Aging Clinical and Experimental Research (2026) 38:17
https://doi.org/10.1007/s40520-025-03216-z

SYSTEMATIC REVIEW

Effect of host and gut microbiota-altering interventions on sarcopenia or its defining parameters: a systematic review and meta-analysis of nutrition-based intervention studies

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Received: 15 May 2025 / Revised: 10 September 2025 / Accepted: 15 September 2025

Abstract

Aim To investigate effects of host- and gut microbiota (GM)-altering interventions on sarcopenia (parameters).

Methods Upon PROSPERO registration (CRD42022347363), six databases and one registry were searched until January 5th 2024 and updated on June 10th 2025 for diet, pre-, pro-, or synbiotics mono-interventions in populations with mean age ≥ 50 years. (Standardized) mean differences (SMD) and 95% confidence intervals (CI) were computed using random-effects models if heterogeneity was > 50%. Risk of bias (Rob) & GRADE assessments were carried out to assess the evidence' quality and certainty.

Results The qualitative analysis included 38 diet, 13 prebiotics, 11 probiotics and 1 synbiotics studies, totaling 4842 participants (59%♀), mostly of high RoB. The quantitative analysis included 49 studies. Probiotics improved muscle strength by 1.90 kg and gait speed by 0.08 m/s. Fiber (whole-food)-enriched diets improved muscle strength with 1.25 kg and energy-restricted diets, aimed at weight loss, improved muscle mass if mean age was < 60 years and if the intervention lasted no longer than 12 weeks. High-protein diets improved muscle mass in women and if the intervention lasted at least 12 weeks. Studies involving participants with sarcopenia were only included in the qualitative analysis, since none provided sufficient data to allow a quantitative synthesis.

Discussion Fiber (whole food)-enriched diets and probiotics improve muscle strength. The latter intervention also improves gait speed. High-protein diets improve muscle mass in women and with intervention durations ≥ 12 weeks. Future studies should include fecal sampling to assess whether GM modulate the observed effects.

Conclusion Specific diets and probiotics offer potential to improve sarcopenia parameters.

Keywords Sarcopenia · Prebiotics · Probiotics · Synbiotics · Diets · Meta-analysis

Introduction

Sarcopenia, a progressive generalized skeletal muscle disorder, characterized by loss of muscle mass and function, increases the risk of deleterious health outcomes such as falls, fractures and mortality [1]. Prevalence of sarcopenia is up to 27% in persons aged ≥ 60 years [2], depending on the community setting, underlying comorbidity and sarcopenia definition [3]. Sarcopenia puts significant burden on health care systems [4, 5], warranting accurate treatment, and preferably preventive measures, which in turn requires an in depth comprehension of the pathophysiology of sarcopenia. Multiple factors contribute to this process, e.g., anabolic resistance, alterations at the neuromuscular junction (NMJ)

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Published online: 21 November 2025

and low-grade systemic inflammation or 'inflammaging' [6]. Additionally, gut microbiota (GM) have emerged as a potential driver of sarcopenia. Gut microbiota contribute to various physiological processes such as metabolism of undigested food, antioxidant activity, maintenance of the gut barrier and suppression of chronic inflammation. However, prior research found less rich and diverse or 'dysbiotic' GM in persons with low muscle mass or strength [7]. Decreased absorption of protein in the gastro-intestinal (GI) track or high-protein diets (mostly consumed in animal form), a suggested treatment for sarcopenia, may lead to increased protein in the colon, shifting GM towards a proteolytic metabolism. Some of these metabolites may increase permeability of the gut barrier, leading to leakage of toxic byproducts to the systemic circulation, eventually contributing to 'inflammaging' and thus sarcopenia [8]. Prior meta-analyses have reported on the health-promoting effects of supplementing with gut dysbiosis restoring compounds, such as pro-, pre- or synbiotics. To illustrate, probiotics can improve i.e. systemic inflammatory levels and high blood pressure [9, 10] and both pre- and synbiotics have been shown to improve lipid profiles [10–12]. Probiotics are 'live organisms that confer a health benefit to the host if administered in adequate amounts' [13] and prebiotics are defined as 'substrates selectively utilized by host microorganisms conferring a health benefit', whereas synbiotics are a combination of both [14]. Besora-Morena et al. investigated the effect of these compounds on sarcopenia-parameters (muscle mass, strength and physical performance) in persons aged >60 years [15]. Although reporting positive effects of probiotics on muscle strength, studies with multiple interventions were included, namely physical exercise and supplementation with leucine and omega-3, which also influence GM, and may therefore confound the results [15]. Moreover, populations aged ≥ 60 years were included, whereas muscle mass deterioration has previously been shown to accelerate from 50 years on [1]. Therefore changes in GM composition associated with worsening muscle status could already occur earlier in the life course [16]. Finally, Besora-Moreno et al. did not consider the potential dual role of diet, exerting both GM- and host-altering effects in relation to skeletal muscle parameters. While certain dietary strategies, such as high-protein diets, are primarily designed to directly influence the host – for example, by stimulating muscle protein synthesis (MPS) – they may also exert indirect effects by modulating the GM. Indeed, several studies have suggested that dietary components can alter GM composition and activity [17, 18]. However such dual effects of dietary interventions have been insufficiently addressed in previous meta-analyses.

The primary aim of this systematic review and meta-analysis was to investigate the effect of GM-altering interventions, being diets, pre-, pro or synbiotics, on sarcopenia or its defining parameters (muscle mass, strength and physical performance) in middle-aged and older adults ≥ 50 years. We hypothesize that pre-, pro and synbiotics will especially improve muscle strength and physical performance, whereas we expect specific diets, such as high-protein ones, to improve muscle mass.

Methodology

Search strategy and study selection

This systematic review was preregistered on PROSPERO (CRD42022347363) and a search was carried out in six databases (PubMed, Embase, Scopus, CENTRAL, CINAHL and Web of Science) and one registry (ClinicalTrials.gov). The search string combined Medical Subject Headings (MeSh) terms (e.g. 'sarcopenia', 'probiotic', 'prebiotic', 'synbiotic' and 'diet' and free text terms/keywords (e.g., older adults, Lactobacillus, inulin, fructo-oligosaccharides) (Appendix I). Grey literature was not included in the search strategy, as we aimed to limit our review to peer-reviewed sources to ensure methodological rigor and data reliability. The literature search was initially conducted in January 2024 and updated to include newly published papers up to June 10th 2025. Additional articles were identified through forward and backward citation searching. The complete literature retrieval process is given in Fig. 1. Findings were reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines **(Appendix II)**. Inclusion criteria were: intervention studies with diet, pre-, pro- or synbiotics, inclusion of a control group, mean age of study population ≥ 50 years, studies reporting in English, French, Dutch or German and studies reporting on sarcopenia or at least one of its defining parameters. Exclusion criteria were: studies with a postbiotics interventions (which are 'preparations' of inanimate microorganisms and/or their components that confer a health benefit on the host', for example bacteria-produced metabolites) [19], studies with a diet supplementing non-whole foods, such as purified fiber, protein or polyphenol caps, studies implementing a time-restricted diet (e.g., intermittent fasting) and studies including populations suffering from conditions (i.e. malignancy, neurodegenerative disorders) impacting skeletal muscle.

After deduplication in EndNote, titles and abstract were screened by two independent reviewers (LL and NA) using the online Rayyan screening tool, followed by a full-text review if relevance could not be determined from the abstract. All disagreements were subsequently resolved through discussion until consensus was reached or by a

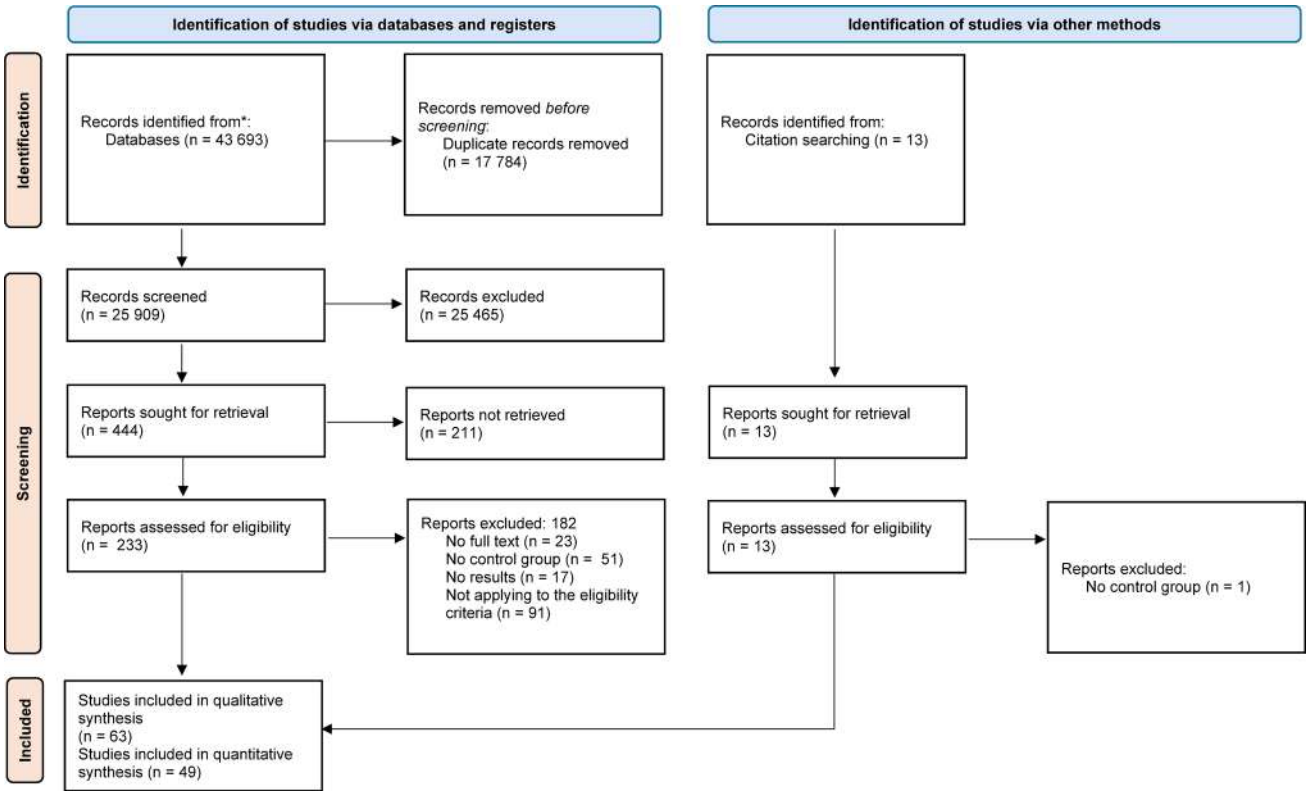

Fig. 1 PRISMA flowchart for study selection process; Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA)

third reviewer (EG). The level of agreement between the reviewers during the initial screening phase was assessed using Cohen's kappa (κ). The resulting statistic was κ = 0.31, $p < 0.001$, with a 95% CI [0.2103–0.4164], indicating fair interrater agreement [20]. A standardized data form was used to extract relevant information from the included studies including author's last name, country, year, journal, study design, number of persons randomized and included, age, distribution of genders, description of GM-altering and placebo interventions, sarcopenia-related outcomes assessed, tools used for assessment of the outcomes, confounders taken into account, compliance to the intervention, drop-outs and adverse events.

Quality assessment

The Cochrane Risk of Bias (RoB2) tool for randomized intervention studies and the 'Risk of Bias In Non-Randomized Studies of Interventions (ROBINS-I) tool were used to assess the quality of the studies [21, 22]. Based on the scoring of five domains, the RoB2 tool comprises the following classification: low risk of bias (if all domains are scored 'low risk of bias'), some concerns for risk of bias (if at least one domain is at some concern for risk of bias, but none at 'high risk') and 'high risk of bias' (if at least one domain is 'at high risk' of bias). For the ROBINS-I tool, seven domains are assessed, resulting in following classification: low risk of bias (if all domains are 'low risk'), 'moderate risk of bias' (if at least one domain is at 'moderate risk', but no domains are at 'serious risk' or 'critical risk'), 'serious risk of bias' (at least one domain is 'at high risk', or several are at 'moderate risk') and 'critical risk of bias' (at least one domain is 'at critical risk' or several are at 'serious risk'). The certainty of evidence was assessed using the Grading of Recommendations, Assessment, Development and Evaluation (GRADE) approach (Appendix III). Two independent reviewers (LL and NA) performed study quality and GRADE assessments. A third reviewer (EG) was consulted for a final decision if no agreement was reached.

Statistical analysis

Changes in outcomes from baseline to follow-up were treated as continuous data and were compared between groups to calculate mean differences (MD) reporting 95% confidence intervals (CI). If outcomes were determined on different scales, Standardized Mean Differences (SMD) were computed by dividing the MD by the pooled standard deviation (SD) to determine effects of GM-altering interventions (diet and supplementation of pre-, pro-, and synbiotics) on sarcopenia or its parameters. For outcomes assessed on different scales, the SMD was multiplied by

-1 if a positive effect of the intervention implied opposite directions on the scale (e.g. higher values in Hand Grip Strength (HGS) indicate better muscle strength whereas higher values of the 5-time Chair Stand test (CST) indicate worse muscle strength). The SMD was re-expressed on its original scale through multiplication by a representative standard deviation (SD_{rep}), equal to the pooled SD. Random-effects models were applied if significant heterogeneity was detected (χ^2 – based Cochran's Q statistical test, I^2, its 95% CI and τ^2 as absolute estimate of heterogeneity) and a fixed-effect model was applied if no heterogeneity was detected. If heterogeneity was significant, meta-regression was performed to identify potential sources of heterogeneity if information was available. Sensitivity analyses were applied to assess robustness and quality of the results by omitting one study at a time. If outcome data were missing, corresponding authors were contacted. In case of no response, mean change in the outcome was calculated based on means ± standard deviations (SD) or means ± standard error of the means (SEM) of baseline and follow-up values if possible. If those studies did not provide information on inter-person correlation, R, it was assumed a constant. Subgroup analyses were based on age, sex, study duration, community-setting, number of probiotic colony forming units (CFU), intake of single or multiple probiotic strains, type of prebiotic and protein source, if this information was available. Publication bias was assessed if possible based on funnel plots and Egger's tests. Studies assessing effects on multiple sarcopenia-defining parameters were included in separate analyses. Analyses were conducted using the meta package version 17.0 (STATA Corp LLC, Texas). All results were deemed significant if the p-value was <0.05.

Results

Study selection and characteristics of included studies

A complete overview of the retrieval process is shown in Fig. 1. Sixty-three studies were included in the qualitative analysis with samples sizes between 14 and 396 persons, amounting a total of 4842 persons of whom 59% ($n = 2875$) were women. The mean age range of the included population was 50 to 84.9 years. Thirty-eight studies investigated a dietary intervention [23–52], categorized as energy-restricted ($n = 14$), fiber-enriched ($n = 4$), energy-enriched ($n = 3$), high-protein ($n = 11$), fermented foods-enriched ($n = 3$), low-fat vegan ($n = 1$), Mediterranean ($n = 1$) and Dietary Approaches to stop Hypertension (DASH), which is a heart-healthy eating plan designed to lower blood pressure ($n = 1$). Thirteen studies investigated a prebiotic intervention [53–62], 11 studies a probiotic intervention [63–73] and one a synbiotics intervention [74]. Thirty-seven studies [23, 25, 27–30, 34, 36–38, 40–43, 45, 46, 48–51, 53, 54, 56, 57, 59–62, 65, 69, 74–78] included community-dwelling persons, three studies hospitalized persons [35, 68, 79], two studies [67, 80] nursing-home residents and 22 studies [24, 26, 31, 32, 39, 44, 47, 52, 55, 58, 63, 64, 66, 73, 81–88] did not clearly report about the living arrangements of the included population. All studies were randomized-controlled trials (RCT), one was a registry study [53] and a non-randomized intervention study exempted [35]. Fifteen [27–29, 32, 36, 38, 40, 44, 49, 51, 56, 58, 59, 75, 84] studies were conducted in North-America, five in South-America [25, 26, 37, 39, 74], 17 in Asia [34, 47, 48, 61–64, 66, 67, 72, 73, 76–78, 80, 85, 89], five in Oceania [24, 35, 41, 55, 60] and 21 in Europe [23, 30, 31, 42, 43, 45, 46, 50, 52–54, 57, 65, 68, 69, 79, 81, 83, 86–88].

Nine studies were conducted in persons with sarcopenia, defined according to the European Working Group for Sarcopenia in Older People (EWGSOP2) [66, 70, 71], the International Working Group on Sarcopenia (IWGS) [44], the Asian Working Group on Sarcopenia [34], the residuals method [26], self-defined low Appendicular Lean Mass (ALM) [24] or Appendicular Skeletal Muscle Mass (ASMM) [25] cut-offs, respectively. Sarcopenia prevalence before the intervention ranged between 8.3% and 100%, high prevalence attributable to studies including only persons with sarcopenia [25, 26, 34]. One study investigated progression towards EWGSOP2-defined sarcopenia, without reporting prevalence or incidence [83]. Therefore, effects of interventions on sarcopenia were only qualitatively described. Only two of three studies assessing effects of probiotics on sarcopenia, reported sarcopenia incidence at the end of the intervention, which was non-significantly decreased in both studies [70, 71] (Table SI). Further, only Mason et al. reported a decreased incidence of sarcopenia in both energy-restricted diet and control groups (Table SXIII). None of the other studies reported effects of GM or host-altering nutritional interventions on sarcopenia. Various tools were used to assess sarcopenia-defining parameters (muscle mass, muscle strength and physical performance). Muscle mass was estimated in 44 studies, using dual X-ray absorptiometry (DXA) in **19 studies** [24, 25, 29, 32, 36, 40, 44, 49, 51, 58, 59, 65, 67, 75, 78, 83, 84, 86, 87], bio-electrical impedance analysis (BIA) in 15 studies [34, 41, 46–48, 57, 60, 62, 66, 68, 70, 71, 73, 80, 85], computed tomography (CT) in two studies [38, 57], Magnetic Resonance Imaging (MRI) in five studies [27, 49, 51, 81, 89], anthropometrics (e.g. calf circumference (CC) or triceps skinfold thickness (TSF)) in six studies [34, 42, 74, 80, 81, 85], air displacement plethysmography in two studies [30, 52] and one study used ultrasound [89]. One study stated to

have assessed muscle mass with "an electronic scale", without further specifying the underlying method [63]. Muscle strength was estimated in 41 studies through assessment of hand grip strength (HGS) via hand-held dynamometry in 30 studies [23, 25, 26, 34, 35, 37, 41, 43, 45, 47, 50, 53, 59, 61, 62, 64, 66, 67, 69–74, 79–81, 83–85], variants of the chair stand test (CST) in 15 studies [25, 30, 32, 34, 41, 45, 50, 54, 55, 59, 67, 73, 80, 83, 84], lower limb torque in seven studies [27, 32, 46, 47, 56, 59, 78] and one repetition maximum (1-RM) in three studies [27, 51, 87]. Physical performance was estimated in 36 studies using the Short Physical Performance Battery (SPPB) in ten studies [25, 30, 32, 34, 39, 45, 52, 56, 70, 80], variants of composite physical performance tests in four studies [27, 28, 51, 88], variants of gait speed tests in 29 studies [23, 25, 29–32, 34, 36, 39, 41, 50, 51, 53–56, 59, 61, 62, 66, 67, 69–72, 79, 80, 83, 84] **and the Timed up and Go (TUG) test in nine studies** [23, 54, 55, 67, 69, 73, 81, 83, 84]. Of 63 included studies, 49 were included in the quantitative analysis.

Quality of studies in the systematic review

Of the 61 studies that included a randomized intervention, 53 were classified as having overall high RoB, seven studies had some concern for RoB and one was at low RoB. The two studies comprising non-randomized interventions had serious RoB [35, 53]. A complete overview of the risk of bias assessment for each subdomain is given in Figures SIA and SIB.

Results of the meta-analysis

Effect of probiotics on sarcopenia and its defining parameters

Eleven studies [63–73, 82] investigated the effect of probiotics on sarcopenia [66, 70, 71] or its defining parameters, involving a total of 1148 persons who completed the intervention period (Table 1). Probiotic supplements included one to eight bacterial strains, which were from the *Bifidobacterium* [63, 66, 69–72], *Streptococcus* [66, 70–72] and *Lactobacillus* [63–73] (note: the *Lactobacillus* genus has recently been reclassified to the genera *Lactobacillus*, *Lactiplantibacillus* and *Lacticasiebacillus* [90], but for this review original GM names were kept) with dosing ranges between $5*10^9$ to $1.5*10^{11}$ colony forming units (CFU) of the probiotic. Probiotics were administered as capsules [66, 67, 70–73], via sachets [63, 69] or as whole foods [64, 68]. Control groups received maltodextrin (without further specification on digestibility) [65, 67], corn starch [63], maltose [69, 72], 'a food item without probiotics' [64, 68], microcrystalline cellulose [73] and 'inactive agents' which were not further specified [66, 70, 71]. Duration of the intervention varied between 3 and 52 weeks. A complete overview on effects of probiotics on sarcopenia outcomes and GM (if available) of interest is given in Table SI.

Of the eleven studies investigating probiotic supplementation, 10 [63, 65–73] were included in the quantitative analysis, comprising 768 persons who completed the interventions, with study durations varying between 3 and 52 weeks. The study by Lei et al. was not included in the quantitative analysis due to lack of data on means and SD or SEM for outcomes of interest [64]. The study by Lee et al. compared a placebo with two intervention groups, one receiving a 'low dose' of probiotics, containing $2 * 10^{10}$ CFU, and the 'high dose' group receiving $6 * 10^{10}$ CFU. Two studies by Karim et al. reported a slight non-significant decrease of sarcopenia incidence in the probiotics group and a slight increase in the placebo group [70, 71].

From the quantitative analysis, a significant effect on muscle strength in favor of probiotics (MD: 1.90; 95% CI [0.965; 2.25]) was reported, although with significant heterogeneity (I^2 = 51.53%; 95% CI [0–91.94]; τ^2 = 0.6143) (Fig. 2A). This suggests that persons with mean age ≥ 50 years who take probiotics improved HGS with on average 1.90 kg as compared to those not taking probiotics. From subgroup analysis, intake of multiple probiotic strains comprising ≥ $1.12*10^{11}$ CFU beneficially impacted HGS. We also found that especially in community-dwelling persons probiotics intake resulted in a significant average HGS gain of 1.71 kg as compared to persons residing in a nursing-home, and if the intervention lasted longer than 12 weeks (Table SII). Univariate meta-regression was applied to identify potential sources of heterogeneity and reported sex as a potential source of heterogeneity (Table SIII). Furthermore, a significantly beneficial effect of probiotics on gait speed was reported (MD: 0.08; 95% CI [0.05; 0.11]) without significant heterogeneity (I^2 = 29.70%, 95% CI [0–98.22], τ^2 < 0.001) (Fig. 2B). This suggests that intake of probiotics improves gait speed on average by 0.08 m/s as compared to placebo consumption. The meta-analysis assessing effect of probiotics on muscle mass, including seven studies [63, 65, 66, 68, 70, 71, 73] did not report significant findings (Figure SII). Sensitivity analyses did not change significance of probiotics' effects on muscle strength, mass or physical performance outcomes (Tables SIV-SVI).

Effect of prebiotics on sarcopenia and its defining parameters

A total of **13** studies [53–62, 79, 84, 86] assessed the effect of prebiotics on sarcopenia or its defining parameters, comprising 820 persons who completed the intervention (Table

Table 1 Characteristics of studies assessing effects of probiotics on sarcopenia and its defining parameters

Author, year, country	Age (mean ± SD)/ age range (years)	(♂/♀), population characteristics, *n* per group	Intervention	Sarcopenia (-defining parameters)
Sharafedtinov 2013, Estonia [68]	**PRO**: 52.0 ± 10.9 **PBO**: 51.7 ± 12.1 [30–69]	*13♂/27♀, hospitalized persons **PRO**: *n* = 25 **PBO**: *n* = 11	3 weeks, 50 g/day **PRO**: cheese with 1.5* 10^{11} CFU *Lactobacillus (*now *Lactiplantibacillus) plantarum* **PBO**: cheese without probiotic	Muscle mass (kg) (BIA)
Lei 2016, China [64]	**PRO**: 64.3 ± 3.7 **PBO**: 65.1 ± 3.7	187♂/194♀, community-dwelling persons **PRO**: *n* = 189 **PBO**: *n* = 192	24 weeks, 2x/day **PRO**: 6*10^9 CFU *Lactobacillus (now Lacticaseibacillus) casei* Shirota **PBO**: skimmed milk without probiotic	HGS (kg)
Nilsson 2018, Sweden [65]	[75–80]	90 community-dwelling women **PRO**: *n* = 45 **PBO**: *n* = 45	52 weeks, 2x/day **PRO**: 5*10^9 CFU *Lactobacillus reuteri* 6475 **PBO**: maltodextrin	Lean mass (kg) (DXA)
Román 2019, Spain [69]	**PRO**: 65.8 ± 3.1 **PBO**: 64.0 ± 2.6	*14♂/22♂, community-dwelling persons **PRO**: *n* = 17 **PBO**: *n* = 18	12 weeks, 2x/day 4.4 g **PRO**: *Streptococcus thermophilus* *Bifidobacterium breve* *Bifidobacterium longum* *Bifidobacterium infantis DSM 24,737* *Lactobacillus paracasei* *Lactobacillus acidophilus* *Lactobacillus delbrueckii subsp bulgaricus* *Lactobacillus plantarum* Total: 5*10^9 CFU **PBO**: maltose + silicon dioxide	HGS (kg) Gait speed (m/s) TUG test time (s)
Lee 2021, Taiwan [67]	[55–85]	25♂/17♀, nursing home residents **PRO**: *n* = 25 **PBO**: *n* = 17	18 weeks, 2x/day **PRO** 6*10^{10} CFU *Lactobacillus plantarum* TWK10 **PBO**: maltodextrin	Lean mass (kg) (DXA) HGS (kg) 30s-CST (times) TUG test time (s) 10 m walk time (s)
Chaiyasut 2022, Thailand [63]	**PRO**: 58.79 ± 1.21 **PBO**: 61.63 ± 0.84	10♂/38♀, community-dwelling persons; **PRO**: *n* = 24 **PBO**: *n* = 24	12 weeks, 1x/day **PRO**: *Lactobacillus paracasei HII01* (2*10^{10} CFU) *Bifidobacterium breve* (2*10^{10} CFU) *Bifidobacterium longum* (1*10^{10} CFU) **PBO**: corn starch	Muscle mass (kg) (assessment tool not clearly stated)
Karim 2022, Pakistan [71]	[58–73]	92 men, outpatients suffering from heart failure **PRO**: *n* = 44 **PBO**: *n* = 48	12 weeks, 1x/day **PRO**: *Bifidobacterium longum* *Bifidobacterium breve* *Lactobacillus delbrueckii subsp bulgaricus* *Streptococcus Thermophilus* total:1.12*10^{11} CFU **PBO**: inactive agent, not further specified	EWGSOP2-defined sarcopenia HGS (kg) ASMI (kg) (BIA) Gait speed (m/s)

Table 1 (continued)

Author, year, country	Age (mean ± SD)/ age range (years)	(♂/♀), population characteristics, *n* per group	Intervention	Sarcopenia (-defining parameters)
Karim 2022, Pakistan [70]	[63–73]	100 older men, outpatients suffering from COPD **PRO**: *n* = 47 **PBO**: *n* = 53	16 weeks, 1x/day **PRO**: *Bifidobacterium longum* *Bifidobacterium breve* *Lactobacillus delbrueckii subsp bulgaricus* *Streptococcus thermophilus*, total $1.12*10^{11}$ CFU **PBO**: inactive agent, not further specified	EWGSOP2-defined sarcopenia HGS (kg) ASMI (kg) (BIA) SPPB Gait speed (m/s)
Qaisar 2024, Pakistan [66]	71.4 ± 3.9	123 men, community-setting not clearly stated **PRO**: *n* = 60 **PBO**: *n* = 63	16 weeks, 1x/day **PRO**: *Bifidobacterium longum* *Streptococcus thermophilus* *Lactobacillus delbrueckii subsp. Bulgaricus* Total $1.12*10^{11}$ CFU **PBO**: inactive agents	EWGSOP2-defined sarcopenia HGS (kg) SMI (kg/m^2) (BIA) Gait speed (m/s)
Karim 2024, Pakistan [72]	[64–75]	40♂/95♀, community-dwelling persons suffering from osteoarthritis **PRO**: *n* = 65 **PBO**: *n* = 71	12 weeks, 1x/day **PRO**: *Streptococcus thermophilus* *Bifidobacterium longum* *Bifidobacterium breve* *Lactobacillus delbrueckii bulgaricus* **PBO**: inactive agent, not further specified	HGS (kg) Gait speed (m/s)
Lee 2025, Taiwan [73]	69.3 ± 3.0	23♂/44♀ **PRO**: *n* = 33 **PBO**: *n* = 33	12 weeks, 2x/day **PRO**: *Lactobacillus paracasei 23* Total: 10^{10} CFU per capsule **PBO**: microcrystalline cellulose	Muscle mass (kg) HGS (kg) 30 s -CST TUG (s)

2). Prebiotics investigated in included studies were established ones: inulin alone [57, 60–62], inulin + fructo-oligosaccharide (FOS) [62, 79, 84], and other, so-called candidate compounds, such as curcumin [54–56, 59, 86] and high amylose maize resistant starch [58]. Placebo compounds included maltodextrin (without specification of digestibility) [54, 59, 79, 84, 86], rapidly digestible amylopectin [58], microcrystalline cellulose [55, 56], food grade starch [61], standard management [53] or was not further specified [60]. A complete overview on effects of prebiotics on sarcopenia outcomes and GM (if available) of interest is given in Table SVII.

Of these 13 studies, nine [53–55, 59, 60, 62, 79, 84, 86] were included in the quantitative analysis, comprising a total of **670** persons who completed the intervention. Duration of the prebiotic intervention varied between 8 and 24 weeks. No studies reported upon effect of prebiotics on sarcopenia incidence. No significant effects of prebiotics on muscle strength (SMD: 0.08; 95% CI [-0.08; 0.24], seven studies [53–55, 59, 62, 79, 84] (Figure SIII)), muscle mass (MD: -0.19; 95% CI [-0.76; 0.38], five studies [59, 60, 62, 84, 86], Figure SIV) or physical performance (SMD: − 0.03; 95% CI [-0.191; 0.125], seven studies [53–55, 59, 62, 79, 84] Figure SV) were reported. Subgroup analyses based on age, prebiotic type, study duration and community setting did not reveal significant results (Table SVIII - SX). Sensitivity analyses did not alter the effects of prebiotics on muscle strength, muscle mass or physical performance (Table SXI – SXIII).

Effect of synbiotics on sarcopenia and its defining parameters

Only the study by Neto et al. investigated the effect of synbiotics (fructo-oligsaccharides (FOS) and *Lactobacillus paracasei*, *Lactobacillus rhamnosus*, *Lactobacillus acidophilus and Bifidobacterium lactis*) [74] on muscle strength and anthropometric measures of muscle mass, being TSF and CC in 17 frail older adults >60 years during a 12-week intervention (Table SXIV). Contrary to the expectations, TSF and CC decreased in the synbiotics group and increased in the placebo group, supplemented with maltodextrin, but both changes were not significant. Hand grip strength was non-significantly increased after the intervention in both the placebo and synbiotics group, with a higher effect in the placebo group.

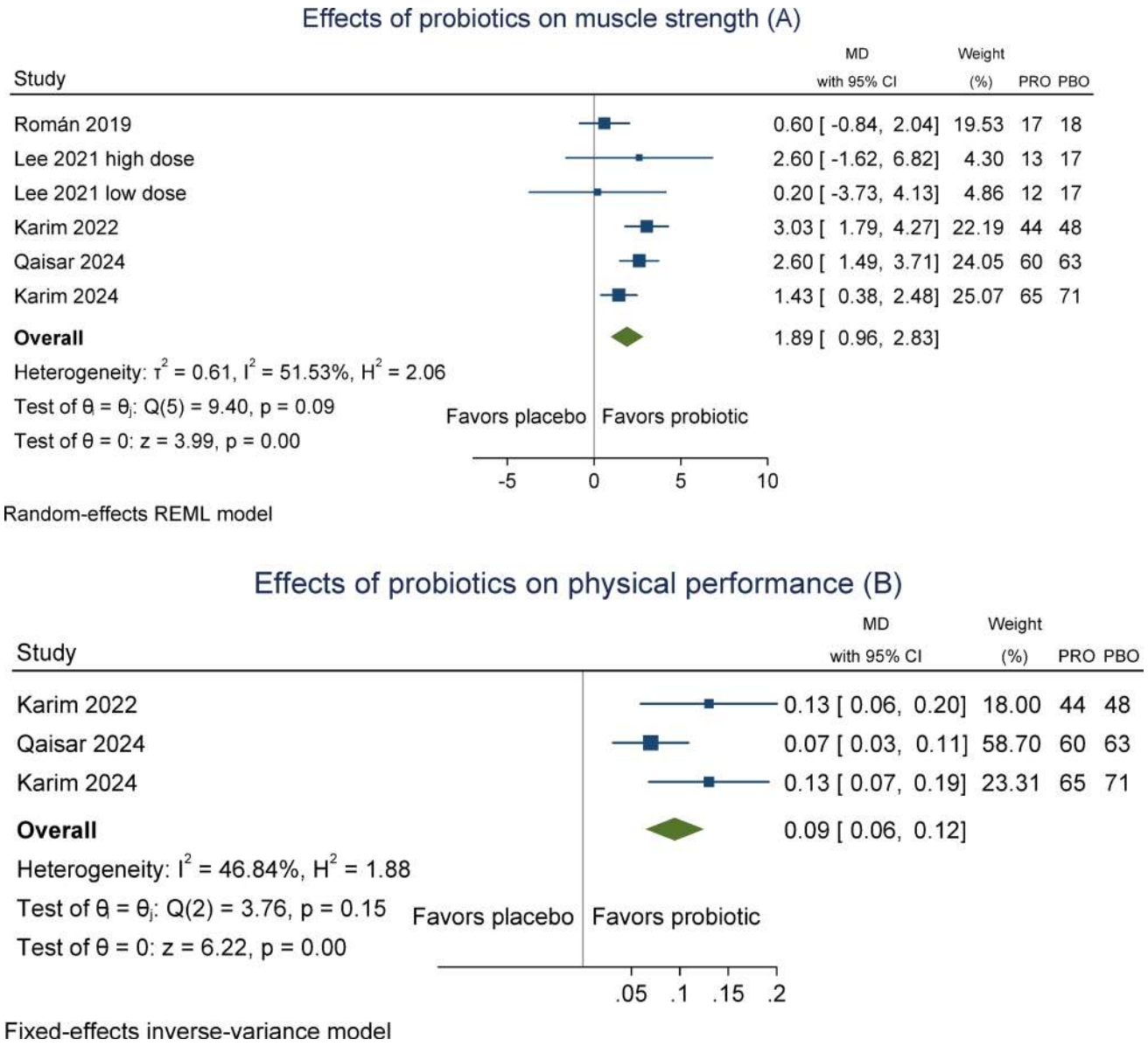

Fig. 2 Effect of probiotics on muscle strength **(A)** and physical performance **(B)** in persons with mean age≥50 years; Mean Difference (MD); Probiotics (PRO); Placebo (PBO)

Effect of diet on sarcopenia and its defining parameters.

This systematic review and meta-analysis also included intervention studies on diet, often overlooked when considering GM-altering interventions in sarcopenia research. From 38 studies (Table 3) assessing the effect of diet on sarcopenia or its defining parameters, we categorized diets into the following types: diets restricting energy intake (14 studies) [27–30, 32, 36, 37, 39, 44, 50–52, 87, 88], fiber-enriched diets [23, 45, 75, 85] (**four studies**), diets increasing energy intake [35, 38, 42] (three studies), diets high in protein intake [25, 26, 34, 41, 46, 49, 78, 80, 81, 83, 89] (eleven studies), diets increasing intake of fermented foods [24, 47, 48] (three studies), Mediterranean diet [43], a vegan diet [40] and a study assessing Dietary Approaches to Stop Hypertension (DASH) [31]. A complete overview on the characteristics of these studies on diet is given in Table SXV.

Effect of energy-restricted diets on sarcopenia and its defining parameters

A total of 14 studies [27–30, 32, 36, 37, 39, 44, 50–52, 87, 88] investigating energy-restricted diets comprising 768 persons were included. Of these 14 studies, all but one [32] were eligible for inclusion in the meta-analysis, comprising 727 persons who completed the intervention. One of these studies compared two energy-restricted diets with a

Table 2 Characteristics of studies assessing effects of established prebiotics (inulin and oligofructose) and candidate prebiotics on sarcopenia and defining parameters

Author, year, country	Age (mean ± SD)/ age range (years)	♂/♀, population characteristics, *N* per group	Intervention	Sarcopenia(-defining parameters)
Buigues 2016, Spain [79]	73.8 ± 1.6 [66–90]	15♂/35♀, hospitalized persons **PRE**: *n* = 28 **PBO**: *n* = 22	13 weeks, 1x/day **PRE**: 3375 mg inulin + 3488 mg FOS **PBO**: maltodextrin	HGS (kg) Walk time (s)
Franceschi 2016, Italy [53]	**PRE**: 74 ± 1 **CON**: 72 ± 2	34♂/30♀, community-dwelling persons **PRE**: *n* = 31 **PBO**: *n* = 33	12 weeks, 1x/day **PRE**: curcumin **PBO**: standard management	HGS (kg) Walk distance (m) Number of stairs climbed
Haroyan 2018, Armenia [54]	56.2 [40–77]	*9♂/125♀, community-dwelling persons with osteoarthritis **PRE**: *n* = 66 **PBO**: *n* = 67	12 weeks, 3x/day 500 mg capsule **PRE**: curcuminoids **PBO**: maltodextrin	30-s CST (times) TUG test (s) Stair climb test 40 m Fast Paced Walk Speed test (m/s)
Peterson 2018, Unites States [58]	**PRE**: 54 ± 10 **PBO**: 55 ± 10 [35–75]	20♂/39♀, persons with prediabetes community-setting not clearly stated **PRE**: *n* = 29 **PBO**: *n* = 30	12 weeks, 45 g/day **PRE**: high amylose maize resistant starch **PBO**: rapidly digestible amylopectin	Lean mass (kg) (DXA)
Santos-Parker 2018, United States [59]	**PRE**: 63 ± 2 **PBO**: 61 ± 2 [45–74]	21♂/18♀, community-dwelling, postmenopausal persons **PRE**: *n* = 20 **PBO**: *n* = 19	12 weeks, 1x/day **PRE**: 400 mg curcumin **PBO**: maltodextrin	HGS (kg) 5-time CST (s) Knee flexion & extension torque Lean mass (kg) (DXA) 6-MWT (m)
Thota 2020, Australia [60]	52.3 ± 1.9	12♂/17♀, community-dwelling persons **PRE**: *n* = 14 **PBO**: *n* = 15	12 weeks, 2x/day with **PRE**: 180 mg curcuminoids **PBO**: not further specified	Muscle mass (kg) (BIA)
Varma 2021, India [61]	69.8 ± 5	13♂/17♀, community-dwelling older adults **PRE**: *n* = 15 **PBO**: *n* = 15	12 weeks of 500 mg/day **PRE**: curcuminoids **PBO**: food-grade starch	HGS (kg) Walk test (s) Walk test (m)
Lopresti 2022, Australia [55]	**PRE**: 59.59 ± 0.92 **PBO**: 57.92 ± 0.88	*51♂/50♀, community-dwelling persons with osteoarthritis **PRE**: *n* = 50 **PBO**: *n* = 44	8 weeks, 2x/day 500 mg capsule **PRE**: curcuminoids **PBO**: crystalline cellulose	30s CST (times) TUG test (s) 6-MWT (m) 40 m Fast Paced Test (s)
Nachit 2021, Belgium [57]	50 ± 11 [18–65]	*24♂/24♀, community-welling persons with obesity and liver steatosis **PRE**: *n* = 16 **PBO**: *n* = 19	12 weeks, 16 g/day **PRE**: inulin **PBO**: maltodextrin	Sarcopenia (defined as SMI < 41 cm/m^2 at L3 in ♀, and SMI < 53 cm/m^2 at L3 in ♂). SMI (cm/m^2) (BIA and CT)
Mankowski 2023, United States [56]	**PRE**: 79.4 ± 10.1 **PBO**: 76.2 ± 5.6 [65–90]	8♂/9♀, moderately functioning, sedentary older adults suffering from chronic inflammation **PRE**: *n* = 9 **PBO**: *n* = 8	12 weeks, 2x/day 500 mg **PRE**: curcumin **PLA**: microcrystalline cellulose	Knee-extension & flexion torque (Nm) SPPB 400 m walk test (m/s)

Table 2 (continued)

Author, year, country	Age (mean ± SD)/ age range (years)	♂/♀, population characteristics, *N* per group	Intervention	Sarcopenia(-defining parameters)
Yang 2024, China [62]	Prefrail: **PBO**: 73.00 [68.75; 80.25] **PRE**: 73.00 [71.00; 77.00] Frail: **PBO**: 77.00 [73.75; 81.00] **PRE**: 77.00 [73.00 ; 81.50]	*79♂/121♀, community-dwelling persons **PRE**: *n* = 91 **PBO**: *n* = 93	12 weeks 1x/day **PRE**: inulin & oligofructose mixture **PBO**: maltodextrin	HGS (kg) Muscle mass (kg) (BIA) Walking time (s)
Fortuna 2024, Canada [84]	**PRE**: 59.2 ± 9.7 **PBO**: 59.1 ± 11.5	5♂/49♀, persons suffering from knee osteoarthritis and overweight **PRE**: *n* = 31 **PBO**: *n* = 23	24 weeks, 16 g/day **PRE**: inulin enriched with oligofructose **PBO**: maltodextrin	HGS (kg) 30 s CST Muscle mass (kg) 40 m fast paced walking test 6 min walk test
*Juesas 2025, Spain [86]	68.2 ± 4.6	**PRE**: *n* = 15 **PBO**: *n* = 17	16 weeks, 2 × 250 mg/day **PRE**: curcumin **PBO**: maltodextrin	Muscle mass (kg)

conventional diet. More specifically, in the 'standard protein' energy-restricted diet, 15% of total energy intake was derived from proteins, while in the 'high-protein' energy-restricted, 30% of total energy intake was derived from proteins [36]. Only Mason et al. reported upon a non-significantly increased sarcopenia incidence in both diet and control groups at the end of the intervention [44].

Energy-restricted diets had no significant effects on muscle strength (SMD: -0.02; 95% CI [-0.25; 0.22]; five studies [30, 37, 50, 51, 87] (Figure SVI)) and physical performance (SMD: 0.12; 95% CI [-0.076; 0.316], 9 studies [28–30, 36, 39, 50–52, 88] (Figures SVIIA, B)). Although the overall effect of the intervention on muscle mass was non-significant (SMD: 0.02; 95%CI [-0.17; 0.190]; 7 studies [27, 29, 30, 36, 44, 51, 52] (Figure SVIII), subgroup analyses based on age and study duration revealed a significant effect of energy-restricted diets on muscle mass in those with mean age younger than 60 years and if the study lasted 12 weeks. This equaled an average gain of 2.94 kg in lean mass in those with mean age < 60 years and adhering to 12 weeks of energy-restricted diets as compared to those with mean age ≥ 60 years and adhering for >12 weeks to the diet. Given that this finding is based on a single study [36], these results should be interpreted with caution and should not be generalized to the broader population. No other significant findings were reported from subgroup analyses (Table SXVI – SXVIII). Sensitivity analyses did not alter the effects of energy-restricted diets on the sarcopenia-defining parameters (Table SXVIV – SXXI). Significant publication bias for effects of energy-restricted diets on physical performance was detected (Egger's β: 1.96, p = 0.017) (Figure SIX).

Effect of fiber-enriched diets on sarcopenia and its defining parameters

Four studies [23, 33, 45, 85], all included in the quantitative analysis, assessed the effect of fiber-enriched diets on defining parameters of sarcopenia, including 289 persons who completed the intervention. These interventions consisted of increasing intake of oats, vegetables and citrus and dried fruits. Persons consuming a fiber-enriched diet improved HGS, reflective of muscle strength, with 1.25 kg as compared to those not consuming a fiber-enriched diet (MD: 1.25; 95%CI [0.55; 1.95], Figure SX), without significant heterogeneity (**I^2** : 0.00%; 95% CI [0; 99.1];τ^2 **=/)**. Systematically omitting the studies from the analysis did not influence significance of the results (Table SXXII). No significant effect of fiber-enriched diets on muscle mass (SMD: -0.09; 95% CI [-0.44; 0.27], two studies [75, 85] Figure SXI) or physical performance was reported (SMD: 0.06 [-0.26; 0.38], two studies [23, 45]) (Figure SXII). Effects on muscle mass were unaltered upon sensitivity analyses

Table 3 Characteristics of studies assessing effects of GM-altering dietary interventions on sarcopenia and its defining parameters

Author, year, country	Age (mean ± SD)/ age range (years),	♂/♀, population characteristics, *N*	Intervention	Sarcopenia (-defining parameters)
Energy-restricted diets (*n* = 14)				
Evangelista 2009, United States [36]	58 ± 9.7	11♂/3♀, community-dwelling persons **DIET: High-protein**: *n* = 5 **Standard protein**: *n* = 5 **CON**: *n* = 4	12 weeks, energy-restricted, High-protein diet (30%) Standard protein diet (15%) CON: conventional diet	Lean mass (kg) (DXA) 6-MWT (ft)
Villareal 2011, United States [51]	DIET: 70 ± 4 CON: 69 ± 4	18♂/35♀, community-dwelling persons **DIET**: *n* = 26 **CON**: *n* = 27	52 weeks of **DIET**: high protein (, calorie-restrictive diet **CON**: habitual diet	1-RM (lb) Lean mass (kg) (DXA) thigh muscle volume (cm^3) (MRI) mPP test Gait speed (m/min)
Mason 2013, United States [44]	SAR: 58.0 ± 5.0 CON: 57.9 ± 5.0 [50–75]	183 women **DIET**: *n* = 103 **CON**: *n* = 80	52 weeks, **DIET**: <30% from energy intake from fat, aiming to reduce 10% of body weight in 6 months **CON**: habitual diet	Sarcopenia (defined as SMI < 5.67 kg/m^2) Lean mass (DXA) ALM (DXA) SMI (DXA)
Armamento-Villareal 2014, United States [27]	DIET: 70 ± 4 CON: 69 ± 4	18♂/35♀, community-dwelling persons **DIET**: *n* = 26 **CON**: *n* = 27	52 weeks of **DIET**: calorie restriction of 500–700 calories deficit/day **CON**: habitual diet	Knee extensor and flexor strength, 1-RM, thigh muscle volume (MRI)
Armamento-Villareal 2016, United States [28]	69.3 ± 4.1	18♂; community-dwelling men **DIET**: *n* = 9 **CON**: *n* = 9	52 weeks of **DIET**: calorie restriction of 500–700 calories deficit/day **CON**: habitual diet	mPP test
Horie 2016, Brazil [39]	68.1 ± 4.9	77♂/3♀, community-setting not clearly stated **DIET**: *n* = 38 **CON**: *n* = 37	52 weeks of **DIET**: calorie restriction **CON**: conventional medical care	SPPB 4 m walk test (s)
Bales 2017, United States [30]	60.0 ± 8.2	42♀, community-dwelling women **DIET**: *n* = 29 **CON**: *n* = 13	26 weeks of **DIET**: calorie-restriction (500 kcal in deficit) + high protein (1.2 g/kg/day) **CON**: calorie-restriction only	30s-CST Lean mass (kg) (air displacement plethysmography) 6-MWT (m) SPPB
Gonzalez 2017, Spain [37]	**DIET**: 68.47 ± 12.65 **CON**: 70.45 ± 12.35	*35♂/53♀; community-dwelling persons suffering from heart failure **DIET**: *n* = 38 **CON**: *n* = 35	8 weeks of **DIET**: low in carbohydrates **CON**: standard diet	HGS (kg)
Verreijen 2017, The Netherlands [50]	62.4 ± 5.4	14♂/29♀, community-dwelling middle aged and older adults suffering from overweight or obesity **DIET**: *n* = 21 **CON**: *n* = 22	10 weeks of **DIET**: hypocaloric of 600 kcal energy deficit + high protein (1.3 g/kg/day) **CON**: hypocaloric of 600 kcal energy deficit	HGS (kg) 5-time CST (s) 400 m gait speed (m/s) 4 m gait speed (m/s)

Table 3 (continued)

Author, year, country	Age (mean ± SD)/ age range (years),	♂/♀, population characteristics, *N*	Intervention	Sarcopenia (-defining parameters)
Beavers 2019, United States [29]	70.3 ± 3.7	*25♂/71♀, community-dwelling persons with obesity **DIET**: *n* = 43 **CON**: *n* = 39	24 weeks, 4 meals/day DIET: weight loss CON: weight maintenance	Lean mass (kg) (DXA) 400 m walking test (m/s)
Porter 2019, United States [52]	68.3 ± 5.6	8♂/31♀, with physical frailty and obesity, community-setting not clearly stated **DIET**: *n* = 25 **CON**: *n* = 14	24 weeks of **DIET**: calorie-restriction of 500 kcal deficit/day + high protein (3x/day) **CON**: calorie-restriction 500 kcal deficit/day	Lean mass (kg) (air displacement plethysmography) SPPB
Brennan 2022, United States [32]	68 ± 4.5 [60–80]	14♂/27♀, community-dwelling persons with prevalence of obesity and type 2 diabetes **DIET**: *n* = 21 **CON**: *n* = 20	24 weeks of **DIET**: calorie-restriction, low-fat diet **CON**: health education	Lower limb peak torque CST (s) lean mass (kg) (DXA), SPPB 4 m walk test (s)
Koutoukidis 2025, United Kingdom [88]	58 ± 7.5	9♂/8♀°, with obesity and compensated liver cirrhosis **DIET**: *n* = 5 **CON**: *n* = 10	16 weeks of calorie-restriction **DIET**: four meal replacements per day providing a total of 880 kcal/day **CON**: standard care	Composite physical function test
Lynbaek 2025, Denmark [87]	**DIET**: 55.9 ± 10.0 **CON**: 59.1 ± 9.2	27♂/14♀, with type II diabetes **DIET**: *n* = 21 **CON**: *n* = 20	16 weeks of calorie-restriction **DIET**: 25–30˜% caloric restriction of daily intake. **CON**: standard care	Lean mass (kg) 1-RM maximal knee extension (kg)
Fiber (whole foods)-enriched diets (*n* = 4)				
Neville 2013, United Kingdom [45]	DIET: 70.9 ± 5.0 CON: 71.1 ± 5.0 [65–85]	28♂/52♀, community-dwelling persons **DIET**: *n* = 39 **CON**: *n* = 41	16 weeks, at least 5 portions/day **DIET**: fruit and vegetable enriched diet **CON**: habitual diet, with maximum intake of 2 portions of fruits/vegetables	HGS (kg) 5-time CST (s) SPPB
Ahles 2022, The Netherlands [23]	DIET & CON: 66 ± 1 DIET & CON: [60–78]	9♂/27♀; community-dwelling persons **DIET**: *n* = 36 **CON**: *n* = 36	4 weeks, 2x/day **DIET**: concentrate of citrus (total of 500 mg) and pomegranate (total of 200 mg) **PLA**: maltodextrin	HGS (kg) TUG-test (s) 6-MWT (m)
Ceglia 2022 United States [75]	69 ± 8	*45♂/42♀, community-dwelling persons **DIET**: *n* = 37 **CON**: *n* = 46	24 weeks of: **DIET**: 100 g mixture of dried apricots, pineapple, raisins and figs, across 4 servings/day **CON**: habitual diet	Fat-to-lean mass ratio (DXA)
Norazman 2025, Malaysia [85]	61 [36–81]	28♂/26♀, persons with metabolic syndrome **DIET**: *n* = 27 **CON**: *n* = 27	12 weeks of **DIET**: intake of 60 g oats/day **CON**: habitual diet	Muscle mass (%) CC (cm) HGS
Energy-increasing diets (*n* = 3)				

Table 3 (continued)

Author, year, country	Age (mean ± SD)/ age range (years),	♂/♀, population characteristics, *N*	Intervention	Sarcopenia (-defining parameters)
Hays 2004, United States [38]	66 ± 1 [55–80 years]	10♂/13♀; community-dwelling persons **DIET**: *n* = 11 **CON**: *n* = 12	12 weeks, 3x/day **DIET**: low-fat high carbohydrate diet, ad libitum **CON**: isocaloric diet	Lean mass (cm^2) (CT)
Manguso 2004, Italy [42]	DIET: 60 ± 9 CON: 60 ± 7	52♂/38♀; outpatients **DIET**: *n* = 45 **CON**: *n* = 45	3 months: **DIET**: supplying 30–40 kcal/kg ideal body weight (16% protein, 28–30% lipids, 55% carbohydrates) **CON**: spontaneous intake	MAMC (cm) TSF (mm)
Collins 2017, Australia [35] High-protein diets (*n* = 11)	83 [75–87]	36♂/35♀; hospitalized persons: **DIET**: *n* = 32 **CON**: *n* = 39	2 weeks of DIET: increased energy intake CON: standard energy intake	HGS (kg)
Alemán-Mateo 2012, Mexico [26]	76 ± 5.4	17♂/23♀ **DIET**: *n* = 20 **CON**: *n* = 20	12 weeks, 3x/day 70 g **DIET**: supplemented with ricotta cheese **CON**: habitual diet	Sarcopenia based on ALM/ $height^2$, adjusted for height and weight (residuals method) HGS (kg) ALM (kg) (DXA)
Alemán-Mateo 2014, Mexico [25]	70.2 ± 7.0	49♂/49♀, community-dwelling persons **DIET**: *n* = 49 **CON**: *n* = 49	12 weeks, 3x/day 70 g **DIET**: supplemented with ricotta cheese **CON**: habitual diet	Sarcopenia: ASMM of 2 SD < ASMM of young population. HGS, 5-time CST, ALM (DXA), SMI, SPPB, gait speed, SCPT
Wright 2018, United States [49]	70 ± 5	12♂/10♀, community-dwelling persons with overweight or obesity **DIET**: *n* = 12 **CON**: *n* = 10	12 weeks, spread over 3 meals: **DIET**: egg-enriched (1.4 g protein/kg/day) **CON**: isocaloric non-egg item	Thigh muscle volume (MRI) ALM (DXA)
Kruger 2023, New Zealand [41]	**DIET & CON**: : 70.1 ± 3.51 **DIET & CON**: [65–80]	*103♀; community-dwelling women **DIET**: *n* = 47 **CON**: *n* = 56	11 weeks, 200 ml/day **DIET**: deer milk **CON**: oral nutritional supplement	HGS (kg) 30s CST 40 m walk test (s) muscle mass (kg) (BIA)
Chen 2024, China [34]	71.57 ± 5.08 [60–80]	68♀, community -dwelling women **DIET**: *n* = 47 **CON**: *n* = 21	12 weeks, 1x/day **DIET**: supplemented 4 slices of cheese with 9 g protein (LP) or with 12 gram protein (HP) **CON**: habitual diet	Sarcopenia defined according to the AWGS criteria HGS (kg) 5-time CST (s) CC (cm) SMI (kg) (BIA) SPPB gait speed (m/s)

Table 3 (continued)

Author, year, country	Age (mean ± SD)/ age range (years),	♂/♀, population characteristics, *N*	Intervention	Sarcopenia (-defining parameters)
Schalla 2024, Germany [46]	**DIET**: 57.83 ± 7.74 **CON**: 58.21 ± 6.44 [40–65]	*10♂/16♀; healthy, (post-menopausal women), community-dwelling adults. **DIET**: *n* = 12 **CON**: *n* =14	8 weeks of **DIET**: high protein, aiming to reach 2.3 g/kg/day **CON**: habitual diet	Upper body strength (kg) Lower body strength (kg) muscle mass (kg) (BIA)
Uchida 2024, Japan [78]	[59–79]	43♀, community-dwelling women **DIET**: *n* = 22 **CON**: *n* = 21	12 weeks of **DIET**: 110 g boiled chicken 3 days/week **CON**: habitual diet	Lean mass (kg) Leg maximal voluntary contraction (Nm)
Yuan 2024, China [80]	84.9 ± 7.0	32♂/52♀, older persons living in a long-term care facility **DIET**: *n* = 43 **CON**: *n* = 41	12 weeks of **DIET**: 3 days/week soy beans reaching up to 50 g/day of soy protein **CON**: habitual diet	ASM (kg), SMI (kg/m^2), CC (cm) HGS (kg) 5-time CST (s) SPPB 6-meter walk test (s)
Fujie 2025, Japan [89]	**DIET**: 67.0 ± 5.3 **CON**: 67.6 ± 6.4	43♀, community-dwelling post-menopausal women **DIET**: *n* = 22 **CON**: *n* = 21	12 weeks of **DIET**: 164 g of chicken meat 3 days/week **CON**: habitual diet	Quadriceps CSA Thickness of the anterior and posterior thigh (cm)
Struszczak 2025, United Kingdom [81]	82 ± 7	17♂/39 ♀, persons who were malnourished or at risk thereof **DIET**: *n* = 24 **CON**: *n* = 26	12 weeks of **DIET**: 1x/day high-protein meals **CON**: habitual diet	Mid-thigh volume (cm^3) CC (cm) MAC (cm) HGS (kg) TUG (s)
Argyropoulou 2025, Greece [83]	[50–75]	13♂/13♀, persons with type II diabetes **DIET**: *n* = 13 **CON**: *n* = 13	12 weeks of **DIET**: increased protein intake via whole foods in the Mediterranean diet, reaching 1.2–1.5 g/kg **CON**: habitual diet	ALM (kg), SMI (kg/m^2) HGS (kg) 5-time CST (s) TUG (s) Gait speed (m/s)
Fermented foods-enriched diets (*n* = 3)				
Pan 2020, China [48]	**DIET**: 53.60 ± 6.77 **CON**: 57.60 ± 6.10 [30–65]	15♂/16♀, outpatients with metabolic syndrome **DIET**: *n* = 15 **CON**: *n* = 16	8 weeks, 75 g/day for ♀ and 90 g/day for ♂ of **DIET**: Lactobacillus fermented barkley wheat noodles **CON**: whole wheat noodles	Muscle mass (BIA)
Rheu 2022, South-Korea [47]	PRE: 72.1 PLA: 73.6 [65–80]	46 women **DIET**: *n* = 23 **CON**: *n* = 23	12 weeks, 1000 mg/day PRE: fermented sarco oyster extract **DIET**: dextrin	Hand grip force knee extension & flexion torque ASM/height^2 (BIA)

Table 3 (continued)

Author, year, country	Age (mean ± SD)/ age range (years),	♂/♀, population characteristics, *N*	Intervention	Sarcopenia (-defining parameters)
Abshirini 2023, New Zealand [24]	DIET: 64.2 ± 5.1 years CON: 62.9 ± 5.4 yers; [55–75 year]	*49♀; post-menopausal women with overweight and obesity **DIET**: *n* = 25 **CON**: *n* = 23	12 weeks, 3x/day **DIET**: 500 mg green-lipped mussel **CON**: dried sunflower seed protein	ALM (DXA) Sarcopenia defined based on ALM, not further specified
Low-fat vegan diet (*n* = 1)				
Kahleova 2020, United States[40]	54 ± 11.6	30♂/193♀ ; overweight, community-dwelling persons **DIET**: *n* = 117 **CON**: *n* = 106	16 weeks of **DIET**: low-fat vegan diet CON: habitual diet	Lean mass (DXA)
Mediterranean diet (*n* = 1)				
Mascaró 2022, Spain [43]	**DIET**: 51.9 ± 7.6 **CON**: 53.2 ± 8.6 [40–60]	*63♂/40♀, community-dwelling persons, suffering from NAFLD & metabolic syndrome. **DIET**: *n* = 44 **CON**: *n* = 41	24 weeks of **DIET**: mediterranean, high meal frequency diet **CON**: No intervention	HGS
DASH (*n* = 1)				
Blumenthal 2020, United States [31]	DIET: 66.0 ± 7.1 CON: 64.7 ± 6.6	27♂/52♀, cognitively impaired persons & cardiovascular comorbidity, community-setting not clearly stated. **DIET**: *n* = 41 **CON**: *n* = 38	26 weeks of **DIET**: DASH **CON**: Health Education	6-MWT (m)

(Table SXXIII), whereas upon omission of Neville et al., the effect on physical performance was significant if the outcome was assessed using the TUG test (Table SXXIVA-B). No study investigated the effect of fiber-enriched diet on the construct of sarcopenia.

Effect of energy-enriched diets on sarcopenia and its defining parameters

Three studies [35, 38, 42] assessed diets aiming to increase total energy intake, comprising 181 persons, but none could be included in the quantitative analysis due to incomplete reporting of (data to calculate) means and SD at baseline and end of interventions for the outcomes of interest. Two studies assessed effects on estimates of **muscle mass**, but reported conflicting findings [38, 42]. More specifically, the study by Hays et al. reported a non-significant improvement in lean mass in the control group, and a non-significant decrease in the intervention group [38]. On the contrary, Manguso et al. reported a significant increase in Mid-UpperArm Muscle Circumference in the intervention group as compared to the control group [42]. The study by Collins et al. in hospitalized older persons found that HGS increased non-significantly in both the intervention and control groups after a 2 week intervention (high-energy vs. standard in-hospital meals) [35]. No studies investigated the effect of energy-enriched diet on the sarcopenia construct.

Effect of high-protein diets on sarcopenia and its defining parameters

Of eleven studies assessing high-protein diets [25, 26, 34, 41, 46, 49, 78, 80, 81, 83, 89], all but one [81] were eligible for quantitative analysis, including 592 persons, with intervention durations ranging from 8 to 12 weeks. One of these studies assessed effects of two dosages of protein intake compared to a habitual diet: in these studies, the 'original cheese' group consumed 9.0 g protein in a 66.4 g portion of cheese, whereas the 'golden cheese' group consumed a 67.4 g portion of cheese comprising 12.7 g of protein [34].

Overall, the meta-analysis showed no significant effects of high-protein diets upper limb muscle strength (SMD: 0.08; 95% CI [-0.10; 0.27], seven studies [25, 26, 34, 41, 46, 80, 83]), lower limb muscle strength (SMD: 0.01; 95% CI [-0.17; 0.19], seven studies [25, 34, 41, 46, 78, 80, 83] or physical performance (SMD: 0.05; 95% CI [-0.15; 0.25]) Figures SXIII - SXV). Although high-protein diets did not show an overall significant effect on muscle mass (SMD:0.15 [-0.01; 0.32]; ten studies [25, 26, 34, 41, 46, 49, 78, 80, 83, 89]), subgroup analyses revealed that high-protein diets improved muscle mass in women (SMD: 0.24, 95% CI [0.004; 0.482]) and if the diet lasted at least 12 weeks (SMD: 0.191; 95% CI [0.003; 0.378] Table SXXV). This equals an average gain of 3.21 kg lean mass, a 0.023 kg/m^2 gain in SMI and a 2.98% gain in quadriceps cross-sectional area (CSA) in women consuming a high-protein diet as compared to women not consuming a high-protein diet. Consuming a high-protein diet for minimum 12 weeks equaled a mean gain of 3.02 kg lean mass, 0.43 kg/m^2 SMI and 2.34% in quadriceps CSA as compared to those consuming the diet for less than 12 weeks. No other significant findings of high-protein diets on muscle strength or physical performance were reported based on subgroup analyses according to sex, age, study duration, protein source or community-setting (data not shown). Sensitivity analyses did not alter the effect of high-protein diets on upper or lower limb muscle strength or physical performance, but altered significance of the effect on muscle mass upon omitting Alemán-Mateo et al. [25] (Table SXXVI – SXXVIIIA, B). No publication bias for effect of high-protein diet on muscle mass was detected (Egger's β: 0.53; $p = 0.197$, Figure SXVI). Of three studies reporting on sarcopenia as a construct [25, 26, 34], none reported upon the effect of the intervention on sarcopenia incidence.

Effect of fermented foods-enriched diets on sarcopenia and its defining parameters

Three studies [24, 47, 48] were found reporting on the effects of fermented foods on sarcopenia-defining parameters, and all three were included in the quantitative analysis for muscle mass, including 125 persons who completed the intervention. Total intervention duration varied between 10 and 12 weeks. No significant effect of these foods was found on muscle mass (SMD: -0.01; 95% CI [-0.36; 0.34]; Figure SXVII) and these results were not affected by sensitivity analyses (Table SXXVIV). The study by Rheu et al. additionally assessed the effect of consumption of Sarco-fermented oysters on HGS, and found that HGS significantly increased in both groups, but the change at the end of the intervention was significantly higher in the intervention group [47]. Only Abshirini et al. reported sarcopenia prevalence, but no statement was made of effect of a fermented foods intake on sarcopenia incidence.

Effect of low-fat vegan, mediterranean and DASH on sarcopenia-defining parameters

In the qualitative analysis, three studies were included assessing the effect of vegan [40], Mediterranean [43] and DASH [31] diets on sarcopenia-defining parameters. More specifically, the study by Kahleova et al. reported on effects of a 16-weeks low-fat vegan diet on muscle mass, and found that in both the intervention and control groups muscle mass

was significantly decreased at the end of the intervention, with a significant time x group interaction ($p < 0.001$). This means that the changes in muscle mass over time are different for both groups [40]. The study by Mascaró et al. assessed the effects of following Mediterranean diet for 24 weeks on HGS in community-dwelling older adults with metabolic syndrome, and somewhat unexpectedly found that in the intervention group, HGS decreased non-significantly, whereas in the controls, HGS significantly increased at the end of the intervention [43]. Finally, the study by Blumenthal et al. investigated whether or not in cognitively impaired persons with cardiovascular comorbidity a 26-week DASH diet could improve physical performance [31]. This study reported an improved 6-minute walking test over time, regardless of the dietary intervention.

Discussion

This systematic review and meta-analysis was the first to investigate the effects of host and GM-altering interventions, including diet, pre-, pro- or synbiotics as mono-interventions on sarcopenia and its defining parameters in persons with mean age ≥ 50 years. Probiotics resulted in muscle strength and gait speed gains of on average 1.90 kg and 0.08 m/s, respectively as compared to placebo. The significant positive effect of probiotic supplementation on muscle strength and physical performance, aligns with prior meta-analyses [15, 91], but absence of effects on muscle mass contributed to inconsistent findings from prior meta-analyses [91–93]. This discrepancy in findings may be due to those meta-analyses including studies that combined probiotics with additional interventions (i.e. resistance training, leucine supplements). This may have potentially amplified anabolic response to what probiotics alone could achieve. To avoid such potential confounding of the true effects, we assessed probiotics as single intervention. Additionally, prior reviews also included populations with mean age < 50 years, who may respond differently to probiotics as compared to those ≥ 50 years. We found a significant effect on muscle strength if multiple probiotic strains were supplemented as compared to single strains. Multiple strains may increase distinct and possibly complementary effects and ability to survive harsh conditions [94]. We also found that doses of ≥ $1.12 * 10^{11}$ CFU significantly improved HGS, as hypothesized, since these doses are considered high [95]. The finding that probiotics improve HGS with interventions >12 weeks, aligns with prior research, and is due to that reaching GM stability and immunomodulatory changes, through which probiotics exert effects, requires long-term exposure [96]. The significant effect of probiotics on muscle strength in community-dwelling persons, but not in nursing-home residents may be explained by increased prevalence of polypharmacy, antibiotics use and comorbidity, all potentially diminishing probiotics effects [97].

We did not report an effect of prebiotics on sarcopenia or any of its defining parameters, a finding somewhat confirming the inconsistent effects of prebiotics supplementation on several health outcomes. Besora-Moreno et al. [15], suggested prebiotics to be effective for muscle strength, but with limited evidence and high inconsistency. Also, Ni-Lochlainn et al. reported that prebiotics supplementation did not improve lower limb muscle strength [98]. These conflicting findings may at least be partially explained by several factors. First, seven [54, 57, 59, 62, 79, 84, 86] out of 13 studies assessing effects of prebiotics on sarcopenia (-defining parameters) stated to have supplemented maltodextrin as placebo, without reporting on its digestibility. There are two types of maltodextrin, digestible and non-digestible, of which the latter can reach the colon to exert prebiotic effects [99]. Since we cannot rule out that the maltodextrin in these studies was non-digestible, these might have levelled out potential effects of the prebiotic supplement, eventually resulting in a non-significant effect. This hypothesis is supported by findings from the only two [62, 84] out of thirteen studies assessing prebiotics effects, that collected fecal samples. One reported a significant increase in alpha-diversity (Shannon index) in the placebo group receiving maltodextrin, while the other observed a non-significant increase in SCFA-producing genera *Faecalibacterium* and *Roseburia*. These findings suggest that the placebo itself may have exerted mild prebiotic effects, thereby potentially confounding the interpretation of the intervention's efficacy. This also might have been the case in the study by Neto et al. [74]. , where in the placebo group, receiving maltodextrin, non-significant increases of TSF and CC were observed at the end of intervention. Second, the majority of studies assessing prebiotic effects, did not take into account the habitual diet of included populations, although prior research has shown that for example habitual fiber intake may increase 'treatment success' with prebiotics (and probiotics) [100, 101]. Finally, eight [53–56, 59–61, 86] of 13 studies used curcumin as prebiotic-like intervention. Although curcumin has been shown to exert prebiotic-like effects, it does not meet the defining criteria of a prebiotic, as for instance it does not promote selective growth of specific bacteria. Moreover, prior research has shown that curcumin attenuates inflammatory status, but has a less pronounced direct (anabolic) effect on skeletal muscle [102].

The main effects of probiotic interventions on muscle function (muscle strength and physical performance), but not on muscle mass are consistent with prior research. Absence of effects on muscle mass may be explained by the fact that probiotics primary mode of action may rather

attenuate systemic inflammation than directly stimulate anabolic signaling, the latter needed for muscle hypertrophy. As such, some probiotics strains of *Lactobacillus casei* and Bifidobacterium longum have been shown to attenuate pro-inflammatory markers such as IL-6, TNF-α and high sensitivity C reactive protein (CRP), one of the driving mechanisms of sarcopenia [103]. However, this effect does not directly induce hypertrophy. Indeed, some health-promoting metabolites, such as the SCFA butyrate, may directly stimulate muscle anabolic pathways. However, the SCFA's main function remains to enhance the gut-barrier to avoid leakage of inflammatory compounds to the systemic circulation. Therefore probiotics may primarily counter muscle atrophy rather than directly stimulate muscle anabolism. Known butyrate-producing strains, i.e. *Akkermansia muciniphila*, are not probiotics, but are considered 'postbiotics' when administered in its pasteurized form. Prior research supplementing pasteurized *Akkermansia muciniphila* reported improved peak torque of the leg extensors in older adults compared to placebo [82]. Interest in such postbiotic interventions is growing and may offer a window of opportunity for future research.

Probiotic strains can in turn be attenuated to favor human health, for example through diet, which has been shown to be of major dynamic, long-term influence to the gut microbiome, especially fiber [104]. Therefore, in this meta-analysis we investigated effects of several diets on sarcopenia (parameters), and found that fiber-enriched diets resulted in an average 1.25 kg increase of HGS in persons with mean age ≥ 50 years as compared to those not following fiber-enriched diets. Generally, cereals (i.e. oats), fruits and vegetables are the primary dietary sources of fiber and phytochemicals (i.e. polyphenols). Dietary fibers are non-digestible carbohydrates reaching the colon, where they are available for saccharolytic fermentation. Fermentation products of dietary fiber include the SCFA butyrate, mainly (indirectly) impacting skeletal muscle through exerting its priorly described properties [101]. Currently, there is a large dietary fiber gap across most Western countries, with in Belgium only 16% of persons aged between 40 and 64 years reaching the recommended daily allowance of 14 g/ 1000 kcal (~ 28–34 g/day) [105]. In addition to fiber, vitamin C may play a role, since in one of the two studies included in the quantitative analyses, persons consumed a citrus complex equal to 0.9 l orange juice. Prior studies have shown the beneficial effect of increased vitamin C on GM diversity, 'health promoting' GM and on muscle function [106]. Unfortunately, of four studies assessing effect of fiber-enriched diets, none reported on changes in the GM composition (i.e., through fecal sampling). Therefore it's not possible to confirm or dismiss whether the positive effect on muscle strength is mediated through GM.

Energy-restricted diets – most of which (except one study [88]) aimed to induce weight loss – were found to significantly increase muscle mass in individuals with mean age below 60 years, but only when the intervention lasted up to 12 weeks. No significant effects were observed in longer-duration interventions. This contradicts prior systematic reviews reporting on the negative effects of energy-restriction on muscle mass in middle-aged and older adults [107, 108]. However, the significant effect in these subgroups appears to stem from one study [36], including three dietary intervention groups: an energy-restricted diet with a high-protein component, an energy-restricted diet with a standard protein component and a control group. The positive effect on muscle mass was specifically observed in the high-protein, energy-restricted group, suggesting that the improvement is likely attributable to the increased protein intake rather than caloric restriction alone. The beneficial effect of energy-restricted diets on muscle mass up till 12 weeks, aligns with prior research [109]. It is hypothesized that the effect of energy-restriction (combined with a high-protein component) may only preserve skeletal muscle over a shorter period, but after 12 weeks, the effect of energy-restriction is hypothesized eventually outweigh the effects of high-protein components.

This meta-analysis also investigated the effects of high-protein diets on sarcopenia (-defining parameters). No overall effects of high-protein diets were reported on sarcopenia or any of its defining parameters. However, in sensitivity analyses we found a significantly positive effect of high-protein diets on muscle mass upon omitting the study by Alemán-Mateo et al. **2014** [25], a study contributing high weight and heterogeneity to the meta-analysis. Moreover, upon subgroup analyses, we found a significant positive impact of high-protein diets in women and if the intervention lasted at least 12 weeks. The latter finding aligns with a prior meta-analysis demonstrating that at least 12 weeks of adherence to a high-protein diet is necessary to induce change in skeletal muscle size [110]. The effect observed in women may be at least partially explained by their lower baseline muscle mass (in comparison to men), and thus may have more room for improvement upon intervention. Moreover, the subgroup analyses for effects of high-protein diets included studies including only women or both sexes, but no men-only studies were included. Therefore, the observed results may be more specific to female physiology. The anabolic, hypertrophy-inducing effects of high-protein diets are well established. However, such diets may also influence gut microbiota composition, although these effects appear to be less consistent and are influenced by factors such as protein source, baseline GM composition, and overall dietary context [111, 112]. In our review, only one of 11 studies investigating high-protein diets in relation to skeletal

muscle outcomes also reported on GM impact, limiting generalizability of the findings. The reported (non-significant) decrease in α-diversity in the dietary group somewhat aligned with prior findings from studies with high-protein diets [112]. Although both control and diet groups did not cluster significantly different from another before nor after the intervention (β-diversity), in the high-protein group the health-promoting, SCFA producing genera *Bifidobacterium*, *Roseburia and Faecalibacterium* increased (non-significantly), whereas the latter two decreased in the control group.

Currently, pre-, pro or synbiotics are not used as standard care to treat sarcopenia. However, this meta-analysis, aligning with prior findings, suggests that supplementation with multi-strain probiotics may benefit individuals with low muscle strength or impaired physical performance. The effects on muscle strength appear most pronounced in community-dwelling individuals, likely due to greater microbiome stability and responsiveness, which is probably attributable to more diverse diets, higher physical activity level and less exposure to polypharmacy as compared to nursing-home residents [113]. We found that both supplementation with probiotics and adherence to a fiber-rich diet support muscle strength. As such, one may hypothesize that combining these two interventions may exert a synergistic effect on muscle strength. To illustrate, prior research reported higher habitual intake of total and added sugars as well as lactose in persons responding to probiotic intake versus those not responding. This indicates that also other habitual diets, i.e. fiber-enriched ones, may increase nutrient availability for probiotic strains, therefore priming a more robust response [100]. Additionally, our subgroup analysis found that high-protein diets can improve muscle mass, particularly in women, when sustained for at least 12 weeks.

The primary strength of this systematic review and meta-analysis is the assessment of the effect of several types of diet as GM modulator, on sarcopenia and its defining parameters. Although diet is a significant driver of GM composition [114], prior meta-analyses have failed to investigate the effect of several dietary types on sarcopenia or its components. Second, this review included studies in populations with mean age ≥ 50 years, contrarily to prior research that included populations of mean age ≥ 60 years [15]. It has been reported that loss of muscle mass, although already starting earlier in life, accelerates from the age of 50 years. Therefore, assessment of GM-altering interventions at earlier life stages might be valuable. Third, this systematic review ensured inclusion of 'single host or GM altering interventions' rather than multi-interventions, contrarily to prior research [15]. This ensures that potential effects could be attributed solely to the host or GM altering intervention, rather than to other (anabolic) interventions (i.e. resistance exercise). A final strength is the elaborate subgroup analyses that were performed, whenever possible, to look at the effects of interventions according to age, sex, study duration, study quality, dose of the intervention (for probiotics) and type of intervention (for both pre- and probiotics), community-setting, and protein source (for high-protein diets). However, since these subgroup analyses often included a low number of studies, the results should be interpreted with caution.

However, a limitation was presence of heterogeneity among some analyses, with possible sources of heterogeneity being populations characteristics (e.g. community-settings, comorbidity), tools for outcome assessment and different intervention duration, frequency and doses. We mitigated this limitation by exploring potential sources of heterogeneity through meta-regression for outcomes with significant heterogeneity based on I^2 statistic, if data were available. Although confidence intervals around I^2 were wide—likely due to small sample sizes in some included studies—we mitigated this by also reporting Tau^2, a more absolute measure of heterogeneity that is not influenced by sample size. Second, some ES were expressed as SMD due to use of different outcome scales across studies. Although this allows for statistical pooling, it can complicate clinical interpretation. Therefore we have back-calculated the SMD to the original scale units for significant findings to increase interpretability of the results. Third, only 25 of 64 included studies took into account at least one covariate, such as medications intake, physical activity and habitual diet intake, with the latter of major modulating influence to the GM, potentially even influencing 'treatment success' with pre-, pro or synbiotics [100]. Of 25 only two [34, 80] accounted for habitual diet, despite the significant impact of diet on GM being known. Forth, from 13 studies assessing pro-and synbiotics intake, three [63, 68, 69] collected fecal samples, of which only two [68, 69] reported it for confirmation of gut colonization with the study product. Of 13 and 38 studies assessing prebiotics and diet, only Yang et al. and Fortuna et al. [62, 84] and Abshirini et al. and Uchida et al. [24, 78], respectively, collected fecal samples to assess intervention effects on GM. Although not the main aim of this review, fecal sampling should be included in future studies to help to determine whether the intervention may also (in)directly affect host physiology via GM. To illustrate, high-protein diets exert both host and GM-mediating effects, by stimulating MPS directly – a host-altering effect - and indirectly via modulating GM, respectively. Without fecal data, it remains unclear to what extent specific interventions are host or GM-altering or both. Finally, no studies included in the quantitative analyses assessed the effect of interventions on the construct of sarcopenia as relevant

data such as changes in incidence or case numbers were not reported.

Conclusions and future perspectives

From this systematic review and meta-analysis, we can conclude that probiotics offer potential to improve sarcopenia-defining parameters, especially due to the beneficial impact on muscle strength and physical performance. Also fiber whole food-enriched diets (containing oats, vegetables and citrus or dried fruits) offer potential to improve muscle strength, since fiber intake has been reported to positively influence the fermentation properties of GM and may contain other microbiome modulators (i.e. polyphenols). High-protein diets improved muscle mass in women and if the intervention lasted at least 12 weeks. However, high heterogeneity, low study quality, as well as difference in community-settings, types and duration of interventions might have influenced results. Also only few studies collected fecal samples to assess effects of the interventions on GM composition. Future research should aim to conduct high quality RCTs including assessment of habitual dietary intake, fecal sampling for GM analyses and other host parameters, and assessment of intervention effect on incidence of sarcopenia as a construct.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s40520-025-03216-z.

Author contributions L.L. wrote the main manuscript, carried out statistical analyses, prepared figures and tables; N.A. assisted in screening of eligible articles and in performance of quality and certainty of evidence assessments; E.S. assisted in screening of eligible articles; J.D., L.V., M.D., J.R. and E.G. revised the manuscript and provided suggestions; All authors reviewed the manuscript.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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