

Polyphenols and Muscle Atrophy

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Skeletal muscle atrophy is the decrease in muscle mass and strength caused by reduced protein synthesis/accelerated protein degradation. Various conditions, such as denervation, disuse, ageing, chronic diseases, heart disease, obstructive lung disease, diabetes, renal failure, AIDS, sepsis, cancer, and steroidal medications, can cause muscle atrophy. Mechanistically, inflammation, oxidative stress, and mitochondrial dysfunction are among the major contributors to muscle atrophy, by modulating signalling pathways that regulate muscle homeostasis. To prevent muscle catabolism and enhance muscle anabolism, several natural and synthetic compounds have been investigated. Recently, polyphenols (i.e., natural phytochemicals) have received extensive attention regarding their effect on muscle atrophy because of their potent antioxidant and anti-inflammatory properties. Numerous in vitro and in vivo studies have reported polyphenols as strongly effective bioactive molecules that attenuate muscle atrophy and enhance muscle health.

antioxidants

polyphenols

flavonoid

muscle atrophy

proteolysis

mitochondrial dysfunction

mitochondrial biogenesis

myogenesis

oxidative stress

1. Introduction

The skeletal muscle is a plastic organ and the most abundant tissue in vertebrates. It plays a significant role in metabolism, movement, respiration, protection, daily physical activities, and the maintenance of posture and balance ^[1]. Generally, a healthy skeletal muscle always maintains a good equilibrium between protein synthesis and protein degradation. Any physiological (aging) or pathological conditions that interfere with the catabolic and anabolic symmetry of proteins will lead to a reduced cross-sectional area (CSA) of muscle fibers and decreased muscle strength and mass, resulting in muscle atrophy. The three main conditions that trigger muscle atrophy are (I) disuse, including immobilization, denervation, bed rest, space flight, and aging; (II) chronic disease, including chronic heart failure, obstructive lung disease, diabetes, renal failure, AIDS, sepsis, and cancer; and (III) medications, such as glucocorticoids ^{[2][3]}. Atrophy of the muscle reduces the quality of life and movement independence of the patients, thus imposing an additional financial burden on the health care system and causing increased morbidity and mortality. Hence, maintaining healthy muscles is necessary for preventing metabolic diseases and achieve healthy aging.

Muscle mass is maintained via the regulation of various anabolic pathways. Among them, the PI3K/Akt/mTOR pathway is the most important, in which insulin/IGF-1 acts as the upstream molecule to promote protein synthesis and block protein degradation ^[4]. The activation of Akt, a serine/threonine kinase, through phosphatidylinositol 3-

kinase (PI3K) activates the mammalian target of rapamycin (mTOR) to induce protein synthesis by activating its downstream effectors, the ribosomal protein S6 kinase beta-1 (S6K1), and the eukaryotic translation initiation factor 4E (eIF4E)-binding protein 1 (4E-BP1) [4]. Activated Akt also phosphorylates the Forkhead box O (FoxO) transcription factors, leading to their expulsion from the nucleus, thereby preventing the transcription of genes encoding vital E3 ubiquitin ligases, such as muscle atrophy F-Box (MAFbx/atrogen-1) and muscle RING finger-1 (MuRF-1), or autophagy-related genes, such as those encoding the microtubule-associated protein 1A/1B-light chain 3 (LC3) and Bcl2/adenovirus E1B 19-kDa-interacting protein 3 (Bnip3), which are responsible for protein breakdown mediated by the ubiquitin-proteasome system (UPS) and autophagic-lysosomal pathway, respectively [4][5][6]. Various proatrophic factors, such as inflammatory cytokines (tumor necrosis factor- α (TNF- α), interleukin-6 (IL-6), and IL-1 β), glucocorticoids, oxidative stress, and mitochondrial damage, were found to reduce Akt activation and induce muscle atrophy [7][8][9]. Among the protein catabolic pathways, the UPS is the chief proteolytic system, which degrades muscle proteins by upregulating the ubiquitin ligases atrogen-1, MuRF-1, and casitase-B-lineage lymphoma (Cbl-b). Generally, the UPS is activated by impaired PI3K/Akt signaling, inflammatory cytokines, oxidative stress, and mitochondrial dysfunction [9][10][11]. Furthermore, the nuclear factor- κ B (NF- κ B) transcription factor, which is an inducer of atrogen-1 and MuRF-1, is activated by inflammation and oxidative stress and initiates protein degradation via direct binding to the *MuRF-1* promoter [12]. Additionally, myostatin, a potent negative regulator of muscle growth and differentiation, induces muscle atrophy by inducing the expression of atrogen-1 and MuRF-1 [13].

Oxidative stress and inflammation are important factors strongly associated with muscle atrophy [14]. Oxidative stress can be defined as an imbalance between oxidants (ROS) and antioxidants in the body. Several conditions such as chronic diseases, cachexia, disuse, denervation, aging, etc. are associated with increased oxidative stress, that causes activation of proteolytic pathways as well as mitochondrial dysfunction [15]. The catabolic regulatory elements such as NF- κ B, FoxOs, AMPK, etc. are activated by oxidative stress that induce muscle protein catabolism by regulating UPS. It also induces the ubiquitin ligase Cbl-b, which disturbs IGF-1 signaling by ubiquitinating the insulin receptor substrate-1 (IRS-1), which leads to the activation of FoxOs and FoxOs-mediated ubiquitin ligases [16][17]. Inflammation triggers muscle atrophy during cachexia, chronic disease, aging, denervation, and obesity. Inflammatory cytokines (TNF- α , IL-6, IL-1 β) are released during the above conditions, that interfere with the pathways associated with protein synthesis and proteolysis [18]. They activate various pathways including NF- κ B and p38-MAPK as well as myostatin to induce proteolysis via UPS [19] (**Figure 1**).

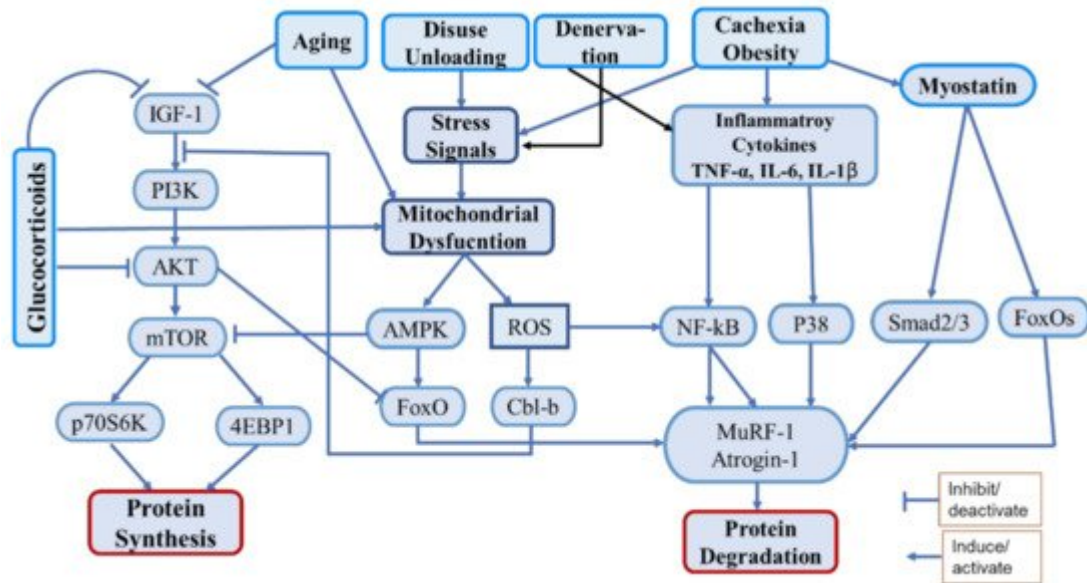


Figure 1. Schematic diagram of the main pathways associated with protein synthesis and degradation under various proatrophic conditions.

Muscle atrophy is closely associated with mitochondrial quality. Mitochondrial quality and biogenesis are indispensable factors for proper muscle function, as impaired mitochondrial activities lead to muscle atrophy via the activation of various catabolic pathways [9][20]. Healthy mitochondria always maintain muscle homeostasis by producing adequate adenosine triphosphate (ATP) via the tricarboxylic acid cycle and oxidative phosphorylation (OXPHOS) [21]. They also regulate the antioxidant defense system and apoptosis (a type of programmed cell death). Moreover, the biogenesis of mitochondria is regulated by the peroxisome proliferator-activated receptor- γ coactivator 1- α (PGC-1 α), which activates nuclear respiration factors (Nrf1 and Nrf2) and the estrogen-related receptor- α , which further activates the mitochondrial transcription factor A (TFAM) to promote mitochondrial DNA (mtDNA) replication [21].

Furthermore, myogenesis plays a vital role in the preservation of muscle health and the attenuation of atrophy. Myogenesis is a process via which satellite cells are differentiated to myofibers to maintain muscle tissue regeneration. This process is regulated by various myogenic regulatory factors, namely, the myoblast determination protein (MyoD), myogenic factor 5 (Myf5), myogenin, and myogenic regulatory factor 4, which lead to the determination and differentiation of skeletal muscle cells [22]. Hence, both healthy mitochondria and myogenesis are required for healthy muscle activities.

Polyphenols (PPs) are naturally occurring organic compounds that are abundantly found in different plants, fruits, vegetables, nuts, seeds, flowers, tea, and beverages [23]. PPs are worthier because of their diversity, bioactivity, easy accessibility, and specificity of the response, with lower toxicity effects. However, rapid metabolism and low bioavailability are their major drawbacks [24]. PPs are classified mainly into four groups, i.e., (a) phenolic acids, (b) flavonoids, (c) stilbenes, and (d) lignans, depending on the number of phenol rings included in their structure and the structural components that bind these rings together [25]. Researchers have reported the wide-ranging health benefits of PPs, including the neuroprotective, cardioprotective, renoprotective, hepatoprotective, antidiabetic,

anticancer, antioxidant, anti-inflammatory, and antimicrobial activities of PPs, which can be attributed to their diverse biological properties [24]. Thus, recently, PPs have drawn extensive attention among nutrition scientists regarding the exploration of their improved consumption as functional foods that counteract different diseases. Many of them have been trialed for their possible use as clinical treatments [26]. PPs have also been reported to exert strong antiatrophic effects by modulating the proatrophic factors or signaling pathways that contribute to muscle atrophy [27]. Because of their lower toxicity and higher target-specific response, PPs are being vigorously investigated as muscle atrophy countermeasures.

2. Polyphenols in Managing Muscle Atrophy and Muscle Health

2.1. Phenolic Acids

Phenolic acids are important bioactive compounds of the polyphenolic group. They consist of an aromatic ring with several hydroxyl groups attached to it. They are primarily subclassified into two classes: hydroxybenzoic acids and hydroxycinnamic acids. Generally, hydroxybenzoic acid and hydroxycinnamic acid contain seven (C6-C1) and nine (C6-C3) carbon atoms, respectively, in their structure, with few exceptions. For example, compounds such as Ellagic acid of the hydroxybenzoic acid group contain 14 carbon atoms in their structure. Similarly, Chlorogenic acid of the hydroxycinnamic acid group has 16 carbon atoms in its structure. Most commonly they are distributed in cereals: fruits, such as pomegranates, apples, grapes, raspberries, strawberries, cranberries, blackcurrants, and walnuts, and vegetables [28]. Pharmacologically, they exhibit antioxidant, anti-inflammatory, neuroprotective, cardioprotective, hepatoprotective, antidiabetic, anticancer, and antimicrobial effects [28]. Some representative phenolic acids have been reported to exert beneficial effects on muscles by promoting their growth and/or reducing their wasting while improving mitochondrial quality and preventing inflammation and oxidative stress, as summarized in **Table 1**.

Table 1. Function of phenolic acids and their derivatives in promotion of muscle health and prevention of muscle atrophy. DMD, Duchenne muscle dystrophy; EC, epicatechin; EGC, epigallocatechin; GA, gallic acid; HF: high-fat diet.

Class	Sub-Class	Compound/Derivatives/Compounds Mixture	Model	Effects	References
Phenolic Acid	Hydroxybenzoic Acid	Gallic Acid (GA)	C2C12 Myotubes	Increased Mitochondrial Function and mitochondrial biogenesis, Enhanced myosin heavy chain expression	[29]
		EC, EGC and GA	Normal and oxidative	Increased myotube density	[30]

Class	Sub-Class	Compound/Derivatives/Compounds Mixture	Model	Effects	References
			stress-induced C2C12 cells	upregulated genetic expression of myogenic factors	
			Ellagic acid	Reduced muscle tissue damage induced caspase-3, Nrf-2 and antioxidant enzymes suppressed inflammatory markers	[31]
			Ellagic Acid	Protects muscle tissue prevented mitochondrial dysfunction and oxidative stress	[32]
			Urolithin A	Induced autophagy and mitophagy both invitro and in vivo increased muscle function improved exercise capacity	[33]
			Urolithin A	Induced mitophagy and improved muscle function and MuSCs regeneration increased skeletal muscle respiratory capacity	[34]
			Urolithin A	Strengthen skeletal muscle and angiogenesis Increase ATP and NAD+ level Upregulates angiogenic pathways	[35]
			Urolithin B	Enhanced growth and differentiation of C2C12 myotubes and muscle hypertrophy Increased protein synthesis and suppressed UPS	[36]

Class	Sub-Class	Compound/Derivatives/Compounds Mixture	Model	Effects	References
	Hydroxycinnamic Acid	Pomegranate extract	TNF-α induced muscle atrophy in mice	Prevented muscle wasting suppressed cytokines and NF-kB level activated protein synthesis pathway	[37]
		Ferulic acid	Mouse C2C12 myotubes	Regulates muscle fiber type formation activated SIRT1/AMPK pathway Increased PGC-1α expression	[38]
		Ferulic Acid	Corticosteroid-Induced Rat Myopathy	Induced growth of fast glycolytic and slow oxidative muscle fiber suppressed myostatin and oxidative stress	[39]
		Ferulic Acid	Zebrafish model	Enhanced muscle mass and MyHC fast type Increased myogenic transcriptional factors activated zTOR/p70S6K/4EBP1	[40]
		Chlorogenic acid	Resistance training-induced rat model	improved muscle strength by promoting mitochondrial function and cellular energy metabolism	[41]
		Caffeic acid phenethyl ester	Eccentric exercise-induced skeletal muscle injury in rats	Protected skeletal muscle damage down-regulated NF-kB activation	[42]
		Caffeic acid	Human fibroblast cell line	Decreased spinal muscular atrophy increased SIRT1 transcripts	[30] [43]
		Coffee	In-vitro and in-vivo model	Skeletal muscle hypertrophy and	[44]

acid. Few reported activates regulated topophagy, tion with regulatory d, exerts treatment ess and (COX-2) and upregulated antioxidant enzymes (catalase and glutathione [GSH]), together with its transcriptional factor nuclear factor erythroid 2-related factor 2 (Nrf2). Furthermore, suppressing B-cell lymphoma 2 (bcl-2) and inducing caspase-3 led the damaged tissues to apoptosis [31]. It has also been shown to improve muscle dysfunction in cuprizone-induced demyelinated mice by imparting mitochondrial protection, oxidative stress prevention, and Sirt3 overexpression [32].

Urolithins are metabolites obtained from the transformation of ellagic acid. Urolithin A and urolithin B have positive effects on muscle cells. Urolithin A, a mitophagy activator, stimulated muscle function and exercise capacity by inducing autophagy and mitophagy in rodents [33]. In a mouse model of Duchenne muscular dystrophy (DMD), it

Class	Sub-Class	Compound/Derivatives/Compounds Mixture	Model	Effects	References
	[34]			myoblast differentiation	
		P-Coumaric acid	C2C12 myotubes	Reduce differentiation of muscle cells by reducing MyoD and Myogenin.	[35] [45]

mice. It decreased muscle atrophy by decreasing protein synthesis and increasing protein degradation. The anabolic activity of urolithin B was attributed to the activation of the androgen receptor, which activates the mTOR pathway. Additionally, it suppressed the upregulation of ubiquitin ligases, MAFbx/atrogenin-1, MuRF-1, and myostatin [\[36\]](#). Pomegranate, which is a rich source of ellagic acid, protected tibialis anterior muscle loss in TNF-α induced muscle atrophy. This protective effect was mediated by the suppression of the inflammatory cytokines, TNF-α, IL-1β, monocyte chemoattractant protein 1 (MCP-1), and NF-κB signalling-mediated ubiquitin ligases; however, it preserved the Akt/mTOR protein synthesis pathway [\[37\]](#).

Among the various hydroxycinnamic acids, ferulic acid (FA), chlorogenic acid, and caffeic acid have been reported to have positive effects on muscle. In mouse C2C12 myotubes, ferulic acid increased the MyHC protein (MyHC-I and MyHC-IIa) and decreased fast-type MyHC-IIb expression. The mRNA expression of sirtuin1 (Sirt1), PGC-1α, and myocyte enhancer factor 2C (MEF2C) was induced by FA. These effects were mediated by the phosphorylation of AMPK, followed by Sirt1 activation, as inhibition of AMPK or Sirt-1 abolished the effects of FA [\[38\]](#). In another study, the administration of FA promoted the growth of both fast glycolytic and slow oxidative muscle in dexamethasone (Dex)-induced myopathic rats by downregulating myostatin and oxidative stress. FA induced the expression of mechano growth factor and enhanced the antioxidant enzymes superoxide dismutase (SOD), GSH, and catalase in the tibialis anterior (TA) and soleus muscles [\[39\]](#). In a zebrafish model, FA administration for 30 days caused the hypertrophic growth of fast-type skeletal muscle via the phosphorylation of zebrafish target of rapamycin, p70S6K, and 4E-BP1. Moreover, the myogenic transcription factors myogenin, MyoD, and serum response factor were increased via FA treatment [\[40\]](#). Chlorogenic acid has been reported to increase muscle strength by enhancing mitochondrial function and cellular energy metabolism in resistance training-induced rats [\[41\]](#). Caffeic acid, which is found in fruits, wine, and coffee, exhibits some interesting effects against muscle injury. The administration of caffeic acid phenethyl ester (CAPE) protected muscles against eccentric exercise-induced injury in rats. This effect was mediated by the blockage of NF-κB activation and NF-κB-mediated prooxidant and proinflammatory responses. Inflammation-related genes, i.e., *IL-β*, *MCP-1*, *iNOS*, and *COX-2*, and the oxidative stress marker MDA were significantly suppressed via CAPE treatment [\[42\]](#). Caffeic acid in combination with curcumin improved autosomal recessive spinal muscular atrophy (SMA) by promoting *SMN2* gene expression, which controls the severity of SMA. Etiologically, SMA is caused by a loss of α-motor neurons in the anterior horn of the spinal cord, leading to neurogenic muscle atrophy [\[43\]](#). Moreover, the consumption of coffee, a good source of caffeic acid, has been reported to increase skeletal muscle function and hypertrophy by increasing MyHC, MyHC-IIa, and MyHC-IIb in the quadriceps muscle. It suppressed transforming growth factor-beta (TGF-β) and myostatin expression and upregulated the levels of the insulin-like growth factor-1 (IGF-1), and subsequently phosphorylated Akt and mTOR. It also enhanced PGC-1α expression, which is vital for myogenic differentiation. Hence, coffee exerted a protective effect by regulating the TGF-β/myostatin–Akt–mTORC1 pathway [\[44\]](#). However,

P-coumaric acid, of the phenolic acid group, reduced the differentiation of skeletal muscle cells by downregulating myogenin and MyoD [45].

2.2. Flavonoids

Flavonoids are bioactive polyphenolic compounds that are found in almost all fruits and vegetables. They are the most studied natural compounds for their valuable pharmacological effects in different diseases. Approximately 6000 flavonoid compounds are estimated to be distributed in different fruits, vegetables, herbs, and plants [47]. Flavonoids offer diverse health benefits against chronic diseases, including cardiovascular disease, kidney disease, cancer, diabetes, obesity, and hepatic disease, which lead to increased mortality and morbidity [48][49][50]. Because of their potent antioxidant and anti-inflammatory activities, they can modify various enzymes and signaling molecules that are responsible for disease prognosis [51]. Numerous in vitro and in vivo studies have reported flavonoids as potential therapeutic countermeasures for treating muscle atrophy or muscle injury via different mechanisms. The effects of each subclass of flavonoid, i.e., flavanols, flavanones, flavones, isoflavones, flavonols, and anthocyanin, have been summarized in **Table 2** and are discussed below.

Table 2. Function of flavonoids and its derivatives in promotion of muscle health and prevention of muscle atrophy. 8-PN, 8-prenylnaringenin; Dex, dexamethasone; EGCG, epigallocatechin gallate.

Class	Sub-Class	Compound/Derivatives	Model	Effects	References
Flavonoids	Flavanols	EC	Young and old C57BL/6 mice and human tissue samples	Decreased myostatin and β -galactosidase Increased follistatin and markers of muscle growth and differentiation	[52]
		EC	Young and old C57BL/6 mice	Increased survival of aged mice prevented muscle wasting	[53]
		EC	HLS-induced muscle atrophy in mice	Counteracts muscle degradation maintains muscle angiogenesis and mitochondrial biogenesis	[54]
		EC	Denervation-induced muscle atrophy in rats	Reduced muscle wasting down regulated Foxo1a, Atrogin-1 and MuRF-1	[55]
		EC	Ambulatory adults with	Induced mitochondrial biogenesis and	[56]

Class	Sub-Class	Compound/Derivatives	Model	Effects	References
			Becker Muscular Dystrophy	muscle regeneration factors increased follistatin decreased myostatin	
			EC	C2C12 myotubes	Stimulates mitochondrial biogenesis and cell growth through GPER
			EC	C2C12 cells	Enhanced myogenic differentiation and MyoD activity
			EC	HF-induced muscle damage in aged mice	Improved physical performance increased follistatin and MEF2A decreased Foxo1a and MuRF-1
			EC, ECG, EGCG	3D-clinorotation induced C2C12 atrophy	Suppressed Atrogin-1 and MuRF-1 dephosphorylated the ERK signaling
			EGCG	Aging-induced sarcopenic rat model	Attenuated muscle atrophy and protein degradation Increased protein synthesis
			EGCG	Aged mice and late passaged C2C12 cells	Attenuated muscle atrophy and protein degradation upregulated miR-486-5p
			EGCG	Starvation and TNF- α -induced C2C12 atrophy	Attenuation of muscle wasting inhibited protein degradation and activated protein synthesis
			EGCG	Tumor induced LLC and C57Bl/6 mice atrophy	Attenuates muscle atrophy inhibits NF- κ B, atrogin-1 and MuRF-1

Class	Sub-Class	Compound/Derivatives	Model	Effects	References
		EGCG	Mouse model of Duchenne muscular dystrophy	Protected from muscle necrosis improved muscle functions	[65]
		EGCG	HLS-induced muscle atrophy in aged rats	Improved Plantaris muscle weight and fiber size reduced pro-apoptotic signaling	[66]
		EGCG	HLS-induced muscle atrophy in aged rats	Maintained autophagy signaling in disuse muscle prevented autophagy and apoptosis during reloading	[67]
		EGCG	Dex-induced C2C12 myotubes and tail-suspended mice	Prevented muscle atrophy suppressed MuRF1	[68]
		Green tea extracts (EGCG)	HF diet-induced muscle atrophy in SAMP8 mice	Ameliorated HF-induced muscle wasting Decreased insulin resistance and LECT2 expression	[69]
		EGCG	Live skeletal muscle fibers model	Promoted nuclear efflux of Foxo1 activated PI3K/Akt pathway	[70]
		Catechin (ECG+EGCG)	C2C12 cells and Cardiotoxin induced C56BL/6 mice	Stimulated muscle stem cell activation and differentiation for muscle regeneration.	[71]
		Catechin	Downhill running-induced muscle	Attenuated downhill running-induced muscle damage suppressed oxidative	[72]

Class	Sub-Class	Compound/Derivatives	Model	Effects	References
Polyphenols	Flavanones	catechins	damage in ICR mice	stress and inflammation	[73]
			Tail-suspension induced muscle atrophy in mice	Minimized contractile dysfunction and muscle atrophy decreased oxidative stress	
		Hesperidin	Human skeletal muscle cell and mice	Reverted aging-induced decrease in muscle fiber size increased mitochondrial function and running performance reduced oxidative stress	[74]
		Naringenin	L6 and C2C12 cells	Delays skeletal muscle differentiation	[75]
		8-Prenylnaringenin (8-PN)	Denervated Mice	Prevented muscle atrophy suppressed Atrogin-1 Phosphorylated Akt	[76]
	Flavones	8-PN	C2C12 myotubes and casting-induced muscle atrophy in mice	Reversed casting-induced loss of tibialis anterior muscle activated PI3K/Akt/mTOR pathway	[77]
		Apigenin	Aged Mice	Relieved muscle atrophy and increased myofiber size inhibited hyperactive mitophagy/ autophagy and apoptosis.	[78]
		Apigenin	Obesity-induced muscle atrophy in Mice	Attenuated muscle atrophy and mitochondrial dysfunctions.	[79]
		Apigenin	Denervated-induced	Protected muscle loss Upregulated MyHC	[80]

Class	Sub-Class	Compound/Derivatives	Model	Effects	References
			muscle atrophy in mice	reduced TNF-α and MuRF-1 level	[81]
			Apigenin	C57BL/6 mice and C2C12 cells	Promotes skeletal muscle hypertrophy enhanced myogenic differentiation upregulated Prmt7-PGC-1α-GPR56 pathway
			Flavones	LPS-induced muscle atrophy in C2C12 myotube	Prevented myotube atrophy suppressed Atrgoin-1 inhibited JNK phosphorylation
			Luteolin	LLC-induced muscle atrophy in mice	Prevented muscle atrophy downregulated MuRF-1, Atrgoin-1, cytokines/inflammatory markers
			Luteolin	Dex-Induced muscle atrophy in mice	Prevented muscle atrophy Induced antioxidant and antiapoptotic activity
	Isoflavones	Isoflavone (genistein and daidzein)	TNF-α induced C2C12 myotubes	Suppressed MuRF1 promoter activity and myotube atrophy	[85]
		Isoflavone	Tumor-induced muscle atrophy in mice	Prevented muscle wasting suppressed ubiquitin ligases expression	
		Isoflavone	Denervation-induced muscle atrophy in mice	Prevented muscle fiber atrophy decreased apoptosis-dependent signaling.	
		Genistein	Denervation-induced muscle	Mitigated soleus muscle atrophy	

Class	Sub-Class	Compound/Derivatives	Model	Effects	References
			atrophy in mice		
		Genistein	C2C12 myoblast	Enhanced proliferation and differentiation downregulated miR-222	[89]
		Daidzein	Young female mice	Down-regulated ubiquitin-specific protease 19 increased soleus muscle mass	[90]
		Daidzein	Cisplatin-induced LLC bearing mice	Alleviated skeletal muscle atrophy prevented protein degradation	[91]
		Daidzein	C2C12 cells	Promotes myogenic differentiation and myotube hypertrophy	[92]
		Soy protein	Rats	Improved muscle function	[93]
		Formononetin (isoflavone)	CKD rats and TNF- α -induced C2C12 myotubes atrophy	Prevented muscle wasting suppressed MuRF-1, MAFbx and myostatin expression Phosphorylated PI3K, Akt and FoxO3a	[94]
	Flavonols	Glabridin	Dex-induced atrophy (in vitro and in vivo)	Inhibited protein degradation and muscle atrophy in vitro and in vivo	[95]
		Quercetin	HF-diet induced muscle atrophy in mice	Protected muscle mass and muscle fiber size reduced ubiquitin ligases and inflammatory cytokines	[96]
		Quercetin	TNF- α induced myotube and Obesity induced	Averted muscle atrophy Upregulated HO-1 and Nrf2 Inactivates NF-kB	[97]

Class	Sub-Class	Compound/Derivatives	Model	Effects	References
		Quercetin	mice muscle atrophy		
			Murine C26 cancer-cachexia model	Prevented body and muscle weight loss tended to decrease Atrgoin-1 and MuRF-1	[98]
			A549 cells injected tumor model in mice	Prevented loss of GM and protein degradation Increased MyHC level	[99]
			Dex-Induced C2C12 cell injury	Increased C2C12 cell viability exerted antiapoptotic effects reduce oxidative stress regulates mitochondrial membrane potential	[100]
			Dex-induced-muscle atrophy in mice	Prevented muscle loss reduced myostatin, atrgoin-1 and MuRF-1 increased Akt phosphorylation	[101]
			Tail-suspension induced muscle atrophy in mice	Prevented GM loss suppressed ubiquitin ligases and lipid peroxidation	[102]
			Denervation-induced muscle atrophy in mice	Prevented muscle atrophy suppressed mitochondrial hydrogen peroxide generation elevated mitochondrial biogenesis	[103]
		Quercetin Glycosides	Male C57BL/6J aged mice	Improved motor performance Increased muscle mass	[104]

Among the three main compounds of the flavanol group, EC and epigallocatechin gallate (EGCG) have been extensively studied regarding their effects in muscle atrophy. In aged mice and human muscle samples, EC administration reversed the aging-induced expression of myostatin and β -galactosidase while increasing the level

Class	Sub-Class	Compound/Derivatives	Model	Effects	References
Anthocyanins	[53]	Quercetin	Mice	Mitochondrial biogenesis Increased endurance and running capacity	[105]
		Morin	LLC cell-bearing mice and C2C12 myotubes atrophy	Suppressed muscle wasting and myofiber size reduction by binding to ribosomal protein S10	[106] [54]
		Morin [56]	Dex-induced atrophy of C2C12 skeletal myotubes	Prevented protein degradation reduced oxidative stress, Atrogin-1, MuRF-1 and Cbl-b Phosphorylated Foxo3a	[107]
		Delphinidin [57]	Dex-induced C2C12 atrophy and tail-suspension induced atrophy in mice	Suppressed MuRF-1 expression Prevented muscle weight loss upregulated miR-23a and NFATc3	[108]
		Delphinidin	Dex-induced C2C12 atrophy and tail-suspension induced atrophy in mice	Suppressed disused-muscle loss suppressed Cbl-b and stress related gene	[109]
	[62]	Delphinidin [61]	LPS-induced atrophy in C2C12 myotubes	Reduced atrogin-1 expression insignificantly	[82]
		Cyanidin	Dystrophic alpha-sarcoglyan (Sgca) null mice [63]	Reduced progression of muscular dystrophy Reduced inflammation and fibrosis	[110]

our previous study, in which EGCG decreased 3D-climorotation-induced atrogin-1 and MuRF-1 expression by dephosphorylating ERK [60]. In Lewis lung carcinoma (LLC) tumor-bearing mice, EGCG attenuated muscle atrophy by suppressing NF-κB and its downstream mediators MuRF-1 and MAFbx [64]. Similarly, in the dystrophic mdx5Cv mouse model, EGCG protected the fast-twitch extensor digitorum longus (EDL) muscle from necrosis and stimulated muscle function, thus showing a positive effect on dystrophic abnormalities [65]. In disuse-induced aged rats, EGCG improved plantaris muscle weight and size during reloading followed by unloading by suppressing

proapoptotic signaling in reloaded muscle [66]. In a similar model, EGCG induced autophagy during unloading, whereas it suppressed autophagy in the reloaded condition, to improve muscle health [67]. Moreover, EGCG administration suppressed MuRF1 expression in Dex-induced C2C12 cells through the activation of the 67-kDa laminin receptor (67LR) [68]. The same study reported the protection afforded by EGCG against GM loss in disused mice, which was further potentiated by the use of eriodictiol [68]. EGCG prevented HF-induced muscle atrophy in SAMP8 mice by improving insulin resistance, together with a change in serum leukocyte cell-derived chemotaxin 2 (LECT2) [69]. Interestingly, in human skeletal muscle fibers, ECGC treatment had a similar effect, as did the insulin growth factor 1 (IGF-1) and insulin, thus suppressing the action of the atrophy-promoting transcription factor Foxo1 via the net translocation of Foxo1 out of the nucleus [70].

Catechin flavanol-activated satellite cells, which induce the Myf5 transcription factor via Akt phosphorylation. It also promoted myogenic differentiation by inducing the myogenic markers myogenin and muscle creatine kinase for muscle regeneration in C2C12 cells. The same study, which was performed using mice, reported increased fiber size and muscle regeneration after EGCG treatment [71]. Furthermore, it attenuated downhill running-induced muscle damage by suppressing muscle oxidative stress and inflammation and hastened the recovery of physical performance in mice [72]. Catechin also diminished unloading-induced contractile dysfunction and muscle atrophy in unloaded mice by suppressing oxidative stress [73].

2.4. Flavanones

Flavanones, also called dihydroflavones, are another class of flavonoid compounds that are most commonly found in citrus fruits, such as oranges, lemons, and grapes. Hesperidin, naringenin, and eriodictiol are the main compounds in this group. They exhibit antioxidant, anti-inflammatory, antitumor, and cholesterol-lowering effects [111]. In aged mice, hesperetin reverted the aging-induced decrease in muscle fiber size and improved running performance. The same in vitro study using human skeletal muscle cells showed that hesperidin increased mitochondrial function by promoting ATP production and mitochondrial spare capacity. Moreover, it reduced oxidative stress in vitro and in vivo [74], proving that this compound is a potential agent for the retardation of sarcopenia and mitochondrial dysfunctionalities. Conversely, naringenin delayed the differentiation of skeletal muscle cells by hampering ER α -mediated Akt phosphorylation [75]. Intriguingly, we found that the chemical modification of naringenin to 8-prenylnaringenin (8-PN) by substituting the 8-prenyl group in the hydrogen atom of the eighth position of the molecule significantly alleviated denervation-induced loss of GM, whereas intact naringenin was found to be ineffective. Moreover, 8-PN, which acts as a powerful phytoestrogen, attenuated the induction of atrogin-1 by denervation and accelerated Akt phosphorylation. The accumulation of 8-PN in the GM was 10-fold higher than that observed for naringenin, which suggested that the prenylation of naringenin is required for its accumulation in the GM and for improving muscle atrophy [76]. Similarly, we reported that 8-PN treatment in mouse C2C12 skeletal myotubes increased the phosphorylation of PI3K, Akt, and p70S6K1, which was associated with its estrogenic activity. It also enhanced the weight of the tibialis anterior muscle in casting-induced muscle-atrophied mice [77].

2.5. Flavones

Flavones represent one of the important groups of flavonoids and are commonly found in fruits, vegetables, and plant-derived beverages, such as those from grapefruits, oranges, parsley, onions, tea, chamomile, and wheat sprouts [112]. Apigenin (AP), luteolin, tangeritin, and chrysin are the main compounds of this group. Among them, AP and luteolin have been highlighted for their antiatrophic effect in vitro and in vivo. AP administration prevented aging-induced loss of TA, EDL, and soleus muscle mass, and increased the muscle fiber size in aged mice. The attenuation of muscle atrophy was associated with a reduction of oxidative stress and the inhibition of hyperactive mitophagy/autophagy and apoptosis. AP increased SOD and GSH expression and enhanced mitochondrial function by increasing ATP levels and mitochondrial biogenesis by inducing the expression of PGC-1 α , TFAM, Nrf-1, and ATP5B [78]. Furthermore, AP treatment ameliorated obesity-induced skeletal muscle atrophy and increased muscle mass, the CSA of muscle fibers, and exercise capacity. Moreover, it suppressed the expression of the atrophic genes *MuRF1* and *atrogen-1*. The expression of the inflammatory cytokines TNF- α , IL-6, and IL-1 β was attenuated by AP in the serum and GM muscle tissue. The mitochondrial function was enhanced by AP through the upregulation of citrate synthase, complex-I, and complex-II activities, leading to increased OXPHOS. AP also caused increased mitochondrial biogenesis by upregulating PGC-1 α , TFAM, cytochrome c, somatic (CyCs), and mtDNA content. The same study found that AP suppressed palmitic acid-induced muscle atrophy and mitochondrial dysfunction in C2C12 myotubes, and further reported that the beneficial effect of AP was regulated by AMPK activation [79]. In denervation-induced mice, AP attenuated the loss of GM and soleus muscle weight and increased muscle fiber CSA. Additionally, it upregulated the total MyHC protein and the mRNA expression of MyHC-IIb in the GM, as well as MyHC-IIa in the soleus muscle, with suppression of MuRF1 expression. Furthermore, TNF- α was downregulated both in the GM and soleus muscles, whereas IL-6 was decreased only in the soleus muscle [80]. Similarly, AP increased the mRNA expression of MyHC-I, MyHC-IIa, and MyHC-IIb in the quadriceps muscles of mice. The G-protein-coupled receptor 56 (GPR56) and its ligand, collagen III, were upregulated, as were PGC-1 α , PGC-1 α 1, PGC-1 α 4, IGF1, and IGF2. The protein arginine methyltransferase 7 (Prmt7) was also enhanced by AP. The same in vitro study found that AP stimulated C2C12 myogenic differentiation by regulating MyoD protein expression. Thus, the beneficial effect of AP was regulated via the Prmt7–PGC-1 α –GPR56 pathway, as well as by the Prmt7–p38–myoD pathway [81].

Previously, we reported that treatment with AP and luteolin prevents the lipopolysaccharides (LPS)-mediated reduction of myotube diameter by suppressing atrogen-1/MAFbx expression through the inhibition of the JNK signaling pathway in C2C12 myotubes [82]. Moreover, in cachexia-induced muscle atrophy, luteolin treatment protected against the loss of GM, which was associated with the attenuation of the expression of inflammatory cytokines (TNF- α and IL-6) and the ubiquitin ligases MuRF-1 and Atrogen-1. Here MuRF-1 expression was reduced via the deactivation of NF- κ B both at the transcription and translation level, whereas atrogen-1 was suppressed by the downregulation of p-38 [83]. Luteolin also improved GM mass and strength in Dex-induced myopathy by exerting its antioxidant and antiapoptotic activities. Moreover, it reduced oxidative stress with attenuation of MDA and enhancement of the GSH antioxidant. Finally, it suppressed apoptosis by regulating caspase-3 expression [84].

2.6. Isoflavones

Isoflavones are flavonoid compounds that are most commonly present in soybeans, soy foods, and legumes. They act as phytoestrogen and exhibit pseudohormonal activity in conjugation with the ER. They possess antioxidant, anticancer, antimicrobial, and anti-inflammatory activities [113]. Genistein and daidzein are the representative elements of this group. Isoflavones have been reported to exert favorable effects on inflammation and glucocorticoid-induced muscle myopathies. We reported the effects of isoflavone treatment (daidzein and genistein) in muscles in vitro and in vivo. Isoflavone suppressed TNF- α -induced C2C12 myotube atrophy by attenuating MuRF-1 activity. This effect was regulated by AMPK-mediated SIRT-1 activation, in which SIRT-1 caused deacetylation of p65, which is involved in the activation of MuRF-1 [85]. Similar effects were noted in an in vivo model, where isoflavone supplementation in tumor-bearing mice attenuated the decrease in GM mass and myofiber size. Isoflavone decreased the expression of the ubiquitin ligases atrogin-1 and MuRF-1 by reducing the phosphorylation of ERK [86]. In denervation-induced muscle atrophy in mice, supplementation with the isoflavone aglycone (AglyMax) at a 0.6% dose significantly attenuated fiber atrophy by suppressing apoptosis-dependent signaling, as manifested by decreased apoptotic nuclei, but not caspase-3 [87]. In the same model of atrophy, genistein protected against soleus muscle atrophy by suppressing the transcription of FOXO1 via the recruitment of FOXO1 to ER- α . Sequentially, the activation of ER- α , attenuates FOXO1 and subsequently the expression of atrogin-1 and MuRF-1 [88]. In C2C12 myoblasts, genistein treatment at a lower concentration prompted myoblast proliferation and differentiation; however, at higher concentrations, it inhibited both of these processes. It also downregulated miR-222, therefore increasing the miR-222 target genes *MyoG*, *MyoD*, and *ER- α* , which are necessary for the differentiation of myoblasts [89]. Dietary daidzein decreased the mRNA and protein expression of ubiquitin-specific protease 19, which is a negative regulator of muscle mass, through the recruitment of ER β , and increased soleus muscle mass in young female mice but not in male mice [90]. In cisplatin-induced LLC-tumor-bearing mice, daidzein attenuated the loss of myofiber CSA and prevented changes in fiber-type proportion. Moreover, it inhibited protein degradation by suppressing atrogin-1 and MuRF1 via the regulation of the Glut4/AMPK/FoxO pathway [91]. A similar effect was suggested by an in vitro experiment, in which cisplatin-induced C2C12 myotube atrophy was reversed by inhibiting the Glut4/AMPK/FoxO pathway [91]. Furthermore, In Dex-induced atrophy in C2C12 myotubes, daidzein prevented myotube atrophy and promoted myotube growth and myogenic differentiation. The promyogenic activity was mediated by two kinases, Akt and P38MAPK, which in turn activated the key myogenic transcription factor MyoD. Moreover, daidzein encouraged myotube growth via the activation of the Akt/mTOR/S6K pathway [92]. In high-fat diet-induced rats, chronic soy protein consumption resulted in improved muscle function, regardless of muscle mass or fiber cross-section area improvement [93]. Formononetin, which is an isoflavone that is found in *Astragalus membranaceus*, ameliorated chronic kidney disease (CKD)-induced muscle atrophy. In formononetin-treated mice, body weight, the weight of the tibialis anterior and GM, and the CSA of skeletal muscles were significantly improved compared with CKD mice. Moreover, it effectively suppressed MuRF-1, MAFbx, and myostatin expression in TNF- α -induced cells and CKD-mice, whereas the phosphorylation of PI3K, Akt, and Foxo3a was enhanced by formononetin in both in vitro and in vivo models [94]. Glabridin, which is a prenylated isoflavone, inhibited Dex-induced protein degradation in C2C12 myotubes and in the tibialis anterior muscle of mice through the suppression of the ubiquitin ligases MuRF1 and Cbl-b but not atrogin-1. Mechanistically, glabridin inhibited the binding of Dex to its receptor, i.e., the glucocorticoid

receptor. Moreover, glabridin prevented the Dex-induced phosphorylation of p38 and FoxO3a, which act as upstream molecules to enhance the expression of ubiquitin ligases [95].

2.7 Flavonols

Flavonols are PPs that belong to the flavonoid family. They are found in a variety of fruits and vegetables, such as apples, apricots, beans, broad beans, broccoli, cherry tomatoes, chives, cranberries, kale, leeks, pears, onions, red grapes, sweet cherries, and white currants. They exert antioxidant, anti-inflammatory, cardioprotective, neuroprotective, anticancer, antibacterial, and antiviral effects [47][114]. Among the different compounds of this group, such as kaempferol, quercetin, myricetin, and morin, quercetin is the most-studied compound in the context of muscle atrophy as it acts against obesity, disuse, cachexia, and glucocorticoids.

In obesity-induced muscle atrophy, supplementation with quercetin for 9 weeks prevented the reduction of quadriceps and GM mass and muscle fiber size by attenuating protein degradation through MuRF-1 and Atrogin-1 downregulation. It significantly reduced the expression of macrophage or inflammatory cytokines (TNF- α , IL-6, MCP-1, F4/80, and CD68), as well as inflammatory cytokine receptors such as toll-like receptors (TLR) and 4-1BB in skeletal muscle. The transcripts of inflammatory receptors and their signaling molecules (ERK, p38MAPK, and NF- κ B) were significantly reduced together with atrogin-1 and MuRF-1 in cocultured myotubes/macrophages [96]. Thus, obesity-induced muscle atrophy was alleviated by quercetin via the modulation of inflammatory cytokines, their receptors, and their downstream signaling pathways [96]. Quercetin suppressed TNF- α -induced C2C12 myotube atrophy by reducing the ubiquitin ligases atrogin-1 and MuRF-1. The downregulation of ubiquitin ligases was triggered by the inhibition of NF- κ B and the activation of Heme Oxygenase 1 (HO-1) in myotubes, as the HO-1 inhibitor, ZnPP abolished the inhibitory actions of quercetin. In the same study, quercetin suppressed the muscle atrophy caused by obesity by upregulating HO-1 and inactivating NF- κ B, which was lost in Nrf-2 deficient mice. These results suggest that quercetin suppresses TNF- α -induced muscle atrophy under obese conditions via Nrf2-mediated HO-1 induction accompanied by the inactivation of NF- κ B [97]. Quercetin also limited body weight, GM and tibialis muscle loss in C26-cancer-associated cachectic mice, with a substantial decrease in atrogin-1 but not in MuRF-1 [98]. Similarly, in an A549-cell-injected tumor mouse model, quercetin increased the antitumor activity of trichostatin A (TSA) and suppressed the TSA-induced loss of GM. It further attenuated the TSA-induced activation of FOXO1, atrogin-1, and MuRF-1. Moreover, oxidative damage and inflammatory cytokines were significantly suppressed by quercetin, and it increased MyHC levels in GM [99]. In C2C12 cells, treatment with Dex (250 μ M) decreased cell viability and exerted apoptosis via hydroxyl-free radical generation. Quercetin treatment prevented Dex-induced cell viability and apoptosis by regulating mitochondrial membrane potential ($\Delta\Psi$ m) and reducing ROS production. [100]. Moreover, in Dex-induced muscle atrophy in mice, quercetin prevented the loss of the GM by suppressing myostatin and the expression of the ubiquitin ligases atrogin-1 and MuRF-1. The suppression of myostatin was attributed to the phosphorylation of Akt [101]. In tail suspension-induced disuse muscle atrophy, we found that injection of quercetin into the GM prevented its loss. Additionally, it suppressed protein degradation by attenuating the expression of the ubiquitin ligases atrogin-1 and MuRF-1 by decreasing oxidative stress, as manifested by a reduced TBARS level [102]. We also reported the effects of quercetin in denervation-induced muscle atrophy, in which pre-intake of quercetin prevented the loss of muscle mass and the atrophy of GM fibers

by opposing decreased mitochondrial genesis and increased mitochondrial hydrogen peroxide release. Overall, it increased the antioxidant capacity of mitochondria, together with increased PGC-1 α expression [103]. Furthermore, quercetin decreased the 3D-clinorotation-induced expression of atrogin-1 and MuRF-1 via the dephosphorylation of ERK [60], which is indicative of its efficacy in disuse muscle atrophy. Interestingly, long-term (24 weeks) oral treatment with quercetin glycoside effectively improved motor performance and increased muscle (quadratus femoris, gastrocnemius, tibialis anterior, and soleus) mass during the early stages of aging [104]. The stimulation of mitochondrial biogenesis by quercetin was also reported in a mouse experiment. Intake of quercetin for 7 days increased the mRNA expression of PGC-1 α and SIRT1, mtDNA, and cytochrome c concentration. Both the maximal endurance capacity and voluntary wheel-running activity of mice were enhanced by quercetin supplementation [105].

Morin is another compound in the flavonol group that is commonly found in plants of the Moraceae family [115]. We reported the antiatrophic effect of morin in cachexia and in a Dex-induced muscle atrophy model. In LLC cell-bearing mice, intake of morin prevented the reduction of muscle wet weight and myofiber size by suppressing cancer growth via binding to the ribosomal protein S10 (RPS10) [106]. In Dex-induced muscle atrophy in C2C12 myotubes, morin attenuated E3 ubiquitin ligases atrogin-1, MuRF-1, and Cbl-b and preserved the fast-type and slow-type MyHC protein content. These actions were mediated by a decrease in oxidative stress and an increase in the phosphorylation of Foxo3a. Morin also upregulated PGC-1 α [107].

2.8. Anthocyanins

Anthocyanins are natural pigments belonging to the flavonoid family. The blue, purple, red, and orange color of many fruits and vegetables stem from the presence of anthocyanins [116]. The most common anthocyanidins in plants are delphinidin, cyanidin, petunidin, pelargonidin, peonidin, and malvidin. Berries, red grapes, cereals, purple maize, vegetables, and red wine are the chief sources of anthocyanins. They exhibit various health benefits, including antioxidant, anti-inflammatory, anticancer, antidiabetic, hepatoprotective, and neuroprotective effects [116] [117]. The antiatrophic effects of delphinidin and cyanidin have been reported.

Delphinidin, which is one of the major anthocyanidins, suppresses MuRF1 expression by preventing the downregulation of miR-23a and the nuclear factor of activated T cells (NFATc3) in Dex-induced C2C12 cells [108]. In the same in vivo study using tail-suspended mice, delphinidin suppressed GM loss by reducing MuRF-1 expression and increasing miR-23a and NFATc3. miR23a, which is a micro-RNA (miRNA), decreases MuRF-1 expression by suppressing its mRNA translation. Hence, the beneficial effect of delphinidin occurred via the modulation of the NFATc3/miR-23a pathway [109]. Similarly, delphinidin suppressed the Dex-induced expression of Cbl-b in C2C12 myotubes. In the same study, oral administration of delphinidin attenuated the loss of quadriceps muscle induced by unloading in mice. These effects were mediated by the attenuation of the expression of Cbl-b and stress-related genes [109]. In our previous study, we found that delphinidin insignificantly suppressed the LPS-induced expression of atrogin-1 [82]. A cyanidin-rich diet delayed the progression of muscular dystrophies by attenuating inflammation and oxidative stress in dystrophic alpha-sarcoglycan (Sgca) gene null mice [110].

3. Conclusion

The polyphenols reported in this review have been found to prevent muscle atrophy via the suppression of muscle protein degradation, mainly by downregulating ubiquitin ligases, and the promotion of protein synthesis, myogenesis, and mitochondrial quality in in vitro and in vivo studies. The main mechanisms associated with the beneficial effects of PPs on muscle atrophy are: inhibition of inflammatory cytokines, oxidative stress, myostatin, and muscle atrophy-related ubiquitin ligases: Atrogin-1, MuRF-1, and Cbl-b. Anti-atrophic effects of PPs are also mediated by activation of the IGF-1 signaling pathway, follistatin, miRNAs, mitochondrial biogenesis, and myogenic differentiation factors involved in myogenesis. Therefore, PPs having effects on the attenuation of muscle proteolysis and maintenance of muscle mass could facilitate the avenue for designing suitable therapeutic strategies for the attenuation of skeletal muscle atrophy and the promotion of muscle health.

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