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Millets have the potential to increase satiety and reduce the feeling of hunger: a systematic review

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A systematic review was conducted to understand the satiety value of millets and their ability to lessen the feeling of hunger. Only six eligible studies had the relevant information for this analysis. These studies compared millet-based foods with refined rice, potatoes, wheat, oats, and rye and found that millets have the potential to lower the hunger index. The proposed mechanism suggests that millets' richness in fiber is responsible for increasing gastric volume and prolonging gastric emptying time. Millet-based food stays longer in the stomach, thereby prolonging the feeling of satiety or fullness. Fiber also helps to slow down the release of glucose into the blood. Furthermore, the protein in millets increases insulin sensitivity, which also reduces the glucose response. This proposed mechanism, which increases satiety and delays the glucose response, is responsible for lowering the blood lipid profile and promoting weight loss.

KEYWORDS

satiety value, feeling fullness, millets, feeling of hunger, glucose response

1 Introduction

Millets (including sorghum) are climate-resilient, nutrient-dense crops that have been domesticated in many African and Asian countries (Vetriventhan et al., 2020). Millets are resilient to climate change, pest attacks, and diseases. They also require minimal water, fertilizer, pesticides, etc., thus making them an ideal crop for sustainable food and nutrition security (Otieno et al., 2020).

Evidence shows that millets have the potential to reduce and manage blood glucose levels (Anitha et al., 2024a) and hyperlipidemia (Anitha et al., 2022a) and improve hemoglobin levels (Anitha et al., 2024b). Millets have a high nutrient value that varies based on their type, variety, and growing conditions (Anitha et al., 2024c). The high nutrient value has been shown to improve growth in children (Anitha et al., 2022b). Finger millet's high calcium content, providing up to 49% of the recommended dietary allowance (Backiyalakshmi et al., 2023), contributes to high calcium retention in the body, crucial for growth (Anitha et al., 2021). Despite these multiple nutritional and health benefits of various millets, consumption of millets as a staple food has declined, whereas that of refined rice, wheat, and maize has increased in most of the developing world (Willett et al., 2019). A healthy diet plays a major role in preventing and managing diet-related health issues. Planetary healthy diet recommendations for an average adult call for the consumption of 232 g of whole grain per day, but, in reality, the global average consumption is less than 75 g (Vaidyanathan, 2021). Refined rice, wheat, and maize occupy a central place in cereal-based diets despite there being an opportunity to diversify staples with indigenous crops such as millets and sorghum (Willett et al., 2019). Millets can replace refined rice in many popular dishes without significantly compromising the sensory characteristics of food (Anitha et al., 2024d) and, at the same time, improve dietary nutrient intake. Considering millet's high nutrient levels and its health benefits, it can be tapped to play a major role in solving world hunger and malnutrition (Barikmo et al., 2004).

Studies indicate that there is receptivity for millets. In a face-to-face consumer study conducted among 15,500 individuals, health benefits were cited as the major reason why people eat millets. Increasing health conciousness of the people is a low-hanging fruit and presents a great opportunity to promote millets (Kane-Potaka et al., 2021). Considering that the year 2023 is the International Year of Millets, it is important to promote millets by raising awareness about the substantial scientific evidence of their benefits.

While the impact of millets on metabolic health is proven, their impact on gut health (Singh et al., 2023) and their ability to improve the satiety value of a diet are less understood. Few studies prove that consuming millet can improve gut microflora in animals (Chen et al., 2022); however, human studies are not yet available in this area. There is also a perception that consuming millets leads to indigestion. Therefore, it is important to clarify such perceptions by understanding the science behind the feeling of fullness experienced by consumers due to the satiety value of millets. This systematic review was conducted to throw light on this issue and answer the research question: "Does consuming millets improve satiety?"

Review Question: Does consumption of millet-based diets reduce the feeling of hunger and increase satiety value?

2 Methodology

The current study followed a 27-item PRISMA checklist (Mohar et al., 2009; Page et al., 2021) during the data collection, extraction, and result synthesis.

2.1 Search strategy

The published research articles were obtained using predetermined terminology such as "satiety value AND millets," "fullness AND millets," and "hunger index AND millets."

2.2 Eligibility

Regardless of the year of publication, studies published until June 2023 were included in this review, using the following criteria: (1) randomized studies conducted on humans; and (2) laboratory studies equivalent to human studies, such as simulation studies. Thus, studies conducted on animals and review papers were excluded. The authors (S.A and S.U) reviewed eligible publications to extract data, such as year of publication, location of the study, sample size, methodology, and the results (Table 1).

2.3 Result synthesis

The results were synthesized by comparing the impact millet consumption had on the hunger index, satiety score, and glycemic response in the experimental group with the effects seen in the control group, which consumed food made of refined rice, potato, barley, oats, wheat, etc.

3 Results and discussion

Only six studies met the eligibility criteria for addressing the review question. Of these, one was a laboratory study that used simulation methods, while the remaining five were human studies. These human studies examined the impact of millets on glucose response, gastric emptying time, and hunger index, comparing them to other common foods (Figure 1; Table 1).

Using *in vivo* imaging, Alyami et al. (2019) measured the effect of consuming breakfast porridge made from different modern and ancient cereal grains, such as Scottish oats and pearl millet flakes on glycemic, gastrointestinal, and appetite responses. The randomized crossover study was conducted with 26 participants. After overnight fasting, the baseline measurement of glycemic, gastrointestinal, and appetite response was taken. After 2 h of post-consumption of the breakfast porridge, the same measurements were repeated. The results showed high gastric volume, delayed gastric emptying, low appetite score, and low glycemic response when a pearl millet-based meal was consumed. This indicates that pearl millet porridge leads to longer satiety than porridge made from oats and rye. This could be related to the greater gastric volume and less gastric emptying time, causing prolonged distension of the stomach and delaying the delivery of nutrients into the small intestine, which probably accounts for the blunted glycemic response (Alyami et al., 2017). Clegg and Shafat (2014) also show that delayed gastric emptying is associated with low glycemic response.

Alyami et al. (2017) conducted a randomized crossover study with 17 participants to test the postprandial glucose level and gastric volume after providing breakfast porridge prepared with pearl millet, finger millet, oats, and rye. The result indicates lower postprandial blood glucose response and appetite scores in pearl millet. They also reported that pearl millet porridge lowered the glucose-dependent insulinotropic peptide (GIP) response, which is linked to triacylglycerol absorption. This leads to the possibility that it could reduce triacylglycerol absorption, which means that it could help manage the lipid profile. Anitha et al. (2022a) and Anitha et al. (2022b) confirmed that millet (finger millet, barnyard millet, foxtail millet, mixed millet, and sorghum) consumption is associated with the management of hyperlipidemia by reducing low-density lipoprotein-cholesterol (LDL-C), very low-density lipoprotein-cholesterol (VLDL-C), and triglyceride level while increasing high-density lipoprotein-cholesterol level (HDL-C).

Cisse et al. (2018) tested gastric emptying time through the crossover study in two stages with 14 participants in the first stage and 6 participants in the second validation stage by providing traditional sorghum and millet foods (consumed in the form of both thick porridge and non-viscous couscous) in comparison with traditional starchy foods such as refined rice, boiled potato, and non-whole-grain pasta. A visual analog scale (VAS) was used to assess fullness, hunger, desire to eat, and prospective food consumption at baseline and 2 and 4 h after consumption. The results showed that traditional sorghum and millet foods (thick porridge and couscous) had gastric half-emptying times of

TABLE 1 Summary of the studies analyzed for the systematic review.

Author	Location	Food tested	Sample size	Age (years)	Study design	Parameters	Results	Remarks
Alyami et al. (2017)	Nottingham, UK	Pearl millet, finger millet, oats, and rye porridge	Oats ($n = 15$), rye ($n = 15$), finger millet ($n = 9$), and pearl millet ($n = 12$) tested on 16 participants (10 women, 6 men)	21	Randomized four-way crossover study	Periodic MRI scan to measure gastric volume; Fasting and postprandial blood glucose level	Pearl millet had lower postprandial blood glucose levels and appetite scores. Incremental area under the curve (iAUC) for blood glucose at 0–2 h was lowest after consuming pearl millet porridge (109.6 mmoL/L 120 min) compared to Scottish oats porridge (131.1 mmoL/L 120 min), rye porridge (119.5 mmoL/L 120 min), and finger millet porridge (145.4 mmoL/L 120 min).	Pearl millet curbs the glucose response and reduces appetite scores; however, the difference is minimal compared to finger millet, rye and oats.
Alyami et al. (2019)	Nottingham, UK	Pearl millet porridge and Scottish oats porridge for breakfast	26 healthy participants (17 women, 9 men)	28.5 ± 9.6	Randomized two-way crossover trial	Glycemic, gastrointestinal, hormonal, and appetitive responses	Glucose-dependent insulinotropic peptide (GIP) was low for pearl millet porridge compared to oats porridge. The hormone and appetite responses were similar for both porridges.	GIP is a hormone linked to triacylglycerol absorption. The lower GIP response with pearl millet porridge is an added advantage.
Cisse et al. (2018)	Bamako, Mali	Sorghum, millet, refined rice, potato, and wheat pasta	14 healthy participants (12 men; 2 women) included in the main study; 6 participants (3 men, 3 women) included in the validation study	20–50	Crossover study for 16 consecutive days and validation after 1 year	Gastric emptying time, visual analog scale to measure satiety value	Millets and sorghum as thick porridge and millet couscous have a slow gastric emptying time of 2.5 h compared to refined rice (1.3 h), boiled potato (1.5 h), and wheat pasta (1.2 h) in normal-weight individuals.	There is a significant difference between millets and sorghum in slowing down gastric emptying
Hayes et al. (2019)	West Africa	Pearl millet couscous and wheat couscous	NA	NA	Simulated oral and gastric digestion	Hydrolysis of starch	Millet couscous had slow hydrolysis compared to wheat couscous.	Millet has a shorter amylose chain length (amylose is one of the molecule that makes starch) that is densely packed; therefore, hydrolysis in millet was slow. This could be the reason for its slow gastric emptying rate.
Hayes et al. (2020)	USA	Thick millet porridge, pearl millet couscous (self-made), millet couscous (commercially available), wheat couscous, and refined rice	Thick millet porridge ($n = 14$), millet couscous (self-made) ($n = 15$), millet couscous (commercial) ($n = 14$), wheat couscous ($n = 15$), white rice ($n = 15$)	18–50	Crossover study with a 5- to 7-day washout period	Continuous glucose monitoring for glycemic response, visual analog scale rating for appetite sensation	Millet couscous (self-made) consumption had a significantly lower hunger rate and higher fullness rate than refined rice, thick millet porridge, and commercially available millet couscous. However, gastric emptying rate was normal in all the foods (<3 h). Glycemic response in all millet-based foods and wheat was lower compared to refined rice.	Millet-based products have high satiety value and reduce glycemic response compared to refined rice. Thick millet porridge had a higher gastric emptying time compared to white rice and wheat couscous.

(Continued)

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TABLE 1 (Continued)

Author	Location	Food tested	Sample size	Age (years)	Study design	Parameters	Results	Remarks
Skotnicka et al. (2018)	Northern Poland	Pearl barley groats, millet groats, buckwheat groats, oat groats, and grits	54 women	20–28	Crossover single-blind study	Satiety score	All the groats exhibited high satiety value. Oats and barley groats had the highest satiety value, followed by buckwheat groats, which were associated with dietary fiber and hydration degree. Millet groat was found to have less fiber compared to oats and barley groats.	The study suggests that oats and barley could be good dietary options for people who are overweight.

2.5 ± 0.04 h and 2.5 ± 0.1 h, respectively, approximately twice as long as refined rice (1.3 ± 0.2 h), boiled potato (1.5 ± 0.1 h), and non-whole-grain pasta (1.2 ± 0.05 h). In the case of sorghum and millet foods, >50% of stomach content was retained at 4 h compared to 50% retention at 5.4 h for thick sorghum porridge, 4.5 h for thick millet porridge, and 5.3 h for millet couscous. The results from the VAS indicated that millet couscous and rice provided a similar feeling of fullness, and there is not much difference between millet and rice in hunger rating, although the gastric emptying time is twice for millet-based meals, which can delay the feeling of hunger. The study by Cisse et al. (2018) suggested that the feeling of fullness reported by the participants after consuming refined rice might be influenced by psychological factors, as the participants were used to consuming refined rice as a staple food, which could have influenced their scoring patterns.

Hayes et al. (2020) conducted crossover trials involving pearl millet couscous ($n = 15$), refined rice ($n = 15$), thick millet porridge ($n = 14$), commercial millet couscous ($n = 14$), and wheat couscous ($n = 15$) to test glucose response, appetitive sensation, and gastric emptying time (Table 1). The study reported lower hunger and higher fullness ratings ($p < 0{\cdot}05$) with consumption of homemade pearl millet couscous than refined rice, thick millet porridge, and commercial millet couscous, although there was no significant difference in the gastric emptying time.

The reason behind the slow gastric emptying when pearl millet couscous was consumed by the participants in the study conducted by Cisse et al. (2018) was further evaluated by Hayes et al. (2019) using the human gastric simulator. The study analyzed the viscosity and starch structure of the millet and wheat couscous using a Rapid Visco Analyzer and high-performance size-exclusion chromatography. The result indicated that the millet couscous significantly exhibited lower starch hydrolysis per unit surface area than wheat couscous ($p < 0.05$). This was associated with the small amylose chain length of 839–963 DP that millet starch possesses compared to wheat couscous amylose chain length of 1,225–1,563 DP, which makes millet starch molecules pack densely and hinder the starch hydrolysis. The author also hypothesized that this could be the reason for the delayed gastric emptying observed in the human study conducted using pearl millet couscous (Cisse et al. 2018).

Studies have shown that a high-fiber meal delays gastric emptying and reduces the feeling of hunger (Benini et al., 1995; Skotnicka et al., 2018). There is evidence that millets are rich in fiber (Longvah et al., 2017) and have been proven to lower blood glucose levels, manage the lipid profile, and slow down gastric emptying. Their high fiber content and gastric emptying time could also be a reason for their high satiety value.

In a crossover study on various groats, Skotnicka et al. (2018) tested the satiety value of five types of groats, namely pearl barley groats, millet groats, buckwheat groats, grits, and oat groats in 63 women in Poland. All the groats were cooked according to the instructions in the package before providing to the participants for breakfast. Each participant assessed the level of hunger and satiety using the VAS before and after consumption. All five groats were also tested for their fiber content. The results confirmed that the high fiber content of oat groats is associated with a low hunger index and high satiety and that millet groats (0.1 g/100 g) had less fiber compared to oat (3.4 g/100 g), barley groats (2.5 g/100 g), and buckwheat groats (1.9 g/100 g), which is the reason why oat and

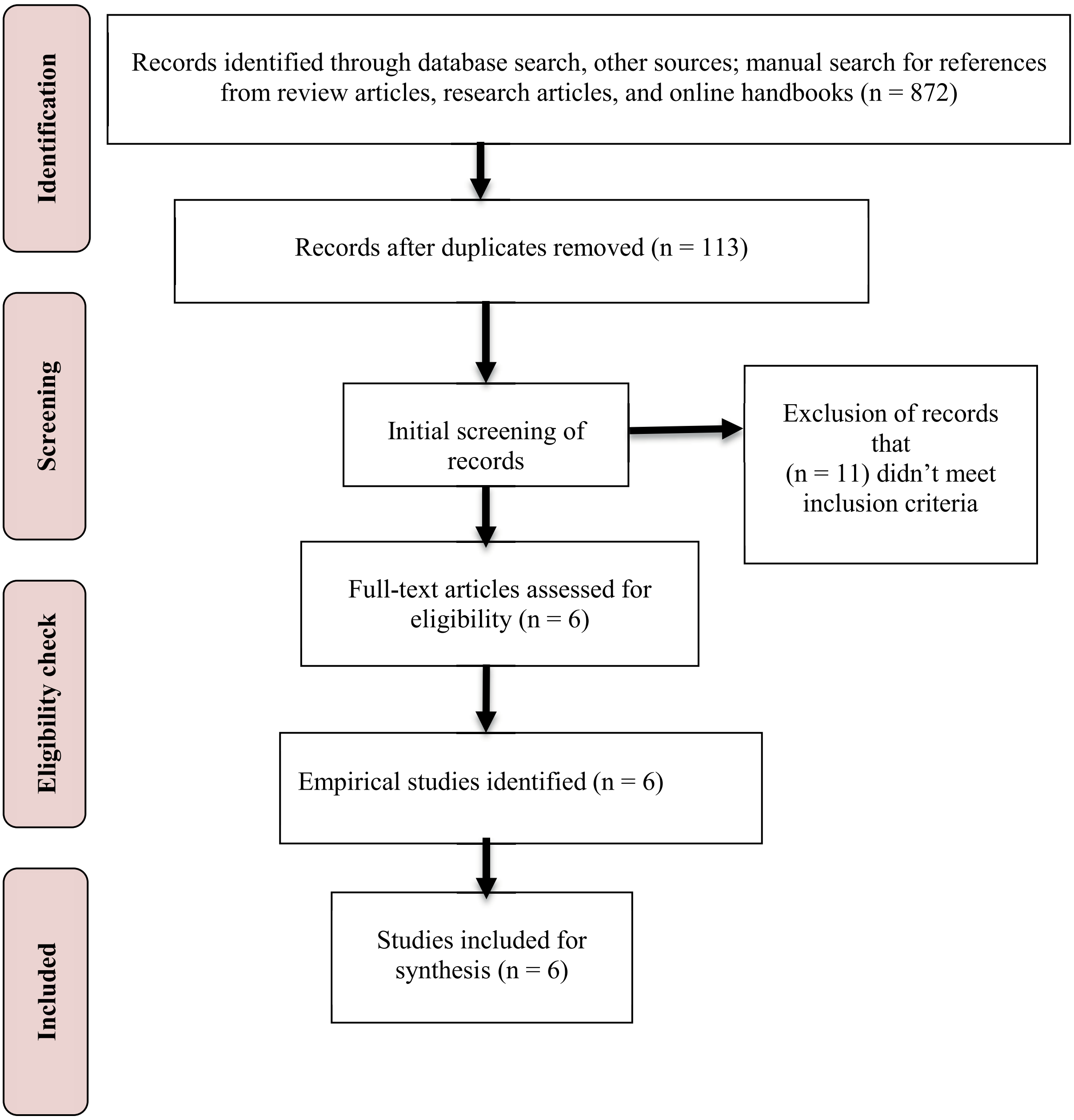

FIGURE 1
PRISMA flow diagram of the systematic review.

barley groats had more satiety value followed by buckwheat groats than millet groats. The study suggests that the use of polished millets may have contributed to the loss of fiber. Extending this logic, refined rice is said to have less fiber compared to millets (Table 2), which is perhaps why refined rice-based foods were found to have faster gastric emptying and less satiety value than millet foods in the study by Cisse et al. (2018). In three studies, millet/pearl millet was compared with wheat (Cisse et al., 2018; Hayes et al., 2019, 2020) for gastric emptying time. Although the protein content of pearl millet (10.96 ± 0.26 g/100 g) and wheat (10.57 ± 0.37) is almost the same (Longvah et al., 2017) the delay in gastric emptying time could be due to the high fiber content and the type of starch in millet.

How the various mechanisms at work in millets have an impact on satiety, blood glucose level, and other relevant health issues is summarized in Figure 2.

4 Limitations of the study and recommendations for future research

4.1 Type and variety of millet

Some of the studies did not indicate what type of millet was used and the fiber content. None of the studies indicated the variety of millet used and the glycemic index.

TABLE 2 Fiber content in various grains (Source: Longvah et al., 2017).

Grain	Fiber content (g/100 g)		
	Total fiber	Insoluble fiber	Soluble fiber
Refined rice	2.81 ± 0.42	1.99 ± 0.39	0.82 ± 0.22
Barley	15.64 ± 0.64	9.98 ± 0.62	5.6 6 ± 0.68
Pearl millet	11.49 ± 0.62	9.14 ± 0.58	2.34 ± 0.42
Finger millet	11.18 ± 1.14	9.51 ± 0.65	1.67 ± 0.55
Sorghum	10.22 ± 0.49	8.49 ± 0.40	1.73 ± 0.40
Dry maize	12.24 ± 0.93	11.29 ± 0.85	0.94 ± 0.18
Refined wheat flour	2.76 ± 0.29	2.14 ± 0.30	0.62 ± 0.14
Whole wheat flour	11.36 ± 0.29	9.73 ± 0.47	1.63 ± 0.64

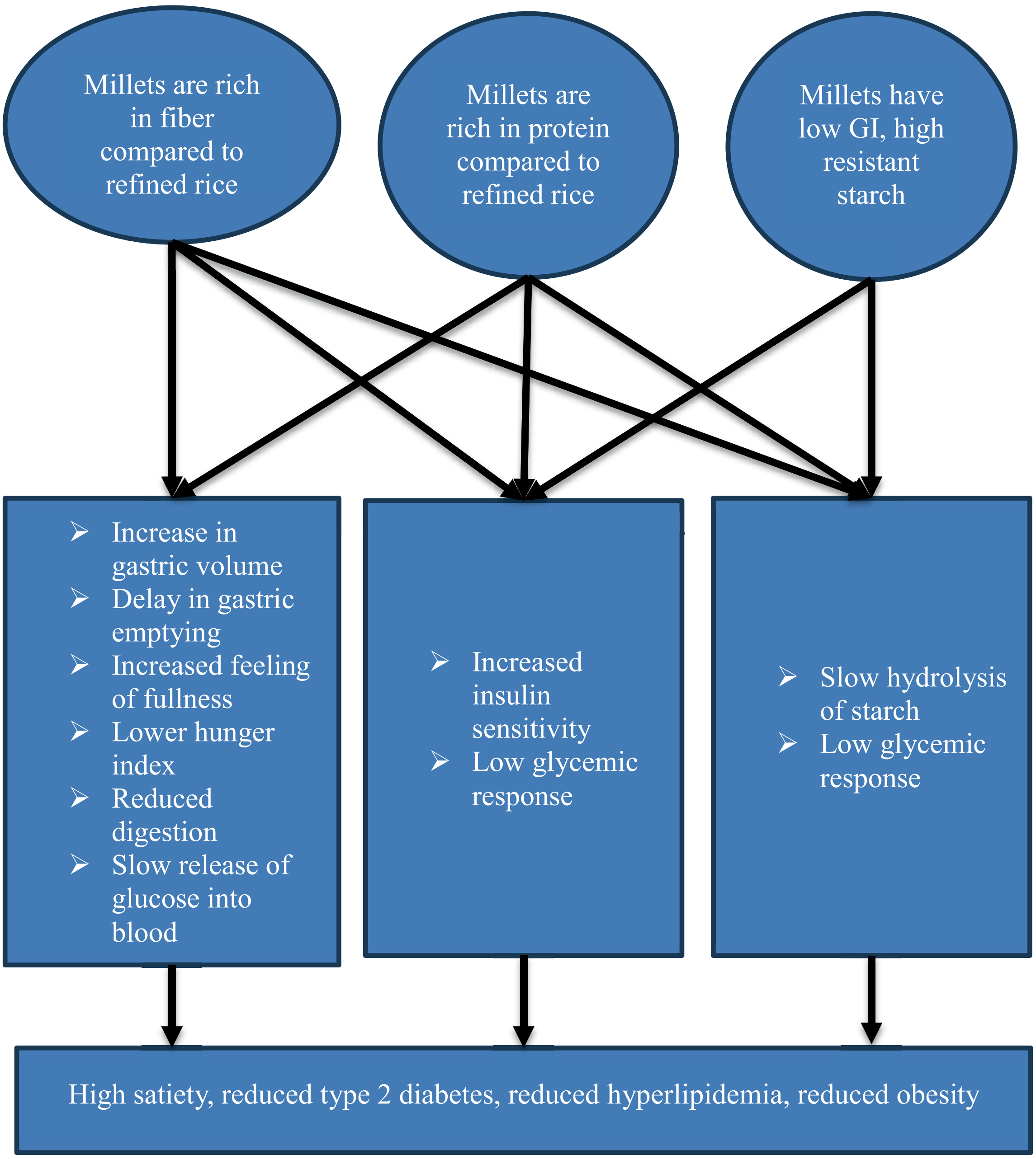

FIGURE 2
Proposed mechanism of action of millets on satiety and other health parameters.

4.2 How these benefits can impact common lifestyle and health needs

Satiety can be beneficial for improving physical endurance as well as managing weight loss. The endurance benefits and weight loss potential of millets, along with the factors influencing these aspects, need to be further studied.

4.3 Processing

The studies did not indicate the level of processing of millets, which limits our understanding of their fiber content and its potential impact. It was assumed that the most commonly available form of grain in the area, e.g., refined rice, was the form used in the studies. Ideally, not only should the use of refined and whole grain be indicated; in addition, the different types of cooking and processing that they undergo should also be analyzed to know their impact on satiety characteristics.

4.4 Geographical location

Though millets are widely produced in Asia, none of the studies were conducted there.

4.5 Number of studies

Given that there were only a limited number of studies (6) eligible for this analysis, more studies are recommended.

4.6 Others

There is a common belief associated with digestion and millets. The feeling of fullness and the low hunger index due to the consumption of high fiber content in millets may be related to slow digestion. This slow digestion can have positive effects on gut health, glucose and lipid levels, and obesity. This requires more research. It will help to prepare appropriate communication information for common people to understand more about the satiety value and the benefits of millets.

5 Conclusion

The evidence available shows that millets have high fiber content—significantly higher than refined rice; have the potential to increase satiety, which can aid in weight loss; and delay gastric emptying, which is useful for the slow absorption of nutrients, especially glucose. All these aspects have multiple benefits, including the reduction of blood glucose, which is important for managing or reducing the risk of diabetes, and lipids, which is important for reducing the risk of hyperlipidemia. Promoting the consumption of non-refined millets will be important for maximizing these health benefits.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SA: Conceptualization, Data curation, Investigation, Methodology, Supervision, Writing – original draft. SU: Methodology, Validation, Writing – review & editing. JK-P: Funding acquisition, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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