



# The current and emerging Klotho-enhancement strategies

Haniyeh Poursistany<sup>a</sup>, Solmaz Tabibi Azar<sup>b</sup>, Mahsan Tabibi Azar<sup>c</sup>, Sina Raeisi<sup>d,\*</sup>

<sup>a</sup> Department of Clinical Biochemistry and Laboratory Medicine, Tabriz University of Medical Sciences, Tabriz, Iran

<sup>b</sup> Department of Cell and Molecular Biology, School of Biology, College of Science, University of Tehran, Tehran, Iran

<sup>c</sup> Student Research Committee, Islamic Azad University, Tabriz Branch, Tabriz, Iran

<sup>d</sup> Pediatric Health Research Center, Tabriz University of Medical Sciences, Tabriz, Iran

## ARTICLE INFO

### Keywords:

Exosomes

Epigenetic modification

Gene regulation

Klotho

Nonepigenetic modifications

## ABSTRACT

Klotho is well known as a gene with antiaging properties. It has membrane and soluble forms, providing a unique system that controls various metabolic processes essential to health and disease. Klotho deficiency has been revealed to be associated with various aging-related disorders. Based on its various known and unknown protective properties, upregulating the Klotho gene may be a possible therapeutic and/or preventive approach in aging-related complications. Some agents, such as hormonal compounds, renin-angiotensin system inhibitors, antioxidants, peroxisome proliferator-activated receptor gamma (PPAR- $\gamma$ ) agonists, statins, vitamin D receptor agonists, antioxidants, anti-inflammatory agents, mammalian target of rapamycin (mTOR) signaling inhibitors, and receptor-interacting serine/threonine-protein kinase 1 (RIPK1) inhibitors, can possibly lead to the upregulation and elevation of Klotho levels. Demethylation and deacetylation of the Klotho gene can also be considered other possible Klotho-enhancement methods. Some emerging techniques, such as RNA modifications, gene therapy, gene editing, and exosome therapy, probably have the potential to be applied for increasing Klotho. In the present study, these current and emerging Klotho-enhancement strategies and their underlying mechanisms were comprehensively reviewed, which could highlight some potential avenues for future research.

## 1. Introduction

Klotho (KL) has been well described as a gene with antiaging properties [1]. The KL gene was initially discovered by Kuro-o et al., in 1997 in a group of mice with complex aging-like phenotypes. They found that the cause of this phenotype was a mutation in the KL gene [2]. The KL-deficient mice not only suffered from several age-related complications, such as renal failure, atherosclerosis, hypogonadism, infertility, growth retardation, vascular calcification, skin atrophy, osteoporosis, and hearing loss but also had short life spans. On the other hand, mice with high expression of KL had a longer lifespan of 20–30 % [2].

The KL family has three members, including  $\alpha$ -KL,  $\beta$ -KL, and  $\gamma$ -KL. In general, the word “Klotho” means  $\alpha$ -KL when no subfamily is mentioned [3,4]. The human KL ( $\alpha$ -Klotho) gene is located on chromosome 13q13.1 and consists of five exons. It is predominantly expressed in the kidneys and brain and to a lesser extent in the heart and parathyroid glands. The gene expresses a type 1 transmembrane protein functioning as a coreceptor for fibroblast growth factor-23 (FGF23) [5].  $\beta$ -KL is a coreceptor for FGF19 and FGF21, while  $\gamma$ -KL is a half-size KL-related protein. The

high-affinity binding of FGF19, FGF21, and FGF23 to their receptors requires the presence of KL [4,6,7].

There are also soluble forms of KL (s-KL) that can be produced not only by shedding the extracellular domain of KL [through proteolytic activities of a disintegrin and metalloproteinases 10 and 17 (ADAM10/17)] but also by alternative splicing of the KL gene. The soluble forms are mainly found in body secretions such as blood, urine, and cerebrospinal fluid (CSF) and have endocrine, paracrine, or autocrine roles independent of FGFs [6]. Collectively, membrane and soluble forms of KL provide a unique system that not only controls a wide range of metabolic processes essential in health, such as mineral and energy metabolism and stress responses but also may play protective roles against chronic kidney disease (CKD), cardiovascular diseases (CVD), neurological diseases, cancer, and diabetes [6,8–10]. Therefore, enhancing KL might have therapeutic benefits in various aging-related disorders. In general, the amount of a protein can be increased by taking supplements, increasing gene expression, and inhibiting protein degradation in the target tissue. Various methods have been introduced that can be considered possible approaches to increase KL. The present study aimed

\* Corresponding author. Pediatric Health Research Center, Zahra Mardani Azari Children Training, Research & Treatment Center, Mardani Azari street, Khavaran town, Tabriz, 5143377505, Iran.

E-mail addresses: [sina.raeisi7007@yahoo.com](mailto:sina.raeisi7007@yahoo.com), [raeisis@tbzmed.ac.ir](mailto:raeisis@tbzmed.ac.ir) (S. Raeisi).

<https://doi.org/10.1016/j.bbrc.2023.149357>

Received 5 September 2023; Received in revised form 24 November 2023; Accepted 4 December 2023

Available online 10 December 2023

0006-291X/© 2023 Published by Elsevier Inc.

to comprehensively review the current and emerging KI-enhancement strategies as a possible therapeutic and/or preventive approach for various aging-related disorders.

## 2. Current methods

Some drugs and agents have been revealed to increase KI levels through different nonepigenetic and epigenetic mechanisms. These agents are briefly described below.

### 2.1. Hormonal agents

There might be a link between KI and the neuroendocrine system. It has been shown that some hormonal agents lead to KI enhancement [11–14]. Hsu et al. examined the regulatory effects of testosterone on KI gene expression *in vivo* and *in vitro* [12]. In their study, KI mRNA and protein were upregulated in testosterone-treated NRK-52E cells and mouse kidneys. KI was enhanced through the upregulation of the nuclear androgen receptor (AR) by testosterone because flutamide, an AR antagonist, attenuated the testosterone-induced KI expression. This receptor directly binds to the KI gene promoter via androgen response elements (AREs) and eventually upregulates KI [12]. Estrogens have been shown to be potent modulators of neurotransmission, synaptic plasticity, and neurogenesis in the hippocampus. Menopause in women is associated with an increased risk of memory disorders, which can be reduced by timely estrogen therapy [11]. Sárvári et al., in a rat model of menopause, showed that the administration of 17 $\beta$ -estradiol (E2) induced the transcriptional activation of some hippocampal genes, including KI, which ultimately improved hippocampus-dependent spatial memory [11]. Mizunoe et al., in an *in vitro* study, investigated the effect of tri-iodothyronine (T<sub>3</sub>) on KI gene expression in 3T3-L1 adipocytes [13]. They revealed that T<sub>3</sub> induced the expression of the membrane form of KI (m-KI), which may play a role in adipose differentiation. The expression of the secreted form of KI was not affected by T<sub>3</sub>; therefore, this hormone might affect the splicing of KI mRNA [13]. Chen et al. found that insulin could enhance s-KI production possibly by inducing the proteolytic activity of ADAM 10/17 [14]. The expression of the genes encoding these proteases was not affected by insulin. Furthermore, they showed that the effect of insulin on KI shedding was inhibited by wortmannin, a covalent inhibitor of phosphoinositide 3-kinases (PI3Ks), suggesting that insulin might act through a PI3K-dependent pathway. It might recruit a signaling cascade and/or gene expression that induces ADAM 10/17 activity and increased shedding of KI [14]. These results show that the expression of membrane and secretory forms of KI can be regulated by some hormones through different mechanisms. Therefore, hormone therapy can be considered a strategy to increase KI expression. However, more studies are necessary to confirm these impressions.

### 2.2. Renin-angiotensin system inhibitors

The renin-angiotensin system (RAS) is one of the main systems controlling blood pressure and body fluid homeostasis. The main biological hormone of this system is angiotensin II (Ang-II), which is produced under the influence of angiotensin-converting enzyme (ACE) on angiotensinogen. Ang-II binds to certain receptors, including the angiotensin type-1 (AT1) receptor, and affects a wide range of biological processes, from inflammation and immune responses to longevity [15]. Accumulating data suggest that there is an association between KI and RAS [16]. Ang-II could downregulate KI [16,17]. Mitani et al. showed that the long-term administration of Ang-II reduced mRNA and protein expression of renal KI through the AT1 receptor [18]. It was also revealed that Ang-II-induced KI downregulation was pressure-independent. Ang II increases the expression of transforming growth factor- $\beta$ 1 (TGF- $\beta$ 1) and p38 MAPK, leading to the activation of P53. Activated P53 forms complexes with the transcription factor SP1 in

the nucleus. P53/SP1 binds to the KI gene promoter and inhibits its transcription [18]. Angiotensin receptor blockers (ARBs), such as losartan and valsartan, and ACE inhibitors, such as enalapril and fosinopril, might enhance KI levels by preventing the inhibitory effect of Ang-II on KI expression [17,19,20]. In a study by Lim et al., the administration of losartan in patients with type 2 diabetes caused a significant increase in circulating s-KI levels [19]. Therefore, inhibiting the RAS may be considered an approach to increase the amount of KI. However, further studies are necessary to confirm the results. It is also imperative that the effects of RAS inhibitors on KI gene expression be evaluated in tissues other than blood and kidneys.

### 2.3. Anti-inflammatory agents

It has been found that inflammation can decrease KI expression [21, 22]. Various proinflammatory and anti-inflammatory cytokines and related molecules may play a role in reducing KI expression [23]. Moreno et al. showed that tumor necrosis factor- $\alpha$  (TNF $\alpha$ ) and TNF-like weak inducer of apoptosis (TWEAK), as inflammatory cytokines, could downregulate KI expression through a nuclear factor kappa-light-chain-enhancer of activated B cells (NF- $\kappa$ B)-dependent mechanism [23]. TWEAK induces RelA binding to the KI promoter, causing its deacetylation and inhibiting KI gene expression [23]. Teocchi et al. also revealed that TNF could downregulate KI through NF $\kappa$ B in resected hippocampal tissue samples from patients with temporal lobe epilepsy [24]. Considering the role of inflammation in KI reduction, the use of anti-inflammatory drugs may be effective in maintaining or even elevating KI expression. Different steroidal and nonsteroidal anti-inflammatory drugs, through different mechanisms, can be effective in relieving inflammation and related complications by reducing inflammatory cytokines or blocking the relevant signals (84). However, more precise studies seem to be necessary to confirm the stimulating effect of these drugs on KI expression.

### 2.4. Antioxidants

It is clear that KI expression is repressed under sustained stress conditions and increased free radicals, indicating a close relationship between oxidative stress and KI expression [25]. Mitobe et al. showed that hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>)-induced oxidative stress downregulated KI dose-dependently in the mouse inner medullary collecting duct (mIMCD3) cell line [25]. Oh et al. showed that circulating s-KI levels were significantly associated with 8-isoprostane levels, an oxidative stress marker, in patients receiving peritoneal dialysis [21]. Antioxidant supplementation might lead to KI enhancement [26]. Jaturakan et al. showed in an animal model study that vitamin C and vitamin E administration could upregulate KI [27]. It has also been shown that N-acetylcysteine (a glutathione precursor) and melatonin administration could upregulate KI by inhibiting AKT and forkhead box O (FOXO) phosphorylation, respectively, as possible mechanisms [28,29]. Based on previous studies, other agents with antioxidant effects, such as lipoic acid, and polyphenols (such as curcumin), might also induce KI expression [26]. Therefore, antioxidant supplementation could be considered a KI enhancement therapeutic or supportive approach for managing aging-related disorders.

### 2.5. Peroxisome proliferator-activated receptor gamma (PPAR- $\gamma$ ) agonists

Peroxisome proliferator-activated receptor gamma (PPAR- $\gamma$ ) is a transcription factor involved in glucose and lipid homeostasis, bone turnover, and inflammation [30]. Previous studies have found evidence of two noncanonical PPAR- $\gamma$  binding sites upstream of the KI gene, suggesting possible regulatory effects of PPAR- $\gamma$  on KI [31]. Zhang et al. showed that PPAR- $\gamma$  upregulated KI both *in vitro* and *in vivo* [32]. The expression of PPAR- $\gamma$  decreases with aging [30]. Since the expression of

PPAR- $\gamma$  decreases during aging, studies on the effect of PPAR- $\gamma$  agonists or thiazolidinediones (TZDs) on aging-related agents have revealed that the widely used TZDs, such as Ciglitazone, Troglitazone, Pioglitazone, and Rosiglitazone, could elevate KI levels [32–34]. Therefore, the use of PPAR- $\gamma$  agonists can be considered a potential strategy to enhance KI gene expression.

## 2.6. Statins

Statins are competitive inhibitors of 3-hydroxy-3 methylglutaryl coenzyme A (HMG-CoA) reductase. It is the main allosteric enzyme catalyzing the conversion of HMG-CoA to mevalonic acid, a necessary step in the biosynthesis of cholesterol and other isoprenoids. Statins such as atorvastatin, rosuvastatin, and pitavastatin are widely used in treating patients with hypercholesterolemia to reduce LDL cholesterol levels [35]. Statins have other beneficial effects, such as anti-inflammatory and antioxidant effects, by modulating nuclear factor erythroid 2-related factor 2 (Nrf2) and Nrf2/HO-1 signaling in different diseases [36]. Convincing evidence indicates that statins could also stimulate KI gene expression by activating the FOXO signaling pathway and inhibiting the Rho/Rho-kinase pathway [37,38]. Therefore, statin administration can also be considered a possible approach to enhance KI expression.

## 2.7. Vitamin D and vitamin D receptor (VDR) agonists

Vitamin D acts as a pleiotropic steroid hormone, which, in addition to its regulatory effects on calcium and bone homeostasis, exerts anti-proliferative, antibacterial, immunomodulatory, and anti-inflammatory properties [39]. The biological effects of 1,25(OH)<sub>2</sub>D<sub>3</sub> (calcitriol), the biologically active form of vitamin D, are mediated by VDR, which belongs to the nuclear hormone receptor superfamily of transcription regulators [39,40]. After binding to VDR, vitamin D can be involved in the regulation of the expression of various genes, including KI [41,42]. After activation by vitamin D or its analogs, VDR forms a heterodimer with the retinoid X receptor (RXR) and translocates to the nucleus, where it binds to vitamin D response elements (VDREs) within the KI gene promoter region, inducing its expression. Lau et al. showed that the administration of calcitriol or its analog, paricalcitol, elevated the serum levels of KI in mice independent of parathyroid hormone and calcium level alterations [41]. Therefore, vitamin D and VDR agonists, including calcitriol, alfacalcidol, doxercalciferol, fluorocalcidol, and maxacalcitol, might have inducing effects on KI gene expression.

## 2.8. Mammalian target of rapamycin (mTOR) signaling inhibitors

The mammalian (or mechanistic) target of rapamycin (mTOR) is a serine/threonine protein kinase that plays roles in regulating cellular growth, proliferation, body energy metabolism, and lifespan [43]. Some evidence has revealed that activation of mTOR signaling suppresses KI expression, while its inhibition could upregulate it [44–46]. Sirolimus, also known as rapamycin, is an mTOR inhibitor that has immunosuppressive effects by inhibiting the activation of T and B cells. This agent has been shown to increase or retain KI levels by inducing KI expression [45]. Mizusaki et al. showed that renal transplantation recipients receiving Everolimus (a rapamycin derivative) had higher s-KI levels than other patients who did not take this agent [46]. The use of mTOR inhibitors can also be considered another possible KI-increasing approach.

## 2.9. Receptor-interacting serine/threonine-protein kinase 1 (RIPK1) inhibitors

Receptor-interacting serine/threonine-protein kinase 1 (RIPK1) has been identified to play roles in several cellular pathways related to cell survival, cell death (apoptosis and necroptosis), and inflammation [47].

It has been considered an encouraging therapeutic target in managing various human neurodegenerative, autoimmune, and inflammatory disorders [48]. In recent years, the therapeutic application of RIPK1 inhibitors has gained attention. The effects of the RIPK1 inhibitors GSK772 and DNL747 have been evaluated in the management of autoimmune diseases and neurodegenerative disorders, respectively, and the results were encouraging [49,50]. Ning et al. revealed that necrostatin-1, a potent and specific small-molecule inhibitor of RIPK1, could alleviate cisplatin-induced nephrotoxicity by retaining renal KI expression and suppressing apoptosis and oxidative stress [51]. Therefore, RIPK1 inhibition may also be a strategy to enhance KI.

## 2.10. Other agents

Other factors, such as aerobic exercise [52], intermedin (a vasoactive factor) [53], and ligustilide (a natural benzoquinone derivative found in some Chinese herbal medicines) [54], may also be effective in enhancing KI.

## 3. Emerging methods

Recently, some new and emerging introduced methods, such as epigenetic modifications [45,55], gene therapy [18,56], gene editing [57], and exosome therapy [58], have the potential to upregulate KI and enhance its amount in the brain. These methods are briefly described below.

### 3.1. Epigenetic modifications

Epigenetics is one of the expanding fields of biology that has been applied in modern and precision medicine [59,60]. Epigenetic modifications are nuclear or molecular alterations affecting gene expression and, eventually, the final product amount of a locus or chromosome without direct interaction with the primary DNA sequence. Histone modification, DNA methylation, and microRNA (miRNA) expression alteration are the most prevalent studied epigenetic modifications [61]. Different types of histone modification, such as acetylation, methylation, phosphorylation, and ubiquitination, have been revealed to affect gene expression and protein production. Acetylation and deacetylation are mainly catalyzed by two enzymes, histone acetyltransferases (HATs) and histone deacetylases (HDACs). Histone acetyltransferase adds an acetyl group to an amino acid in histones that facilitates chromatin opening, leading to gene upregulation. Histone deacetylases with contrasting functions remove acetyl groups, resulting in a more closed chromatin structure and leading to gene downregulation [61,62]. In a study by Lin et al., HDAC inhibition by trichostatin-A attenuated chronic kidney disease-associated bone injury in mice by upregulating KI [63]. DNA methylation is a transfer process of a methyl group to the fifth carbon of a cytosine residue to form 5-methylcytosine in DNA. This process is catalyzed by a family of DNA methyltransferases and affects gene expression by applying proteins involved in gene repression or by interfering with the binding of transcription factor(s) to DNA [64]. Zhu et al. showed that methylation of the KI gene promoter silenced its gene expression in head and neck squamous cell carcinoma [65]. Therefore, DNA methyltransferase inhibitors such as azacytidine, decitabine, and zebularine might have the potential to be used as a KI-elevating approach. MiRNAs are a type of small, noncoding RNA that affects the expression of protein-encoding genes through the RNA interference (RNAi) pathway. They posttranscriptionally repress the target genes by attaching to the 3'UTR of the genes or by inducing mRNA degradation [55]. Liang et al. demonstrated that miR-130a promoted KI expression, leading to protection against lipopolysaccharide-induced glomerular cell injury [55]. These encouraging results could demonstrate that epigenetic modifications have the potential to be applied to enhance KI expression.

**Table 1**  
The current therapies for increasing Klotho levels.

Method	Agent	Key Findings	Target	Ref.
<b>Hormonal Agents</b>	Testosterone	Kl mRNA and protein levels were enhanced through mediating of AR and AREs.	NRK-52E cells and mouse kidneys	[12]
	17 $\beta$ -estradiol (E2)	Transcriptional activation of Kl was induced. Spatial memory was improved.	Rat hippocampus	[11]
	T <sub>3</sub>	The expression of the m-Kl was upregulated. The expression of the s-Kl was not affected.	3T3-L1 adipocytes	[13]
	Insulin	The production of s-Kl was enhanced by inducing the activity of ADAM 10/17.	COS-7 cells, rat kidneys	[14]
<b>RAS inhibitors</b>	Losartan	Circulating levels of s-Kl increased.	Type 2 diabetic patients	[19]
	Fosinopril Valsartan	Kl expression was upregulated.	NRK-52E cells	[20]
<b>Anti-inflammatory and antioxidant agents</b>	N-Acetylcysteine	Kl expression was upregulated. CsA-nephropathy was attenuated.	Rat Kidneys	[28]
	Melatonin	Kl expression was upregulated. Cisplatin-induced acute kidney injury was attenuated.	Rat Kidneys	[29]
<b>PPAR-<math>\gamma</math> agonists</b>	Thiazolidinediones (Troglitazone and Ciglitazone)	Kl expression was increased in a dose and time-dependent manner.	HEK293, IMCD, MCT, and MDCK cells; Mouse Kidneys	[32]
	Pioglitazone	The expression of Kl was increased and aging-related progressive renal injury was ameliorated.	Rat Kidneys	[33]
	Rosiglitazone	Cerebral Kl expression was increased and the impaired baroreflex sensitivity was restored.	Rat Brain	[34]
<b>Statins</b>	Pravastatin	Kl expression was upregulated in a dose-dependent manner. CsA-induced nephropathy was ameliorated.	Mouse Kidneys	[37]
	Atorvastatin Pitavastatin	The reduction of Kl expression induced by NOS inhibition was prevented.	Rat Kidneys	[38]
<b>Vitamin D and VDR agonists</b>	Calcitriol Paricalcitol	The serum levels of Kl were elevated independent of parathyroid hormone and calcium level alterations.	Mice	[41]
<b>mTOR signaling inhibitors</b>	Rapamycin	Membrane and secreted Kl were enhanced. Vascular calcification was ameliorated.	BASMCs HASMCs Rat's aorta and serum	[45]
	Everolimus	s-Kl levels were elevated.	Renal transplantation recipients	[46]
<b>RIPK1 inhibitors</b>	Necrostatin-1	Kl expression was upregulated and Cisplatin-induced nephrotoxicity was alleviated	Mouse Kidney	[51]
<b>Other agents</b>	Aerobic exercise	Kl was upregulated that induced antioxidative effects.	Rat brain and kidneys	[52]
	Intermedin <sub>1-53</sub>	Kl was upregulated that reduced vascular calcification.	Rat aortas	[53]
	Ligustilide	Kl expression increased. Memory deficits, amyloid accumulation, tau phosphorylation, and oxidative stress were reduced.	Mouse brain and serum; 293T cell line	[54]

ADAM, a disintegrin and metalloproteinase; AR, androgen receptor; ARE, androgen receptor element; CsA, Cyclosporin A; Kl, klotho; m-Kl, membrane klotho; mTOR, mammalian target of rapamycin; PPAR- $\gamma$ , peroxisome proliferator-activated receptor gamma; RAS, renin-angiotensin system; RIPK1, receptor-interacting protein kinase 1; s-Kl, soluble klotho; VDR, vitamin D receptor.

### 3.2. Epitranscriptomics

Biochemical modifications of macromolecules have inevitable roles in biological processes. Like DNA and histone modifications, it has been found that RNA modifications also have profound impacts on gene expression [66,67]. RNA epigenetics, also called “epitranscriptomics”, is an emerging field of posttranscriptional regulation of gene expression that has recently attracted the interest of researchers [68]. It is a set of dynamic and reversible biochemical modifications in cellular RNAs (transcriptome) that can alter gene expression levels by affecting the structure and metabolism of mRNA. Some examples of known RNA modifications are N1-methyladenosine (m1A), pseudouridine ( $\Psi$ ), 5-methylcytidine (m5C), and N6-methyladenosine (m6A) modifications [66,69]. They have predominantly been identified in noncoding RNAs (ncRNAs), including tRNA, rRNA, and small nuclear RNAs (snRNAs), that could affect gene expression through various mechanisms, such as affecting the structure, stability, and translation level of mRNA [67,69,70]. RNA modifications have the potential to be applied for altering the expression of a target gene such as Kl. Recently, it has been shown that m6A modification could affect Kl gene expression [71]. M6A modification can be mediated by methyltransferase-like enzymes such as METTL14, which has been revealed to downregulate Kl expression. On the other hand, removing m6A on RNA by demethylase enzymes such as FTO and ALKBH5 or inhibiting METTL14 could lead to Kl upregulation [72]. Therefore, epitranscriptomics could be considered an emerging therapeutic approach to alter the expression levels of related target genes, such as Kl, which play roles in the pathogenesis of different disorders.

### 3.3. Gene therapy

Gene therapy is generally a method to replace a defective gene with a normal version to work properly in the target tissue [26]. Lentivirus and adenovirus-based vectors are practical tools for transmitting genetic material. Recently, these vectors have widely been used in gene therapy due to their characteristics, such as low and acceptable immunogenicity, low toxicity, high stability, and cell-type specificity [73]. A lentivirus encoding the mouse Kl gene was applied in an animal model study by Zhou et al. to sustain Kl expression [56]. These vectors were injected into the bilateral lateral ventricles of 7-month-old mice. Gene delivery increased all forms of Kl in the mouse brain. The results also revealed that lentivirus-mediated upregulation of Kl expression alleviated aging-related memory deficits and oxidative stress in the studied mice [56].

### 3.4. Gene editing

Techniques for transferring exogenous genes to target sequences have improved significantly. Clustered regularly interspaced short palindromic repeats (CRISPR) are nucleic acid sequences that, in coordination with CRISPR-associated (Cas) proteins, act as the immune system that protects bacteria and archaea against the external invasion of viruses, plasmids, and phages.

Type II of this compatible bacterial immune system has been engineered in recent years and presents a new and powerful technique called CRISPR–Cas9 for precise genomic manipulation [26]. Several desired applications, such as gene editing, gene tracking, upregulation,



**Table 2**  
The emerging therapies for increasing Klotho levels.

Method	Agent	Key Findings	Target	Ref.
Epigenetic modifications	Trichostatin-A	HDAC was inhibited leading to Klotho upregulation. CKD-associated bone injury was attenuated.	Mouse kidneys	[63]
	miR-130a	LPS-induced glomerular cell injury was alleviated by upregulation of Klotho expression.	HK-2 cells	[55]
Epitranscriptomic modifications	METTL14-siRNA	Klotho was upregulated by METTL14 knockdown	HRGECs Mice Kidneys	[71, 72]
	FTO, ALKBH5	Klotho can be upregulated by reversing m6A RNA modification.		
Gene therapy	Lentivirus encoding Klotho gene	All forms of Klotho increased. Aging-related memory impairments and oxidative stress were alleviated.	Mouse brain	[56]
Gene editing	CRISPR system	Two gRNA targeting the Klotho promoter regions were recognized and utilized for efficient transcriptional activation of the Klotho gene. Klotho gene expression was enhanced at both the gene and protein levels.	SY5Y, and HK-2 cells	[57]
Exosomes	Klotho-overexpressing exosomes	Caerulein-stimulated apoptosis and inflammation were reversed.	AR42J cells	[58]

ALKBH5, alkylated B Homolog 5; CKD, chronic kidney disease; CRISPR, clustered regularly interspaced short palindromic repeats; FTO, fat mass and obesity-associated protein; HDAC, histone deacetylase; Klotho, Klotho; LPS, lipopolysaccharide; m6A, N6-methyladenosine; METTL14, methyltransferase-like 14.

downregulation, and gene blocking, can be provided by adding suitable and specific peptides, proteins, and enzymes to this system [26,74]. The CRISPR–Cas9 system has recently attracted inclusive attention for therapeutic applications [74]. It may also be considered a possible therapeutic approach in Klotho gene editing and altering its expression. Chen et al. applied the CRISPR–Cas9 system to activate human Klotho gene expression in two human cell lines, neuronal SY5Y and renal HK-2 cells [57]. Two gRNAs targeting the Klotho promoter regions were recognized and utilized for efficient transcriptional activation of the Klotho gene. Klotho gene expression was enhanced at both the gene and protein levels, indicating the efficacy of gene therapy for targeting Klotho using the CRISPR method [57].

3.5. Exosomes

Exosomes are nanosized vesicles (50–100 nm) produced by almost all cells and have received considerable attention in recent years. Exosomes were initially thought of as tools that can be used to dispose of cellular waste. These nanovesicles are currently considered a new form of intercellular interaction [26,75]. They have roles in several

pathophysiological processes. Additionally, some of their characteristics, such as tissue specificity, lack of immunogenicity, and ability to cross the cell membrane and blood–brain barrier, make them a possible tool for therapeutic approaches. They can be applied as a vehicle to transport various contents, such as DNA, miRNA, mRNA, protein, and even drugs, to target cells [26,75]. The transferred exosomal cargo can eventually alter cell function by affecting some metabolic and signaling pathways and altering the expression of target genes and proteins [75]. Thus, exosomes can be used as a possible tool for transporting soluble-Klotho to several target tissues. In a study by Wang et al., exosomes were extracted from Klotho-overexpressing mesenchymal stem cells and subsequently administered in cell culture (AR42J cells) and an animal model of acute pancreatitis induced by caerulein [58]. The administered Klotho-overexpressing exosomes reversed apoptosis and nuclear factor- $\kappa$ B activation and alleviated the severity of pancreatic inflammation [58].

4. Conclusion and future research directions

Klotho is well described as a gene with antiaging properties. Membrane and soluble forms of Klotho provide a unique system that controls a wide range of metabolic processes essential in health and diseases. Based on its various known and unknown protective properties, upregulating the Klotho gene may be a possible therapeutic and/or preventive approach in aging-related disorders. Various drugs and factors have been revealed to enhance endogenous Klotho. They include hormonal agents, renin-angiotensin system inhibitors, antioxidants, PPAR- $\gamma$  agonists, HMG-CoA reductase inhibitors, vitamin D receptor agonists, antioxidants, anti-inflammatory agents, mTOR signaling inhibitors, and RIPK inhibitors (Table 1). Epigenetic modifications such as demethylation and deacetylation of the Klotho gene can also be deemed other possible Klotho-enhancement methods. In addition, some emerging techniques, such as RNA modification, gene therapy, gene editing, and exosome therapy, have the potential to be applied to upregulate the Klotho gene (Table 2).

The use of recombinant therapeutic proteins is another approach to therapeutically increase a protein in the body. Direct treatment with Klotho recombinant protein has been successfully demonstrated in some recent animal model studies [76–78]. Direct administration of exogenous proteins has some advantages compared to traditional small molecule drugs, such as lower toxicity, fewer side effects, more efficacy, greater specificity, and clearer biological functions [79]. However, there are still some challenges that should be addressed, such as the inherent susceptibility of exogenous proteins to aggregation, degradation, denaturation, and concomitant loss of activity. Their untimely clearance from the body, nonspecific distribution, and immunogenicity could be considered other relevant concerns [79,80]. The relatively larger sizes of recombinant protein drugs compared to small molecule agents make it difficult to deliver most exogenous proteins to target tissues, especially in hard-to-target locations in the body, such as the brain. The stability of the recombinant protein drugs under storage conditions that could affect their therapeutic efficacy can be an added concern [80].

Overall, although Klotho might be considered a therapeutic target, it is necessary that the usefulness of Klotho-enhancing strategies in the prevention and treatment of aging-related disorders be investigated by various preclinical studies. In addition, the implementation possibility of Klotho-increasing strategies in different tissues while considering their safety and possible side effects should be precisely evaluated by further animal model studies. These are considered potential avenues for future research.

CRediT authorship contribution statement

**Haniyeh Poursistany:** Writing – original draft, Investigation. **Solmaz Tabibi Azar:** Writing – original draft. **Mahsan Tabibi Azar:** Writing – original draft. **Sina Raeisi:** Conceptualization, Supervision, Writing – original draft, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgment

This work was supported by the Pediatric Health Research Center of Tabriz University of Medical Sciences, Tabriz, Iran. **We would like to thank the Clinical Research Development Unit of Zahra Mardani Azari Children Educational and Treatment Center, Tabriz University of Medical Sciences, Tabriz, Iran.**

## References

- [1] G.J. Prud'homme, M. Kurt, Q. Wang, Pathobiology of the klotho antiaging protein and therapeutic considerations, *Front. Aging.* 3 (2022), 931331.
- [2] M. Kuro-o, Y. Matsumura, H. Aizawa, H. Kawaguchi, T. Suga, T. Utsugi, Y. Ohshima, M. Kurabayashi, T. Kaname, E. Kume, Mutation of the mouse klotho gene leads to a syndrome resembling ageing, *Nature* 390 (1997) 45–51.
- [3] K. Lim, A. Halim, T.-s. Lu, A. Ashworth, I. Chong, Klotho: a major shareholder in vascular aging enterprises, *Int. J. Mol. Sci.* 20 (2019) 4637.
- [4] A. Olejnik, A. Franczak, A. Krzywonos-Zawadzka, M. Kahuźna-Oleksy, I. Bil-Lula, The biological role of klotho protein in the development of cardiovascular diseases, *BioMed Res. Int.* 2018 (2018), 5171945.
- [5] D. Edmonston, A. Grabner, M. Wolf, FGF23 and klotho at the intersection of kidney and cardiovascular disease, *Nat. Rev. Cardiol.* (2023), <https://doi.org/10.1038/s41569-023-00903-0> (Online ahead of print).
- [6] M. Kuro-o, The Klotho proteins in health and disease, *Nat. Rev. Nephrol.* 15 (2019) 27–44.
- [7] F.J. Amaro-Gahete, A. de-la-O, L. Jurado-Fasoli, J.R. Ruiz, M.J. Castillo, Á. Gutiérrez, Role of exercise on S-Klotho protein regulation: a systematic review, *Curr. Aging Sci.* 11 (2018) 100–107.
- [8] M. Torbus-Paluszczak, W. Bartman, M. Adamczyk-Sowa, Klotho protein in neurodegenerative disorders, *Neurol. Sci.* 39 (2018) 1677–1682.
- [9] M.M. Cararo-Lopes, C.H.Y. Mazucanti, C. Scavone, E.M. Kawamoto, D.C. Berwick, The relevance of  $\alpha$ -KLOTHO to the central nervous system: some key questions, *Ageing Res. Rev.* 36 (2017) 137–148.
- [10] N. Ranjbar, M. Raeisi, M. Barzegar, A. Ghorbanighajjo, S. Shiva, S. Sadeghvand, S. Negargar, H. Poursistany, S. Raeisi, The possible anti-seizure properties of Klotho, *Brain Res.* 1820 (2023), 148555.
- [11] M. Sárvári, I. Kalló, E. Hrabovszky, N. Solymosi, A. Rodolosse, C. Vastagh, H. Auer, Z. Liposits, Hippocampal gene expression is highly responsive to estradiol replacement in middle-aged female rats, *Endocrinology* 156 (2015) 2632–2645.
- [12] S.-C. Hsu, S.-M. Huang, S.-H. Lin, S.-M. Ka, A. Chen, M.-F. Shih, Y.-J. Hsu, Testosterone increases renal anti-aging klotho gene expression via the androgen receptor-mediated pathway, *Biochem. J.* 464 (2014) 221–229.
- [13] I. Mizuno, Y. Takahashi, Y. Okimura, H. Kaji, K. Chihara, Upregulation of the klotho gene expression by thyroid hormone and during adipose differentiation in 3T3-L1 adipocytes, *Life Sci.* 68 (2001) 2917–2923.
- [14] C.-D. Chen, S. Podvin, E. Gillespie, S.E. Leeman, C.R. Abraham, Insulin stimulates the cleavage and release of the extracellular domain of Klotho by ADAM10 and ADAM17, *Proc. Natl. Acad. Sci. USA* 104 (2007) 19796–19801.
- [15] M.A. Sparks, S.D. Crowley, S.B. Gurley, M. Mirotso, T.M. Coffman, Classical Renin-Angiotensin system in kidney physiology, *Compr. Physiol.* 4 (2014) 1201–1228.
- [16] M.H. de Borst, M.G. Vervloet, P.M. ter Wee, G. Navis, Cross talk between the renin-angiotensin-aldosterone system and vitamin D-FGF-23-klotho in chronic kidney disease, *J. Am. Soc. Nephrol.* 22 (2011) 1603–1609.
- [17] H.E. Yoon, J.Y. Ghee, S. Piao, J.-H. Song, D.H. Han, S. Kim, N. Ohashi, H. Kobori, M. Kuro-o, C.W. Yang, Angiotensin II blockade upregulates the expression of Klotho, the anti-ageing gene, in an experimental model of chronic cyclosporine nephropathy, *Nephrol. Dial. Transplant.* 26 (2011) 800–813.
- [18] H. Mitani, N. Ishizaka, T. Aizawa, M. Ohno, S.-i. Usui, T. Suzuki, T. Amaki, I. Mori, Y. Nakamura, M. Sato, In vivo klotho gene transfer ameliorates angiotensin II-induced renal damage, *Hypertension* 39 (2002) 838–843.
- [19] S.C. Lim, J.-J. Liu, T. Subramaniam, C.F. Sum, Elevated circulating alpha-klotho by angiotensin II receptor blocker losartan is associated with reduction of albuminuria in type 2 diabetic patients, *J. Renin-Angiotensin-Aldosterone Syst. JRAAS* 15 (2014) 487–490.
- [20] Q. Zhou, S. Lin, R. Tang, P. Veeraragoo, W. Peng, R. Wu, Role of fosinopril and valsartan on klotho gene expression induced by angiotensin II in rat renal tubular epithelial cells, *Kidney Blood Press. Res.* 33 (2010) 186–192.
- [21] H.J. Oh, B.Y. Nam, M.J. Lee, C.H. Kim, H.M. Koo, F.M. Doh, J.H. Han, E.J. Kim, J. S. Han, J.T. Park, Decreased circulating klotho levels in patients undergoing dialysis and relationship to oxidative stress and inflammation, *Perit. Dial. Int.* 35 (2015) 43–51.
- [22] E. Martín-Núñez, J. Donate-Correa, Á. López-Castillo, A. Delgado-Molinos, C. Ferri, S. Rodríguez-Ramos, P. Cerro, N. Pérez-Delgado, V. Castro, C. Hernández-Carballo, Soluble levels and endogenous vascular gene expression of KLOTHO are related to inflammation in human atherosclerotic disease, *Clin. Sci.* 131 (2017) 2601–2609.
- [23] J.A. Moreno, M.C. Izquierdo, M.D. Sanchez-Niño, B. Suárez-Alvarez, C. Lopez-Larrea, A. Jakubowski, J. Blanco, R. Ramirez, R. Selgas, M. Ruiz-Ortega, The inflammatory cytokines TWEAK and TNF $\alpha$  reduce renal klotho expression through NF $\kappa$ B, *J. Am. Soc. Nephrol.* 22 (2011) 1315–1325.
- [24] M.A. Teocchi, A.É.D. Ferreira, E.P.d.L. de Oliveira, H. Tedeschi, L. D'Souza-Li, Hippocampal gene expression dysregulation of Klotho, nuclear factor kappa B and tumor necrosis factor in temporal lobe epilepsy patients, *J. Neuroinflammation* 10 (2013) 1–7.
- [25] M. Mitobe, T. Yoshida, H. Sugiura, S. Shirota, K. Tsuchiya, H. Nihei, Oxidative stress decreases klotho expression in a mouse kidney cell line, *Nephron Exp. Nephrol.* 101 (2005) e67–e74.
- [26] A. Mehdizadeh, M. Barzegar, S. Negargar, A. Yahyavi, S. Raeisi, The current and emerging therapeutic approaches in drug-resistant epilepsy management, *Acta Neurol. Belg.* 119 (2019) 155–162.
- [27] O. Jaturakan, C. Buranakarl, T. Dissayabutra, N. Chaiyabutr, A. Kijawornrat, A. Rungpipat, Changes of Klotho protein and Klotho mRNA expression in a hydroxy-L-proline induced hyperoxaluric rat model, *J. Vet. Med. Sci.* 79 (2017) 1861–1869.
- [28] S.G. Piao, S.H. Kang, S.W. Lim, B.H. Chung, K.C. Doh, S.B. Heo, L. Jin, C. Li, C. W. Yang, Influence of N-acetylcysteine on Klotho expression and its signaling pathway in experimental model of chronic cyclosporine nephropathy in mice, *Transplantation* 96 (2013) 146–153.
- [29] J.W. Ko, N.R. Shin, T.Y. Jung, I.S. Shin, C. Moon, S.H. Kim, I.C. Lee, S.H. Kim, W. K. Yun, H.C. Kim, J.C. Kim, Melatonin attenuates cisplatin-induced acute kidney injury in rats via induction of anti-aging protein, Klotho, *Food Chem. Toxicol.* 129 (2019) 201–210.
- [30] R. Zhang, F. Zheng, PPAR- $\gamma$  and aging: one link through klotho? *Kidney Int.* 74 (2008) 702–704.
- [31] H.C. Yang, S. Deleuze, Y. Zuo, S.A. Potthoff, L.J. Ma, A.B. Fogo, The PPARgamma agonist pioglitazone ameliorates aging-related progressive renal injury, *J. Am. Soc. Nephrol.* 20 (2009) 2380–2388.
- [32] H. Zhang, Y. Li, Y. Fan, J. Wu, B. Zhao, Y. Guan, S. Chien, N. Wang, Klotho is a target gene of PPAR- $\gamma$ , *Kidney Int.* 74 (2008) 732–739.
- [33] H.-C. Yang, S. Deleuze, Y. Zuo, S.A. Potthoff, L.-J. Ma, A.B. Fogo, The PPAR $\gamma$  agonist pioglitazone ameliorates aging-related progressive renal injury, *J. Am. Soc. Nephrol.* 20 (2009) 2380–2388.
- [34] L.-J. Chen, M.-F. Cheng, P.-M. Ku, J.-W. Lin, Rosiglitazone increases cerebral klotho expression to reverse baroreflex in type 1-like diabetic rats, *BioMed Res. Int.* 2014 (2014), 309151.
- [35] C.R. Sirtori, The pharmacology of statins, *Pharmacol. Res.* 88 (2014) 3–11.
- [36] A. Mansouri, Z. Reiner, M. Ruscica, E. Tedeschi-Reiner, S. Radbakhsh, M. Bagheri Ekta, A. Sahebkar, Antioxidant effects of statins by modulating Nrf2 and Nrf2/HO-1 signaling in different diseases, *J. Clin. Med.* 11 (2022) 1313.
- [37] H.E. Yoon, S.W. Lim, S.G. Piao, J.H. Song, J. Kim, C.W. Yang, Statin upregulates the expression of klotho, an anti-aging gene, in experimental cyclosporine nephropathy, *Nephron Exp. Nephrol.* 120 (2012) e123–e133.
- [38] N. Kuwahara, S. Sasaki, M. Kobara, T. Nakata, T. Tatsumi, H. Irie, H. Narumiya, T. Hatta, K. Takeda, H. Matsubara, S. Hushiki, HMG-CoA reductase inhibition improves anti-aging klotho protein expression and arteriosclerosis in rats with chronic inhibition of nitric oxide synthesis, *Int. J. Cardiol.* 123 (2008) 84–90.
- [39] J. Vojinovic, Vitamin D receptor agonists' anti-inflammatory properties, *Ann. N. Y. Acad. Sci.* 1317 (2014) 47–56.
- [40] L. Adorini, G. Penna, B. Fibbi, M. Maggi, Vitamin D receptor agonists target static, dynamic, and inflammatory components of benign prostatic hyperplasia, *Ann. N. Y. Acad. Sci.* 1193 (2010) 146–152.
- [41] W.L. Lau, E.M. Leaf, M.C. Hu, M.M. Takeno, M. Kuro-o, O.W. Moe, C.M. Giachelli, Vitamin D receptor agonists increase klotho and osteopontin while decreasing aortic calcification in mice with chronic kidney disease fed a high phosphate diet, *Kidney Int.* 82 (2012) 1261–1270.
- [42] M.J. Azimzadeh, F. Shidfar, S. Jazayeri, A.F. Hosseini, F. Ranjbaran, Effect of vitamin D supplementation on klotho protein, antioxidant status and nitric oxide in the elderly: a randomized, double-blinded, placebo-controlled clinical trial, *Eur. J. Integr. Med.* 35 (2020), 101089.
- [43] Y. Zhao, M.M. Zhao, Y. Cai, M.F. Zheng, W.L. Sun, S.Y. Zhang, W. Kong, J. Gu, X. Wang, M.J. Xu, Mammalian target of rapamycin signaling inhibition ameliorates vascular calcification via Klotho upregulation, *Kidney Int.* 88 (2015) 711–721.
- [44] Y. Zhao, M.-M. Zhao, Y. Cai, M.-F. Zheng, W.-L. Sun, S.-Y. Zhang, W. Kong, J. Gu, X. Wang, M.-J. Xu, Mammalian target of rapamycin signaling inhibition ameliorates vascular calcification via Klotho upregulation, *Kidney Int.* 88 (2015) 711–721.
- [45] T. Hamano, Klotho upregulation by rapamycin protects against vascular disease in CKD, *Kidney Int.* 88 (2015) 660–662.
- [46] K. Mizusaki, Y. Haseike, T. Kimura, Y. Nagasawa, T. Kuragano, Y. Yamada, M. Nojima, S. Yamamoto, T. Nakanishi, M. Ishihara, Inhibition of the mammalian target of rapamycin may augment the increase in soluble klotho levels in renal transplantation recipients, *Blood Purif.* 47 (2019) 12–18.
- [47] J. Yu, B. Zhong, L. Zhao, Y. Hou, X. Wang, X. Chen, Receptor-interacting serine/threonine-protein kinase 1 (RIPK1) inhibitors Necrostatin-1 (Nec-1) and 7-Cl-O-Nec-1 (Nec-1s) are potent inhibitors of NAD (P) H: Quinone oxidoreductase 1 (NQO1), *Free Radic. Biol. Med.* 173 (2021) 64–69.
- [48] A. Degterev, D. Ofengeim, J. Yuan, Targeting RIPK1 for the treatment of human diseases, *Proc. Natl. Acad. Sci. USA* 116 (2019) 9714–9722.
- [49] M.F. Vissers, J.A. Heuberger, G.J. Groeneveld, J. Oude Nijhuis, P.P. De Deyn, S. Hadi, J. Harris, R.M. Tsai, A. Cruz-Herranz, F. Huang, Safety, pharmacokinetics

- and target engagement of novel RIPK1 inhibitor SAR443060 (DNL747) for neurodegenerative disorders: randomized, placebo-controlled, double-blind phase I/II studies in healthy subjects and patients, *Clin. Trans. Sci.* 15 (2022) 2010–2023.
- [50] L. Mifflin, D. Ofengeim, J. Yuan, Receptor-interacting protein kinase 1 (RIPK1) as a therapeutic target, *Nat. Rev. Drug Discov.* 19 (2020) 553–571.
- [51] Y. Ning, Y. Shi, J. Chen, N. Song, J. Cai, Y. Fang, X. Yu, J. Ji, X. Ding, Necrostatin-1 attenuates cisplatin-induced nephrotoxicity through suppression of apoptosis and oxidative stress and retains klotho expression, *Front. Pharmacol.* 9 (2018) 384.
- [52] N. Ji, J. Luan, F. Hu, Y. Zhao, B. Lv, W. Wang, M. Xia, X. Zhao, K. Lao, Aerobic exercise-stimulated Klotho upregulation extends life span by attenuating the excess production of reactive oxygen species in the brain and kidney, *Exp. Ther. Med.* 16 (2018) 3511–3517.
- [53] J.R. Chang, J. Guo, Y. Wang, Y.L. Hou, W.W. Lu, J.S. Zhang, Y.R. Yu, M.J. Xu, X. Y. Liu, X.J. Wang, Intermedin-53 attenuates vascular calcification in rats with chronic kidney disease by upregulation of  $\alpha$ -Klotho, *Kidney Int.* 89 (2016) 586–600.
- [54] X. Kuang, Y.-S. Chen, L.-F. Wang, Y.-J. Li, K. Liu, M.-X. Zhang, L.-J. Li, C. Chen, Q. He, Y. Wang, Klotho upregulation contributes to the neuroprotection of ligustilide in an Alzheimer's disease mouse model, *Neurobiol. Aging* 35 (2014) 169–178.
- [55] H. Liang, K. Yang, M. Xin, X. Liu, L. Zhao, B. Liu, J. Wang, MiR-130a protects against lipopolysaccharide-induced glomerular cell injury by upregulation of Klotho, *Die Pharmazie-Int. J. Pharmaceut. Sci.* 72 (2017) 468–474.
- [56] H.-J. Zhou, C.-Y. Zeng, T.-T. Yang, F.-Y. Long, X. Kuang, J.-R. Du, Lentivirus-mediated klotho up-regulation improves aging-related memory deficits and oxidative stress in senescence-accelerated mouse prone-8 mice, *Life Sci.* 200 (2018) 56–62.
- [57] C.-D. Chen, E. Zeldich, Y. Li, A. Yuste, C.R. Abraham, Activation of the anti-aging and cognition-enhancing gene klotho by CRISPR-dCas9 transcriptional effector complex, *J. Mol. Neurosci.* 64 (2018) 175–184.
- [58] N. Wang, J. Ma, Y. Ren, S. Xiang, R. Jia, Secreted klotho from exosomes alleviates inflammation and apoptosis in acute pancreatitis, *Am. J. Tourism Res.* 11 (2019) 3375.
- [59] H.S. Kim, J. Shi, Epigenetics in Precision Medicine of Pancreatic Cancer, *Epigenetics in Precision Medicine*, Elsevier, 2022, pp. 257–279.
- [60] A. Portela, M. Esteller, Epigenetic modifications and human disease, *Nat. Biotechnol.* 28 (2010) 1057–1068.
- [61] A. Kale, H. Sankrityayan, H.-J. Anders, A.B. Gaikwad, Epigenetic and non-epigenetic regulation of Klotho in kidney disease, *Life Sci.* 264 (2021), 118644.
- [62] S. Ramazi, A. Allahverdi, J. Zahiri, Evaluation of post-translational modifications in histone proteins: a review on histone modification defects in developmental and neurological disorders, *J. Biosci.* 45 (2020) 1–29.
- [63] W. Lin, Y. Li, F. Chen, S. Yin, Z. Liu, W. Cao, Klotho preservation via histone deacetylase inhibition attenuates chronic kidney disease-associated bone injury in mice, *Sci. Rep.* 7 (2017), 46195.
- [64] L.D. Moore, T. Le, G. Fan, DNA methylation and its basic function, *Neuropsychopharmacology* 38 (2013) 23–38.
- [65] Y. Zhu, X. Cao, X. Zhang, Q. Chen, L. Wen, P. Wang, DNA methylation-mediated Klotho silencing is an independent prognostic biomarker of head and neck squamous carcinoma, *Cancer Manag. Res.* 11 (2019) 1383–1390.
- [66] E. Peer, G. Rechavi, D. Dominissini, Epitranscriptomics: regulation of mRNA metabolism through modifications, *Curr. Opin. Chem. Biol.* 41 (2017) 93–98.
- [67] K.W. Seo, R.E. Kleiner, Mechanisms of epitranscriptomic gene regulation, *Biopolymers* 112 (2021), e23403.
- [68] L. Bataglia, Z.L.P. Simões, F.M.F. Nunes, Active genic machinery for epigenetic RNA modifications in bees, *Insect Mol. Biol.* 30 (2021) 566–579.
- [69] X. Xiong, C. Yi, J. Peng, Epitranscriptomics: toward a better understanding of RNA modifications, *Dev. Reprod. Biol.* 15 (2017) 147–153.
- [70] S. Jurga, J. Barciszewski, Epitranscriptomics, Springer, 2021.
- [71] J. Chen, Y. Ning, H. Zhang, N. Song, Y. Gu, Y. Shi, J. Cai, X. Ding, X. Zhang, METTL14-dependent m6A regulates vascular calcification induced by indoxyl sulfate, *Life Sci.* 239 (2019), 117034.
- [72] M. Li, L. Deng, G. Xu, METTL14 promotes glomerular endothelial cell injury and diabetic nephropathy via m6A modification of  $\alpha$ -klotho, *Mol. Med.* 27 (2021) 1–11.
- [73] M. Nasri, A. Karimi, M.A. Farsani, Production, purification and titration of a lentivirus-based vector for gene delivery purposes, *Cytotechnology* 66 (2014) 1031–1038.
- [74] G. Sharma, A.R. Sharma, M. Bhattacharya, S.-S. Lee, C. Chakraborty, CRISPR/Cas9: a preclinical and clinical perspective for the treatment of human diseases, *Mol. Ther.* 29 (2020) 571–586.
- [75] M. Hosseini, L. Roshangar, S. Raeisi, K. Ghahremanzadeh, S. Negargar, V. Tarmahi, V. Hosseini, M. Raeisi, E. Rahimi, Z. Ebadi, The therapeutic applications of exosomes in different types of diseases: a review, *Curr. Mol. Med.* 21 (2021) 87–95.
- [76] C.V.C. Junho, L. Gonzalez-Lafuente, R.S. Neres-Santos, J.A. Navarro-García, E. Rodriguez-Sanchez, G. Ruiz-Hurtado, M.S. Carneiro-Ramos, Klotho relieves inflammation and exerts a cardioprotective effect during renal ischemia/reperfusion-induced cardiorenal syndrome, *Biomed. Pharmacother.* 153 (2022), 113515.
- [77] S.A. Castner, S. Gupta, D. Wang, A.J. Moreno, C. Park, C. Chen, Y. Poon, A. Groen, K. Greenberg, N. David, Longevity factor klotho enhances cognition in aged nonhuman primates, *Nat. Aging.* 3 (2023) 931–937.
- [78] K. Wang, Z. Li, Y. Ding, Z. Liu, Y. Li, X. Liu, Y. Sun, J. Hong, W. Zheng, L. Qian, Klotho improves cardiac fibrosis, inflammatory cytokines, ferroptosis, and oxidative stress in mice with myocardial infarction, *J. Physiol. Biochem.* 79 (2023) 341–353.
- [79] H. Huang, Y. Lin, Y. Jiang, Q. Yao, R. Chen, Y.-Z. Zhao, L. Kou, Recombinant protein drugs-based intra articular drug delivery systems for osteoarthritis therapy, *Eur. J. Pharm. Biopharm.* 183 (2023) 33–46.
- [80] S.B. Ebrahimi, D. Samanta, Engineering protein-based therapeutics through structural and chemical design, *Nat. Commun.* 14 (2023) 2411.