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***In silico* bioprospecting of bioactive phytochemicals with potential protective effects against exercise-induced muscle stiffness**

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ABSTRACT: Exercise and high physical activity induced muscle stiffness is a multifactorial condition characterized by impaired calcium handling, lactic acid accumulation, oxidative stress and inflammation, leading to reduced muscle elasticity, pain and impaired performance. The growing interest in natural therapeutic interventions has emphasized the need to identify bioactive compounds with multifunctional properties for muscle health. This study aimed to identify and prioritize phytotherapeutic plants with protective effects against muscle stiffness by integrating traditional bioprospection with computational screening. Ethnopharmacological literature was systematically reviewed to identify medicinal plants traditionally used for muscle-related disorders. Ten key bioactivity parameters associated with muscle recovery, including performance enhancement, anti-inflammatory activity, antioxidant activity, muscle relaxation, blood flow improvement, collagen synthesis, energy production, muscle repair and remodeling, immune support and pain relief were used to evaluate the selected plants. The selected phytotherapeutic plants were comparatively assessed and ranked based on their overall potential across these functional attributes. Among the twenty-five medicinal plants evaluated, *Curcuma longa*, *Rhodiola rosea*, *Moringa oleifera*, *Citrus limon*, and *Aloe barbadensis* demonstrated the highest multifunctional potential, with *Curcuma longa* emerged as the most promising phytotherapeutic plants owing to its broad spectrum of bioactive constituents. These findings demonstrated that, integrating traditional knowledge with computational screening is an effective approach for prioritizing multifunctional natural bioactive compounds with potential applications in nutraceutical development for muscle stiffness prevention and post-exercise recovery.

Key words: Ethnopharmacology, Muscle recovery, Nutraceutical, Phytotherapeutic plants

Muscle stiffness is defined as an increased resistance of muscle tissue to deformation or stretch (Padua *et al.*, 2005; Pruyn *et al.*, 2016). It commonly occurs following intense or prolonged physical activity as a result of metabolic disturbances, impaired calcium handling, lactic acid accumulation, oxidative stress, inflammation, ionic imbalance and microstructural damage to muscle fibers (Berchtold *et al.*, 2000; Cai *et al.*, 2023). These physiological changes reduce muscle elasticity, impair relaxation, decrease mechanical efficiency, increase the risk of muscle fatigue and injury (Sousa *et al.*, 2013; Cairns and Lindinger, 2025). Since ATP availability is essential for muscle contraction and relaxation, impaired ATP resynthesis during strenuous exercise further contributes to delayed muscle relaxation and stiffness (Alabduladhem and Bordoni, 2022).

Many studies have investigated dietary interventions, ranging from medicinal plants and herbs to isolated bioactive compounds, for the

prevention and management of muscle stiffness (Sousa *et al.*, 2014). Although many plants possess antioxidant, anti-inflammatory, muscle relaxant and recovery-promoting properties, most investigations focussed on individual compounds or specific biological activities, limiting the identification of multifunctional compounds capable of addressing the complex mechanisms underlying muscle stiffness.

Recent advances in computational approaches have enabled the rapid screening and prioritization of natural bioactive compounds, providing an efficient complement to conventional bioprospecting. Integrating ethnopharmacological knowledge with *in silico* analysis offers a systematic strategy for identifying promising compounds while reducing the time and resources required for experimental screening. However, studies applying this integrated approach for exercise-induced muscle stiffness

remain limited.

Therefore, this study aimed to identify and prioritize phytotherapeutic plants with protective effect against exercise-induced muscle stiffness using ethno-pharmacological bioprospecting and in silico analysis.

MATERIALS AND METHODS

Selection of Phytotherapeutic Plants

Phytotherapeutic plants were identified through a comprehensive review of the ethno-pharmacological literature based on the reported biological activities of their bioactive compounds, documented traditional medicinal use, and established safety for human consumption. The selection focused on ingredients with reported therapeutic properties relevant to the prevention or management of muscle stiffness.

Identification of Bioactivity Parameters

Bioactivity parameters associated with muscle stiffness and recovery were identified through a comprehensive literature review. Ten key parameters selected based on their reported roles in mitigating the physiological mechanisms underlying muscle stiffness were performance enhancement, anti-inflammatory activity, antioxidant activity, muscle relaxation, increased blood flow, collagen synthesis, energy production, muscle repair and remodeling, immune system support and pain relief. The rationale for selecting each parameter is presented in Table 1.

Relevance Assessment of Bioactivity Parameters

The relative importance of each bioactivity parameter was determined using a keyword hit scoring approach. A literature search was conducted in PubMed using the Best Match and Recent search options. Each bioactivity parameter was combined with the keyword muscle stiffness and the first twenty search results were examined for relevance. Relevant and irrelevant articles were identified based on their direct association with muscle stiffness. The percentage of relevant articles was calculated using Equation (1).

$$\text{Percentage of Relevant Hits} = (\text{Number of Relevant Hits} / 20) \times 100 \dots (1)$$

Screening of Phytotherapeutic Plants

Selected phytotherapeutic plants were subsequently screened against the ten bioactivity parameters using PubMed search combining the product name with each parameter. The presence or absence of each parameter was recorded using a binary scoring system, where 1 indicated reported evidence and 0 indicated no reported evidence. Phytotherapeutic plants exhibiting more than four bioactivity parameters were shortlisted for further evaluation.

Weighted Scoring of Phytotherapeutic Plants

The overall score for each shortlisted phytotherapeutic plants was calculated by multiplying the binary score assigned to each bioactivity parameter by its corresponding relevance weight obtained from the keyword hit scoring analysis. The weighted scores for all parameters were then summed to obtain an overall score for each plant.

Fuzzy Membership Analysis

To objectively rank the shortlisted phytotherapeutic plants, weighted scores were normalized using the linear fuzzy membership function as shown in Equation (2). This approach transforms the weighted scores into standardized membership values ranging from 0 to 1, thereby enabling direct comparison among plants.

$$\mu S = (S - \min(S)) / (\max(S) - \min(S)) \dots (2)$$

where μS is the desirability score, $\min(S)$ and $\max(S)$ are the minimum and maximum values in the data set.

Ranking of Phytotherapeutic Plants

The normalized fuzzy membership values were used to rank the shortlisted phytotherapeutic plants based on their relative suitability. Products with higher membership values were assigned higher priority, indicating greater multifunctional potential against exercise-induced muscle stiffness. Normalized fuzzy membership values (0–1) were converted into five linguistic categories using equal interval classification. Membership values of 0.80–1.00 were classified as Very High (*****), 0.60–0.79 as High (****), 0.40–0.59 as Moderate (***), 0.20–0.39 as Low (**), and 0.00–0.19 as Very Low (*). This

approach provides an intuitive representation of the relative ranking of the selected plants while preserving the underlying fuzzy membership values

RESULTS AND DISCUSSION

Relevance Assessment of Bioactivity Parameters

The relevance of the selected bioactivity parameters was determined using the keyword hit scoring approach (Table 2). Among the ten parameters evaluated, performance enhancing activity received the highest relevance score (3.75), followed by anti-inflammatory activity (3.00), antioxidant activity (2.50), muscle relaxation activity (2.25), increased blood flow activity, collagen synthesis activity, energy production activity, muscle repair and remodeling activity, immune system support activity and pain relief activity. These weightages were subsequently used to prioritize phytotherapeutic plants based on their reported multifunctional bioactivities associated with muscle stiffness.

The high relevance assigned to performance enhancement reflects the close association between exercise performance, muscle fatigue, recovery and muscle stiffness reported in the literature. Since muscle stiffness is a multifactorial condition involving oxidative stress, inflammation, impaired calcium homeostasis, ATP depletion and structural muscle damage, evaluating multiple bioactivity parameters provides a more comprehensive strategy for identifying promising phytotherapeutic plants than relying on a single biological activity (Stožer *et al.*, 2020).

Screening of Phytotherapeutic Plants using the Binary Coefficient Matrix

The selected plants were screened against the ten predefined bioactivity parameters using the binary coefficient matrix (0/1) (Table 3). Among the twenty-five plants evaluated, five achieved a binary matrix score of seven or higher (*Curcuma longa*, *Rhodiola rosea*, *Moringa oleifera*, *Citrus limon*, and *Aloe barbadensis*), while two plants scored six (*Punica granatum* and *Camellia sinensis*). Sixteen other plants scored five or below, including *Mentha piperita*, *Crocus sativus*, *Citrullus lanatus*, *Brassica*

(Cruciferous genus), *Withania somnifera*, *Glycine max*, *Allium cepa* L., *Coffea arabica*, *Myrtus communis* L., *Boswellia serrata*, *Hibiscus sabdariffa* L., *Allium sativum*, *Beta vulgaris rubra*, *Cinnamomum zeylanicum*, *Matricaria chamomilla* and *Euphorbia milli*.

The binary coefficient matrix enabled the identification of phytotherapeutic plants possessing multiple reported biological activities relevant to muscle stiffness. Since exercise-induced muscle stiffness results from interconnected physiological pathways, phytotherapeutic plants with broader bioactivity profiles are more likely to provide comprehensive protection than those acting through a single mechanism (Stožer *et al.*, 2020).

Weighted Scoring Analysis

The shortlisted phytotherapeutic plants were further evaluated using the weighted scoring matrix (Table 4). *Curcuma longa* and *Rhodiola rosea* achieved the highest weighted scores (17.5), followed by *Moringa oleifera*, *Citrus limon* and *Aloe barbadensis*. These findings indicate that, these plants collectively possess several bioactivities considered important for muscle stiffness protection.

The high ranking of *Curcuma longa* is consistent with previous studies demonstrating the multifunctional biological activities of curcumin. Curcumin regulates inflammatory signaling pathways, including tumor necrosis factor- α (TNF- α) and cyclooxygenase-2 (COX-2), thereby reducing inflammatory responses associated with muscle damage (Peng *et al.*, 2021). In addition, curcumin enhances endogenous antioxidant enzymes such as superoxide dismutase and glutathione peroxidase, reducing oxidative stress and helping preserve calcium homeostasis required for normal muscle relaxation (Jat *et al.*, 2013).

Similarly, *Rhodiola rosea* exhibited a high weighted score owing to its adaptogenic, antioxidant and anti-fatigue properties. Its principal bioactive compounds, salidroside and rosavin, have been reported to enhance mitochondrial biogenesis and ATP synthesis, thereby improving cellular energy

Table 1: Bioactivity Parameter for Muscle Stiffness

Sl. No	Bioactivity Parameter	Rationale for selection
1	Performance Enhancing (PE)	Intense muscle activity causes fatigue and reduces strength; enhancing performance delays fatigue and improves output.
2	Anti-inflammatory Activity (AIA)	Muscle use induces inflammation leading to soreness; anti-inflammatory agents (e.g., Curcumin, Omega-3 fatty acids) reduce this.
3	Antioxidant Activity (AA)	Exercise generates free radicals that cause fatigue; antioxidants neutralize free radicals to prevent muscle damage.
4	Muscle Relaxation (MR)	Proper muscle relaxation prevents cramps and optimizes coordination, improving speed and strength during movement.
5	Increased Blood Flow (IBF)	Enhanced blood circulation delivers oxygen and nutrients, accelerating muscle recovery and reducing injury effects.
6	Collagen Synthesis (CS)	Low molecular weight collagen peptides improve muscle structure and repair, vital for untrained, elderly, or injured.
7	Energy Production (EP)	Supplements like creatine boost muscle energy stores, enhancing endurance and performance in high-intensity exercises.
8	Muscle Repair and Remodeling (MRR)	Managing initial inflammation, clears debris and promotes tissue regeneration, preventing excessive scarring and fibrosis.
9	Support System Immune (SSI)	The immune system regulates repair and recovery; antioxidants (e.g., quercetin) help maintain post-exercise immune balance.
10	Analgesic properties (AP)	Nutritional interventions (e.g., strawberries, vitamin D) reduces pain and inflammatory markers, aiding recovery.

Table 2: Weightage Assigned to Parameters Based on Average Percentage Relevance

Sl. No	Parameters Chosen	Average Percentage Relevance (%) (Best match)	Average Percentage Relevance (%) (Recent)	Mean Value	Relative Weightage Assigned
1	Performance Enhancing	55.00	20.00	37.50	3.75
2	Anti-inflammatory Activity	35.00	25.00	30.00	3.00
3	Antioxidant Activity	25.00	25.00	25.00	2.50
4	Muscle Relaxation	35.00	10.00	22.50	2.25
5	Increased Blood Flow	25.00	20.00	22.50	2.25
6	Collagen Synthesis	20.00	10.00	15.00	1.50
7	Energy Production	10.00	15.00	12.50	1.25
8	Muscle Repair and Remodeling	5.00	15.00	10.00	1.00
9	Support System Immune	5.00	5.00	5.00	0.50
10	Pain Relief Activity	5.00	5.00	5.00	0.50

metabolism and reducing lactate accumulation during exercise (Xu *et al.*, 2024). These mechanisms may contribute to improved muscle function and reduced muscle stiffness.

Fuzzy Membership Analysis and Ranking of Phytotherapeutic Plants

The weighted scores were normalized using the fuzzy membership function to obtain relative suitability values for each phytotherapeutic plants (Table 5). To facilitate interpretation, the normalized values were classified into five linguistic categories: Very High (*****), High (****), Moderate (***), Low (**) and Very Low (*). Among the selected

twenty-five natural plants evaluated, *Curcuma longa* achieved the highest desirability score ($\mu S = 1.00$) and was classified as Very High (*****), indicating the strongest overall bioactivity profile. *Rhodiola rosea* ($\mu S = 0.97$), *Moringa oleifera* ($\mu S = 0.86$), *Aloe barbadensis* ($\mu S = 0.85$) and *Citrus limon* ($\mu S = 0.83$) were also categorized as Very High, demonstrating excellent cumulative potential based on the selected biological parameters.

The very high ranking of *Moringa oleifera* is supported by previous studies indicating that, its polyphenols and isothiocyanates possess strong antioxidant and anti-inflammatory activities while

Table 3: Selection of Phytotherapeutic Plants Using the Classical Bioprospection Approach

Sl. No	Name	Bio-active Compound	Bio-active Properties	Mechanism of Action	Reference
01	Aleovera (<i>Aloe barbadensis</i>)	Campesterol and β -sitosterol	Antioxidant and Anti-inflammatory	Exhibits antioxidant and anti-inflammatory activities, reducing lactate dehydrogenase and C-reactive protein levels	Barati <i>et al.</i> (2015)
02	Ashwagandha (<i>Withania somnifera</i>)	Catechins	Antioxidant, Adaptogenic and Anti-inflammatory	Enhances muscle mass and strength while reducing exercise-induced muscle damage by stabilizing creatine kinase levels	Wankhede <i>et al.</i> (2015)
03	Beetroot (<i>Beta vulgaris rubra</i>)	Betalains, Polyphenols, Flavonoids and Nitrates	Antioxidant and Anti-inflammatory	Beetroot extract (300 mg/kg for 17 days) reduced inflammatory and oxidative biomarkers while improving muscle strength, muscle weight and muscle fibre cross-sectional area.	Nazari <i>et al.</i> (2024)
04	Brassica (<i>Cruciferous genus</i>)	Isothiocyanate	Antioxidant and Anti-inflammatory	6-Methylsulfinylhexyl isothiocyanate (6-MSITC) activates nuclear factor erythroid 2-related factor 2 (Nrf2) and inhibits mitogen-activated protein kinase (MAPK) pathways, reducing exercise-induced muscle damage and delayed-onset muscle soreness while enhancing muscle strength recovery.	Tanabe <i>et al.</i> (2022)
05	Chamomile (<i>Matricaria chamomilla</i>)	Terpenoids and Flavonoids	Antioxidant, Antiphlogistic, Anticancer and Anti-inflammatory	Chamomile reduced serum creatine kinase and lactate dehydrogenase levels, indicating reduced muscle damage.	Khatami <i>et al.</i> (2017)
06	Cinnamon (<i>Cinnamomum verum</i>)	Cinnamaldehyde, Eugenol and Coumarin	Antioxidant and Anti-inflammatory	Cinnamon exhibits antioxidant activity by reducing malondialdehyde levels and enhancing glutathione peroxidase, superoxide dismutase, and catalase activities. It also increases skeletal muscle glucose uptake, thereby reducing lactate production	Dehghan <i>et al.</i> (2014)
07	Coffee (<i>Coffea arabica</i>)	Caffeine	Antioxidant, Antifatigue and Analgesic agent	Caffeine exhibits ergogenic effects by increasing calcium availability, reducing fatigue, and enhancing Na^+/K^+ -ATPase activity, thereby improving muscle performance and providing analgesic effects..	Bojórquez <i>et al.</i> (2024) and Domaszewski <i>et al.</i> (2021)
08	<i>Euphorbia milli</i>	Spinacetin and Patuletin	Analgesic, Anti-inflammatory, Muscle relaxant, Antinociception and Sedative	Promotes protein synthesis, reduces fat accumulation, and lowers blood urea levels.	Aljohani <i>et al.</i> (2022) and Akomas <i>et al.</i> (2015)
09	Garlic (<i>Allium</i>)	Organic	Antioxidant and	Garlic (1000 mg/day) increased	

	<i>sativum</i>)	sulfides, Saponins and Phenolic compounds	Anti-inflammatory	total antioxidant capacity, enhanced post-exercise glucose uptake, and upregulated transcription factors involved in mitochondrial biogenesis, thereby improving oxidative respiration.	Tsao <i>et al.</i> (2023) and Shang <i>et al.</i> (2019)
10	Ginseng (<i>Panax ginseng</i>)		Antioxidant, Adaptogenic, Antifatigue and Anti-inflammatory	Prolonged ginseng intake reduced creatine kinase and interleukin-6 levels, limited blood lactate accumulation, alleviated muscle fatigue and promoted muscle regeneration through enhanced satellite cell activation.	Muñoz-Castellanos <i>et al.</i> (2023)
11	Golden root Extract (<i>Rhodiola rosea</i>)	Salidroside, Rosavin, Syringin and Triandrin	Antioxidant, Analgesic, Antifatigue and Anti-inflammatory	Rhodiola rosea (400 mg/day for 8 days) reduced lactate dehydrogenase, blood lactate and inflammatory biomarkers, including interleukin-1 β , interleukin-6, tumor necrosis factor- α and C-reactive protein. It also enhanced hepatic and muscle glycogen content, contributing to anti-fatigue effects.	Lu <i>et al.</i> (2022) and Wang <i>et al.</i> (2023)
12	Green Tea (<i>Camellia sinensis</i>)	Catechins and Quercetin	Anti-inflammatory, Antiviral, Antioxidant, Cardio-protective, Anti-carcinogenic, and Neuro protective properties	Green tea catechins promote protein homeostasis, enhance mitochondrial energy metabolism, and reduce age-related muscle atrophy. Quercetin exhibits anti-inflammatory activity, improves endurance, and enhances mitochondrial biogenesis.	Askari <i>et al.</i> (2013)
13	Indian frankincens (<i>Boswellia serrata</i>)	3-Acetyl-11-keto- β -boswellic acid	Anti-inflammatory and Analgesic agent	Boswelliaserrata contains 3-acetyl-11-keto- β -boswellic acid, which reduces inflammatory biomarkers associated with muscle damage. Regular consumption also reduces post-exercise muscle soreness.	Salter <i>et al.</i> (2025)
14	Lemon (<i>Citrus limon</i>)	Quercetin, Limocitrin and Spinacetin	Antioxidant and Anti-inflammatory	Exhibits antioxidant activity by scavenging free radicals and reducing reactive oxygen species (ROS), prostaglandins (PG) and other inflammatory mediators. It also inhibits xanthine-mediated redox reactions, contributing to its anti-inflammatory effects.	Sawada <i>et al.</i> (2025)
15	Mint (<i>Mentha Piperita</i>)	Menthol (29%) and Menthone (20-30%)	Antioxidant, Antispasmodic and Anti-inflammatory	Promotes bronchial smooth muscle relaxation, enhances ventilation and brain oxygenation and reduces blood lactate levels.	Meamarbashi and Rajabi (2013)
16	Moringa (<i>Moringa Oleifera</i>)	Phenolic acids, Isothiocyanates, Tannins, Flavonoids, and Saponins	Antioxidant, Antidiabetic, Antifatigue and Anti-inflammatory	Moringa increases glucose transporter type 4 (GLUT4) expression, improving glucose uptake, and enhances muscle endurance by promoting mitochondrial biogenesis in skeletal muscle.	Barodia <i>et al.</i> (2022)

17	Myrtle (<i>Myrtus communis</i>)	Phenolic acid and Flavonoids	Antiseptic, Astringent, Analgesic and Anti-inflammatory	Reduces blood lactate accumulation and triglyceride levels while promoting protein synthesis.	Hennia <i>et al.</i> (2018)
18	Onion (<i>Allium cepa</i>)	Quercetin	Anti-inflammatory	Onion is rich in quercetin, which enhances mitochondrial biogenesis in skeletal muscle, improving aerobic respiration and reducing lactate accumulation.	Henagan <i>et al.</i> (2015)
19	Pomegranate (<i>Punica granatum</i>)	Flavonoids and Polyphenols	Antioxidant and Anti-inflammatory	Regular consumption of pomegranate significantly accelerates muscle endurance, enhances cardiovascular health, antioxidant activity and effectively boots the rate of muscle recovery.	Bibi <i>et al.</i> (2024)
20	Roselle (<i>Hibiscus sabdariffa</i>)	Anthocyanins	Antitumor, Antioxidants and Anticarcinogenic	Roselle is rich in anthocyanins that enhance muscle protein synthesis by activating mammalian target of rapamycin (mTOR) pathway. They also increase insulin-like growth factor-1 (IGF-1) expression, improve glucose uptake and vascular function through angiotensin-converting enzyme inhibition, and reduce interleukin-6 (IL-6)-mediated inflammation.	Lubis <i>et al.</i> (2024)
21	Saffron (<i>Crocus sativus</i>)	Crocin, Picrocrocin, and Safranal	Antioxidant, Antidepressant, Antinociceptive, Relaxant activity and Anti-inflammatory	Saffron enhances mitochondrial biogenesis, improves skeletal muscle force and promotes muscle blood perfusion and oxygen transport.	Meamarbashi and Rajabi (2016)
22	Soybeans (<i>Glycine max</i>)	Isoflavones, Saponins, Phytosterols, Phenolic acids, Flavonoids, Carotenoids and Tocopherols	Antioxidant, Antidepressant, Anti-inflammatory	Soybean stimulates muscle protein synthesis, promotes muscle repair and recovery and exhibits anti-inflammatory activity that reduces muscle soreness.	Ramos-Jiménez <i>et al.</i> (2024)
23	Tart Cherry (<i>Prunus cerasu</i>)	Phenolic and Anthocyanin	Antioxidant and Anti-inflammatory	art cherry juice reduces post-exercise muscle soreness, inflammation, oxidative stress, and hormonal stress biomarkers.	McHugh (2022)
24	Turmeric (<i>Curcuma longa</i>)	Curcumin	Antioxidant and Anti-inflammatory	Curcumin (90–5000 mg/day) reduces cyclooxygenase-2 (COX-2) expression, prostaglandin levels, creatine kinase release and pro-inflammatory cytokines, while enhancing antioxidant capacity to improve post-exercise muscle recovery and functional performance.	Nanavati <i>et al.</i> (2022)
25	Watermelon (<i>Citrullus lanatus</i>)	Lycopene, Carotenoid, Glutathione, and L-Citrulline	Antioxidant, Hypoglycemic and Anti-inflammatory	Watermelon is rich in citrulline, glutathione and arginine, which reduce post-exercise muscle soreness and promote muscle hypertrophy.	Azizi (2024)

Table 4: Weightage Matrix Scores for Phytotherapeutic Plants Screened on the Basis of Binary Matrix Scores

Character weightage	PE	AIA	AA	MR	IBF	CS	EP	MRR	SSI	PR	Score
Weightage	3.75	3.00	2.50	2.25	2.25	1.50	1.25	1.00	0.50	0.50	18.50
<i>Curcuma longa</i>	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00	1.00	17.50
<i>Rhodiola rosea</i>	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	1.00	17.00
<i>Moringa oleifera</i>	1.00	1.00	1.00	0.00	1.00	1.00	1.00	0.00	1.00	1.00	15.25
<i>Aloe barbadensis</i>	1.00	1.00	1.00	0.00	1.00	1.00	0.00	1.00	1.00	1.00	15.00
<i>Citrus limon</i>	1.00	1.00	1.00	0.00	1.00	1.00	1.00	0.00	1.00	0.00	14.75
<i>Punica granatum</i>	1.00	1.00	1.00	0.00	1.00	1.00	0.00	0.00	1.00	0.00	13.50
<i>Panax ginseng</i>	1.00	1.00	1.00	0.00	0.00	1.00	1.00	0.00	0.00	1.00	12.50
<i>Prunus cerasus</i>	1.00	1.00	1.00	0.00	0.00	1.00	1.00	0.00	0.00	1.00	12.50
<i>Camellia sinensis</i>	0.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	1.00	1.00	12.50
<i>Mentha piperita</i>	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00	12.00
<i>Crocus sativus</i>	1.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00	12.00
<i>Citrullus lanatus</i>	1.00	1.00	1.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	11.50
<i>Cruciferous genus</i>	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	9.75
<i>Withania somnifera</i>	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	9.75
<i>Allium cepa L.</i>	0.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	1.00	1.00	8.75
<i>Glycine max</i>	0.00	1.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	8.50
<i>Coffea arabica</i>	0.00	1.00	1.00	0.00	0.00	1.00	0.00	1.00	0.00	0.00	8.25
<i>Myrtus communis</i>	0.00	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00	8.00
<i>Boswellia serrata</i>	0.00	1.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	1.00	8.00
<i>Hibiscus sabdariffa</i>	0.00	1.00	1.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	7.00
<i>Allium sativum</i>	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	6.50
<i>Beta vulgaris rubra</i>	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	6.50
<i>Cinnamomum zeylanicum</i>	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	6.00
<i>Matricaria chamomilla</i>	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	6.00
<i>Euphorbia milli</i>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	00.00	0.50

supporting mitochondrial function and ATP synthesis (Chi' *et al.*, 2023). These biological properties may contribute to improved muscle recovery following strenuous exercise.

Citrus limon also demonstrated high multifunctional potential. Its flavonoids particularly quercetin, have been associated with improved blood flow, enhanced mitochondrial biogenesis and reduced oxidative stress, which are beneficial for muscle recovery and for the maintenance of muscle function (Sawada *et al.*, 2025).

Aloe barbadensis ranked among the highest-scoring phytotherapeutic plants because of its reported anti-inflammatory properties. Its phytosterols have been shown to reduce exercise-induced muscle damage and may contribute to improved muscle recovery and reduced stiffness (Barati *et al.*, 2015).

The High category included *Punica granatum* ($\mu S = 0.76$), *Panax ginseng* ($\mu S = 0.70$), *Prunus cerasus*

($\mu S = 0.70$), *Camellia sinensis* ($\mu S = 0.70$), *Mentha piperita* ($\mu S = 0.67$), *Crocus sativus* ($\mu S = 0.67$) and *Citrullus lanatus* ($\mu S = 0.64$). These phytotherapeutic plants exhibited strong biological relevance, although their overall desirability scores were slightly lower than those in the Very High category.

Seven plants and their products namely *Cruciferous genus*, *Withania somnifera*, *Allium cepa L.*, *Glycine max*, *Coffea arabica*, *Myrtus communis*, and *Boswellia serrata*, were grouped into the Moderate category, with desirability scores ranging from 0.44 to 0.54. These products possess several beneficial bioactivities but may lack one or more critical properties required for maximizing the overall desirability score.

The Low category comprised *Hibiscus sabdariffa*, *Allium sativum*, *Beta vulgaris rubra*, *Cinnamomum zeylanicum* and *Matricaria chamomilla*, with desirability scores between 0.32 and 0.38. Although

Table 5: Fuzzy Set Membership Analysis for Phytotherapeutic Plants Screened on the Basis of Desirability Score

Sl. No	Phytotherapeutic Plants	Desirability Score (μS)	Star Rating	Category
1	<i>Curcuma longa</i>	1.00	***** (5)	Very high
2	<i>Rhodiola rosea</i>	0.97	***** (5)	Very high
3	<i>Moringa oleifera</i>	0.86	***** (5)	Very high
4	<i>Aloe barbadensis</i>	0.85	***** (5)	Very high
5	<i>Citrus limon</i>	0.83	***** (5)	Very high
6	<i>Punica granatum</i>	0.76	**** (4)	High
7	<i>Panax ginseng</i>	0.70	**** (4)	High
8	<i>Prunus cerasus</i>	0.70	**** (4)	High
9	<i>Camellia sinensis</i>	0.70	**** (4)	High
10	<i>Mentha piperita</i>	0.67	**** (4)	High
11	<i>Crocus sativus</i>	0.67	**** (4)	High
12	<i>Citrullus lanatus</i>	0.64	**** (4)	High
13	<i>Cruciferous genus</i>	0.54	*** (3)	Moderate
14	<i>Withania somnifera</i>	0.54	*** (3)	Moderate
15	<i>Allium cepa L.</i>	0.48	*** (3)	Moderate
16	<i>Glycine max</i>	0.47	*** (3)	Moderate
17	<i>Coffea arabica</i>	0.45	*** (3)	Moderate
18	<i>Myrtus communis</i>	0.44	*** (3)	Moderate
19	<i>Boswellia serrata</i>	0.44	*** (3)	Moderate
20	<i>Hibiscus sabdariffa</i>	0.38	** (2)	Low
21	<i>Allium sativum</i>	0.35	** (2)	Low
22	<i>Beta vulgaris rubra</i>	0.35	** (2)	Low
23	<i>Cinnamomum zeylanicum</i>	0.32	** (2)	Low
24	<i>Matricaria chamomilla</i>	0.32	** (2)	Low
25	<i>Euphorbia milli</i>	0.00	*(1)	Very low

these plants possess documented therapeutic activities, their cumulative contribution across the selected evaluation parameters was comparatively limited. *Euphorbia milli* recorded the lowest desirability score ($\mu S = 0.00$) and was therefore classified as Very Low (*).

Overall, the fuzzy desirability analysis identified five phytotherapeutic plants (20%) as Very High, seven (28%) as High, seven (28%) as Moderate, five (20%) as Low, and one (4%) as Very Low.

CONCLUSION

This study demonstrated that integrating ethnopharmacological knowledge with *in silico* bioprospecting is an effective approach for identifying and selecting phytotherapeutic plants with potential protective effects against exercise-induced muscle stiffness. Among the evaluated plants, *Curcuma longa*, *Rhodiola rosea*, *Moringa oleifera*, *Citrus limon* and *Aloe barbadensis* exhibited the highest multifunctional potential. Since

the findings are based on literature-derived data and computational prioritization, this alone cannot be considered as definitive evidence of therapeutic efficacy. Therefore, further *in vitro*, *in vivo* and clinical studies are required to validate these plants and support their development as nutraceuticals for muscle stiffness management and post-exercise recovery.

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