]. D galactose (D-gal) an Aldohexose naturally present in the body, is widely utilized to induce an accelerated aging phenotype in animal models. Exogenous administration of D-gal at supraphysiological doses accelerates the aging process by promoting oxidative stress, chronic inflammation and apoptosis in multiple organs including the kidneys [4,5]. This model provides a very valuable tool to study accelerated aging mechanism and test therapeutic intervention. A key mechanism in D-galactose induced aging is the formation of advanced glycation end products (AGEs) which accumulates in the renal tissue and induce oxidative damage through multiple pathways [6,7]. These AGE markers accumulate progressively during aging and serve as reliable biomarker for the extent of nonenzymatic glycation induced by the D-galactose exposure, Oxidative stress represents a crucial pathogenic mechanism in D-galactose induced renal aging [7,8]. Omega-3 polyunsaturated fatty acids include eicosapentaenoic acids (EPA) and docosahexaenoic acid (DHA), are known for their potent anti-inflammatory and antioxidant properties [9,10]. these bioactive lipids modulate inflammatory responses, enhance antioxidant enzyme expression and preserve cellular membrane integrity. This study aims to investigate the protective effects of omega-3 supplementation or renal dysfunction in the D-galactose induced aging in rabbit by analyzing these specific biochemical indicators and kidney function parameters, with the goal of establishing omega-3 as potential therapeutic intervention for age related renal disease.

MATERIALS AND METHODS

Ethical Approval and Animal Care

This study was conducted in strict accordance with the code of ethics for animal experiments at the College of Veterinary Medicine, University of Baghdad. Ethical approval was obtained from the local committee of animal care and use (P.G/552, dated 10-3-2025). All procedures involving animals were performed with humane care and minimal suffering.

The institutional review board carefully evaluated all experimental protocol to ensure compliance with international standards for animal research ethics and welfare. Veterinary supervision was maintained throughout the study duration to monitor animal health and ensure appropriate pain management. All staff involved in animal handling receive specialized training in human techniques and a proper anesthesia administration procedure.

Animals and Housing

sixteen adult male New Zealand white rabbits age 8-12 months and waiting 1.250 – 1.500 ± 300 grams, were used in this study. The rabbits were housed in adequately ventilated plastic cages at an ambient temperature of 22 ± 2°C with 12-hours light/dark cycle. All animals had ad libitum access to standard commercial pellet feed and drinking water. The rabbits were acclimatized for two weeks at the animal house in the period from September to November 2025, before the initiation of the experimental protocol

New Zealand White rabbits were selected for this study due to their well-characterized physiological responses and established use in aging research models. In order to reduce stress-related factors influencing experimental results, the controlled ambient conditions maintained constant temperature and humidity levels. Throughout the study period, early detection of any health issues or negative reactions was ensured by routinely monitoring the behavior and physical condition of the animals. Furthermore, the living facilities were built with enough room for natural mobility and behavioral experiences. Visual inspection for indications of distress, illnesses, or aberrant behavior patterns is part of the daily health evaluation. Proper sanitation procedures were put in place to preserve cleanliness and stop the spread of disease among the experimental animal population.

Experimental Compounds

D-galactose Administration

D-galactose ($C_6H_{12}O_6$, molecular weight 180.16 g/mol; Rpicorp, USA) was injected weekly intraperitoneally at a dose of 150 mg/kg body weight after being dissolved in regular saline. Throughout the course of the experiment, the intraperitoneal route guarantees the compound's

constant absorption and systemic dispersion. Sterile technique was used throughout all injection procedures to avoid contamination and infection, and the D-galactose solution was freshly produced before each injection to preserve component stability and efficacy. To guarantee precise dosing and reduce injection-related issues, the injection volume was meticulously determined depending on each rabbit's body weight.

Omega-3 Supplementation Protocol

Eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) from omega-3 supplement capsules (Ferrer Company, Spain) were dissolved in soybean oil and taken orally at a dose of 75 mg/kg body weight weekly. Pilot studies were used to validate this dosage, which was calculated by converting human clinical recommendations. To guarantee a steady daily intake and make adherence to the supplementing strategy easier, oral administration was favored. To maintain the bioactivity of the EPA and DHA components, the omega-3 formulation was kept at the proper temperature. To guarantee precise dosage and avoid supplement loss, oral gavage procedures were used. To enhance therapeutic efficacy and reduce variability, the delivery schedule was kept constant throughout the therapy phases.

Study Design

The study was conducted in two phases over a total of 90 days, with careful monitoring and sampling and predetermined intervals.

Phase one: Induction of aging

The T1 control group consisting of four adult male rabbits received intraperitoneal injections of normal saline and oral soybean oil throughout the initial phase. The D-gal group comprising twelve rabbits received intraperitoneal injections of D-galactose at 150 mg/kg body weight to induce accelerated aging phenotype.

This phase established baseline agent characteristics and confirmed successful aging induction before proceeding to treatment phases. Aging induction was monitored through a clinical observation of behavioral changes including reduced mobility, altered coat appearance and decreased food consumption patterns. Blood samples were collected at 30-day intervals to assess advanced glycation end products accumulation as an objective aging marker. The decision to proceed to phase two was based on confirmation of significant AGE elevation in the D-galactose treated animals.

Phase Two: Omega-3 Treatment

After confirming aging induction at 60 days using AGE markers, the following treatment groups were established for the remaining 30-day period. The T1 control group continued receiving normal saline and soybean oil to maintain baseline conditions. The T2 group received concurrent D-galactose and Omega-3 supplementation to evaluate the protective effects of early intervention.

The T3A Group received D-galactose for the initial 60 days, followed by omega-3 supplementation for the final 30 days to assess delayed therapeutic intervention efficacy. The T3B positive control group continued receiving D-galactose throughout the entire 90-day period without any therapeutic intervention. This design allowed comparison of early prevention versus delayed treatment strategies.

Sampling and Biochemical Analysis

In the scheduled periods (30, 60, and 90 days), blood was drawn by heart puncture under anesthesia with intraperitoneal administration of ketamine 100 mg/kg and xylazine 10 mg/kg. Centrifugation at 3000 rpm for 10 minutes was used to separate serum, which then kept at 18 °C for biochemical analysis. To ensure consistency of analytical results, all samples were processed according to a standard protocol.

Advanced Glycation End Products (AGEs) Assessment

The carboxymethyllysin (CML) level was estimated by using enzyme-linked immunosorbent assay technique (ELISA) with high sensitivity and specificity (Ref. No. CEB977Ge supplied from Cloud Clone Corp, China). Serum Pentosidine concentration is also estimated by using ELISA technique to give attitude about aging biomarkers. These two AGE parameters give a whole appreciation of nonenzymatic glycation processes occurring through D-galactose- induced aging.

CML represents products of early-stage glycation, while Pentosidine reveals accumulation of advanced and cross-linked glycation end products. The combination of both parameters gives temporal information about glycation, severity and progression. ELISA kits were employed to ensure precision of measurements across all samples.

Oxidative Stress Markers Evaluation

Malondialdehyde (MDA) was measured by using ELISA technique as a primary marker of lipid peroxidation and oxidative damage. Protein Carbonyl (PC) was measured by using ELISA

methodology to measure protein oxidation level. (Ref. No. CEB223Hu supplied from Cloud Clone Corp, China). These complementary parameters give complete appreciation of oxidative stress severity in serum and tissue samples.

Superoxide dismutase (SOD) was estimated by using ELISA technique to measure antioxidant enzyme activity (Ref. No. RPB960Hu01 supplied from Cloud Clone Corp, China). Catalase (CAT) activity was measured by using ELISA technique as an extra antioxidant enzyme marker (Ref. No. SEC418Ra supplied from Cloud Clone Corp, China). The combination of oxidative damage parameter and antioxidant enzyme activity provides balanced appreciation of redox status.

Inflammatory Markers Quantification

Tumer Necrosis Factor-alpha (TNF- α) level was measured by using ELISA technique to measure proinflammatory cytokines levels. Interleukin-1 beta (IL-1β) was measured by using ELISA methodology to estimate secondary inflammation response (Ref. No. SEA133Si supplied from Cloud Clone Corp, China). These cytokine measurements give direct indication of inflammatory status in aged rabbits.

Kidney Function Parameters Assessment

Blood urine nitrogen (BUN) concentration was measured by using spectrophotometry to measure glomerular filtration rate and renal function. Serum creatinine concentration is measured by using spectrophotometry as a primary renal function parameter. Serum albumin was measured by using spectrophotometry to measure protein metabolism and nutritional condition.

Cystatin C concentration was measured by ELISA technique as an alternative glomerular filtration rate parameter (Ref. No. SEA896Hu supplied from Cloud Clone Corp, China). This part of kidney function parameters provides broad attitude of renal dysfunction severity progression. The combination of multiple markers boosts diagnostic accuracy and provides complementary information about another aspects of kidney function.

Statistical Analysis

Data were analyzed using SPSS software (Version 22). Independent t-tests and one-way analysis of variance (ANOVA) with Tukey's post-hoc test were used for group comparisons. A P-value<0.05 was considered statistically significant. All data are presented as mean ± standard error of the mean (SEM).

RESULTS

Table 1 presents serum concentrations of Carboxymethyllysin (CML) and Pentosidine, which are key biomarkers for cellular aging and oxidative stress. These AGE markers accumulate in renal tissues during aging and serve as indicators of the extent of nonenzymatic glycation induced by D-galactose administration.

Table 1: Effect of Advanced Glycation End Products (AGEs) and Omega-3 on Aging Markers in Serum during (30 ,60 & 90 days) in adult male rabbits.

Biochemical Parameter	T1 (Control)	T3B (D-gal)	P-value	Time Point
Serum CML (ng/mL)	82.23 ± 5.74	109.71 ± 5.93*	P<0.05	30 days
Serum CML (ng/mL)	82.50 ± 5.66	118.76 ± 6.65*	P<0.05	60 days
Serum Pentosidine (ng/mL)	48.65±4.05*	20.96 ± 1.32	P<0.05	30 days
Serum Pentosidine (ng/mL)	49.83±6.07*	23.20 ± 0.41	P<0.05	60 days

- Values are expressed as the mean ± standard error
- Different letters in each row and column indicate the presence of significant differences at the probability level (P≤0.05).

The significant increase in serum CML and pentosidine in the D-galactose-treated group (T3B) confirms the successful induction of an aging phenotype with prominent AGE accumulation in aged rabbits. This finding is consistent with [7], who demonstrated that D-galactose accelerates aging by increasing free radical production and AGE formation [11,12]. The formation of AGEs occurs via the non-enzymatic Maillard reaction, which is accelerated by excess D-galactose [13,14]. These AGEs then bind to their cellular receptors (RAGE), triggering NADPH oxidase activation and increasing reactive oxygen species (ROS) production, which drives further oxidative stress and inflammation in renal tissues [15,16].

The time-dependent increase in AGE markers from 30 to 60 days indicates progressive accumulation of glycation products in the kidney of aged rabbits. While some studies suggest that

the relationship between AGEs and functional decline may not always be linear [17], our results demonstrate a clear time- dependent progression, supporting their use as reliable aging biomarkers in renal tissue. AGEs are chiefly breaking in the kidney, where they cross-link structural protein in the glomerular basement membrane and mesangial matrix, contributing to global glomerulosclerosis and proteinuria [18].

Table 2 shows parameters of oxidative stress (MDA and protein carbonyl), and antioxidant enzyme activity (SOD and Catalase) in serum. These parameters reflect the balance among oxidative damage and endogenous antioxidants defense systems in D-galactose-induced aging in rabbits

Biochemical Parameter	T1 (Control)	T2 (D-gal + Omega-3)	T3A (D-gal + Omega-3 late)	T3B (D-gal)	P-value
Serum MDA (nmol/mL)	1.8 ± 0.3	2.4 ± 0.4*	3.2 ± 0.5*	5.9 ± 0.8	P<0.05
Serum PC (nmol/mg protein)	0.9 ± 0.2	1.3 ± 0.3*	1.8 ± 0.4*	3.4 ± 0.5	P<0.05
Serum SOD (U/mL)	128.5 ± 9.2	118.3 ± 8.7*	102.1 ± 7.9*	71.2 ± 6.5	P<0.05
Serum Catalase (U/mL)	95.2 ± 7.1	82.4 ± 6.8*	68.9 ± 5.9*	48.3 ± 4.2	P<0.05
*Significantly different from T3B group (P<0.05)					

The D-galactose-treated group (T3B) showed significant increasing in the levels of MDA and protein carbonyl, indicating sever protein oxidative damage and peroxidation of lipids in serum and renal tissues of aged rabbits. This results is supported [12], who exhibited that D-galactose oxidation generates aldehydes and hydrogen peroxide, contributing to generation of ROS and lipid peroxidation [19]. The elevation in oxidative stress markers was accompanied by significant decreasing in the SOD and catalase activities, denoted to compromised antioxidant defense capability. This imbalance among oxidative damage and antioxidant defense is a characteristic feature of D-galactose-induced aging and contributes to progressive renal dysfunction.

The supplementation of Omega-3 with (T2 and T3A groups) significant reduced the oxidative stress parameters while accompanied by increasing in antioxidant enzyme activities. The T2 group showed most positive antioxidant profile, with reducing in the levels of MDA and protein carbonyl, otherwise increasing in the levels of SOD and catalase activities. This protective ability is consistent with many studies demonstrating omega-3 has ability to enhance endogenous antioxidant system [20,21]. The mechanism involves omega-3 ability to modulate antioxidant enzyme expression through signaling pathways such as Nrf2/ARE (Nuclear factor erythroid 2-related factor 2/Antioxidant Response Element), by improving total antioxidant capacity and protecting renal tissues from oxidative damage [22].

Table 3 presents serum level of pro-inflammatory cytokines (TNF-α and IL-1β) and kidney function parameters (BUN, creatinine, albumin and cystatin C). These markets reflect both the inflammatory burden and the functional capacity of the kidneys in aged rabbits.

Table 3: Effect of Advanced Glycation End Products (AGEs) on Serum Inflammatory Cytokines and Kidney Function Parameters in adult male rabbits.

Biochemical Parameter	T1 (Control)	T2 (D-gal + Omega-3)	T3A (D-gal + Omega-3 late)	T3B (D-gal)	P-value
Serum TNF-α (pg/mL)	28.5 ± 4.2	52.3 ± 6.8*	71.2 ± 8.9*	125.8 ± 13.2	P<0.05
Serum IL-1β (pg/mL)	18.2 ± 3.1	38.9 ± 5.4*	54.7 ± 7.2*	92.1 ± 10.5	P<0.05
Blood Urea Nitrogen (mg/dL)	18.5 ± 2.1	24.3 ± 2.8*	32.1 ± 3.5*	48.7 ± 4.9	P<0.05
Serum Creatinine (mg/dL)	0.72 ± 0.08	1.05 ± .12*	1.38 ± 0.15*	2.15 ± 0.22	P<0.05
Serum Albumin (g/dL)	3.85 ± 0.25	3.42 ± .22*	3.08 ± 0.19*	2.31 ± 0.18	P<0.05
Cystatin C (mg/L)	0.58 ± 0.06	0.89 ± .08*	1.24 ± 0.11*	1.95 ± 0.15	P<0.05
*Significantly different from T3B group (P<0.05)					

The D-galactose group (T3B) demonstrated significantly elevated levels of pro- inflammatory cytokine TNF-α and IL-1β, confirming a strong pro-inflammatory response characteristic of aging in rabbits. This finding is supported by multiple studies that showed D-galactose activities NF-κB signaling pathway, leading to chronic inflammation [23].

The elevated inflammatory markers in the T3B group were accompanied by severe renal dysfunction, as evidenced by markedly elevated BUN and serum creatinine levels, reduced serum albumin, and elevated cystatin C. these findings indicate compromised glomerular filtration rate and impaired renal protein metabolism in aged rabbits

Omega-3 Supplementation significantly reduced pro-inflammatory cytokines levels and improved kidney function parameters. The T2 group (concurrent D-galactose and omega-3 treatment) showed the most favorable results, with substantially reduced TNF-α and IL-1β) level and near-normal kidney function markers. This anti-inflammatory effect of omega-3 is attributed to the ability to compete with arachidonic acid, reducing the production of pro-inflammatory eicosanoids [24,25]. Additionally, omega-3 modulates immune cell activation and recruitment, reducing the inflammatory burden in renal tissue and preserving glomerular and tubular function

The T3A group (delayed omega-3 treatment) showed intermediate results, indicating that while omega-3 provides substantial protection, early intervention is superior to delayed treatment and aged rabbits. This finding suggests that preventive supplementation strategies may be more effective and therapeutic approach initiated after aging-related changes have become established. The improved kidney function parameters in omega-3 treated groups correlate with reduced inflammatory markers, supporting the hypothesis that omega-3 has reno-protective effect are mediated through anti-inflammatory mechanisms [26].

Conclusion

D-galactose successfully induced aging in rabbits, characterized by elevated Advanced Glycation End Products (AGEs), increased oxidative stress, and pro-inflammatory cytokine production, resulting in significant renal dysfunction. Omega-3 supplementation demonstrated remarkable protective effects against D-galactose-induced kidney damage through multiple mechanisms: reducing AGE accumulation, suppressing oxidative stress markers, decreasing pro-inflammatory cytokines (TNF-α and IL-1β), and preserving kidney function parameters (BUN, creatinine, albumin, and cystatin C). Early concurrent omega-3 treatment proved superior to delayed intervention, suggesting preventive supplementation strategies are optimal. These findings establish omega-3 polyunsaturated fatty acids as a promising therapeutic intervention for age-related renal dysfunction.

Acknowledgement

We would like to thank College of Veterinary Medicine, Baghdad University for their support during the conducting of the research.

Declaration of interests

The authors declare that they have no conflict of interest.

Funding Sources

Private funding.

Publication consent

Each author has demonstrated their consent for the publication of the current manuscript.

Data and material availability:

All data would be provided based on request.

Author contribution:

SAA and HSMSA: conceptualization, Supervision, Resources. SAA formal analysis, drafting, reviewing and editing. HFA: Did the laboratory work, Data collection, Data curation, writing original draft.

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Tikrit Journal of Veterinary Sciences (2026) 5(1): 215-222
DOI : 10.25130/tjvs.5.1.23

تأثير مكملات أوميغا-3 في وظائف الكلى لدى ذكور الأرانب ذات الشيخوخة المستحثة بـ D -غالاكتوز

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الملخص

الخلفية والهدف : يرتبط التقدم في العمر بتدهور تدريجي في وظائف الكلى نتيجة حدوث التصلب الكبيبي والضمور الأنبوبي ويؤدي الإعطاء التجريبي لـ D- غالاكتوز إلى تسريع عملية الشيخوخة من خلال تحفيز الإجهاد التأكسدي والاستجابات الالتهابية، مما يسبب اختلالًا في وظائف الكلى. هدفت الدراسة الحالية إلى تقصي التأثيرات الوقائية للأحماض الدهنية المتعددة غير المشبعة الأوميغا-3 ضد التلف الكلوي المستحث بـ D-غالاكتوز في ذكور أرانب نيوزيلندا البيضاء البالغة.

المواد وطرائق العمل : قُسم ستة عشر ذكرًا بالغًا من أرانب نيوزيلندا البيضاء عشوائيًا إلى أربع مجموعات تجريبية: مجموعة السيطرة(T1) ، مجموعة المعاملة بـ D -غالاكتوز (T3B) ، مجموعة المعاملة المتزامنة بـD -غالاكتوز وأوميغا-3 (T2)، ومجموعة المعاملة المتأخرة بأوميغا-3 بعد إعطاء D -غالاكتوز (T3A). استمرت التجربة لمدة 90 يومًا. وحُللت عينات مصل الدم لقياس النواتج النهائية المتقدمة للكاربوكسي ميثيل لايسين والبنتوزيدين كمؤشرات للإجهاد التأكسدي ، المالون ثنائي الألدهيد ، كاربونيل البروتين، إنزيم فوق أكسيد الديسميوتاز، إنزيم الكاتاليز، السيتوكينات الالتهابية، عوامل النخر الاتهابية-ألفا والإنترلوكين-1 بيتا ، بالإضافة إلى مؤشرات وظائف الكلى التي شملت نيتروجين يوريا الدم ، الكرياتينين، الألبومين والسيستاتين-C.

النتائج : أدى إعطاء-D غالاكتوز إلى زيادة معنوية في تراكيز النواتج النهائية المتقدمة للتراكم السكري، ومؤشرات الإجهاد التأكسدي، والسيتوكينات الالتهابية، بالتزامن مع تدهور معنوي في وظائف الكلى مقارنة بمجموعة السيطرة. في المقابل، أدى إعطاء أوميغا-3 إلى خفض معنوي في مستويات النواتج النهائية المتقدمة للتراكم السكري ، ومؤشرات الإجهاد التأكسدي، والسيتوكينات الالتهابية، مع تحسين مؤشرات وظائف الكلى. علاوة على ذلك، أظهرت المعاملة المتزامنة بأوميغا-3 مع-D غالاكتوز (T2) تأثيرًا وقائيًا أكبر مقارنة بالمعاملة المتأخرة بأوميغا-3 (T3A) .

الاستنتاج :أدت الشيخوخة المستحثة بـ D -غالاكتوز إلى إحداث إجهاد تأكسدي والتهاب واضحين، فضلًا عن اختلال في وظائف الكلى لدى الأرانب. وقد أسهمت الأحماض الدهنية المتعددة غير المشبعة أوميغا-3 بفاعلية في الحد من هذه التأثيرات الضارة من خلال خصائصها المضادة للأكسدة والمضادة للالتهابات، وكانت المعاملة المتزامنة أكثر فاعلية من المعاملة المتأخرة. وتشير هذه النتائج إلى أن مكملات أوميغا-3 قد تمثل استراتيجية وقائية واعدة للحد من القصور الكلوي المرتبط بالتقدم في العمر.

الكلمات المفتاحية : الشيخوخة، دي-غالاكتوز ، الأحماض الدهنية أوميغا-3، الإجهاد التأكسدي، اختلال وظائف الكلى.