MILLET FOUNDATION GUIDE

Scientific Evidence & Research Priorities

(Revised Edition 2025)

An initiative of

Government of Odisha

ODISHA
SHREE ANNA ABHIYAN

MILLET FOUNDATION GUIDE

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Suggested citation Padhee, A.K., Chaudhary, P.C., Khetarpal, R., Balam, D. , and Kane-Potaka, J. (eds). 2025. Millet Foundation Guide: Scientific Evidence & Research Priorities. revised edn Bhubaneswar, India: Department of Agriculture & Farmers' Empowerment, Government of Odisha.

Acknowledgements Special acknowledgement and thanks to the Asia-Pacific Association of Agricultural Research Institutions (APAARI) and Shubham Saxena, Director, DA&FP, Government of Odisha for their guidance and support.

ISBN 978-81-980398-4-2

Shri Mohan Charan Majhi
Chief Minister, Odisha

Lokaseva Bhavan
Bhubaneswar

Message

Millets are ancient grains with the power to address modern challenges. These modest crops are climate-resilient and hold immense promise for ensuring nutritional security. Recognizing their significance in India's culinary, cultural, and civilizational heritage, the Hon'ble Prime Minister has rightly declared millets as "Shree Anna." Further, on India's initiative, the United Nations declared 2023 as the International Year of Millets (IYM), which generated unprecedented global awareness.

The growing recognition of millets underscores the urgent need for a robust scientific foundation to validate their nutritional, health, environmental, and agricultural benefits. While substantial research has been carried out worldwide, a comprehensive cross-analysis of findings from diverse sources remains lacking. This gap has often resulted in conflicting claims. To enable millets to play their rightful role, it is imperative to build a strong, evidence-based case through rigorous scientific inquiry.

It is in this context that the revised edition of the Millet Foundation Guide, brought out by the Department of Agriculture & Farmers' Empowerment, Government of Odisha, will serve as a vital resource for policymakers, researchers, and practitioners. By providing credible and consolidated information, the guide will support evidence-driven strategies, counter misinformation, and address data inconsistencies that shape public perception.

I am confident this guide will inspire continued research, innovation, and investment to develop sustainable millet value chains - benefiting our farmers, nourishing our people, and safeguarding our planet.

(Mohan Charan Majhi)

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Message

Millets, or *Shree Anna*, are more than just crops they are pathways to nutrition security, ecological resilience, and economic empowerment. With deep roots in India's agrarian heritage, these smart foods are now gaining the recognition they deserve for addressing today's pressing challenges from climate change to malnutrition.

Odisha has been a pioneer in reintroducing millets into mainstream farming systems and diets. Through the *Shree Anna Abhiyan*, we have demonstrated how local knowledge, community participation, and targeted policy support can revive traditional grains while ensuring improved incomes for farmers, especially women and tribal communities. The Mission's success has placed Odisha on the global map for millet promotion.

The *Millet Foundation Guide: Scientific Evidence & Research Priorities* builds on this foundation. It is not just a compilation of data; it is a strategic tool that bridges traditional wisdom and modern science. By presenting rigorously validated findings on health, nutrition, environment, and markets, this Guide empowers all stakeholders from farmers and entrepreneurs to researchers and policymakers with knowledge to act.

As we look ahead, our focus must remain on scaling this transformation by deepening millet cultivation, expanding processing and value addition, and creating consumer awareness. I extend my sincere appreciation to APAARI and all contributing partners for their collaboration in the development of this resource.

Let us continue our journey towards a healthier, more sustainable, and millet-secured future.

(K. V. Singh Deo)

Dr Arabinda Kumar Padhee, IAS
Principal Secretary
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Foreword

The Food and Agriculture Organisation of the United Nations estimates that there are more than 6000 food crops that have been consumed by humans in different parts of the world since times immemorial. Out of this vast diversity, five crops namely rice, wheat, corn, soybean and potato contribute to more than 60% of the energy intake. These crops also happen to focus on agriculture research and development in the last 50 years. Due to this lopsided focus, nutri-cereals such as Millets have relegated to the margins of research and development. Due to lack of research or concentrated research, the right information on different claims related to the advantages and disadvantages of millets are often not known. Even when they are claimed, it is done without reference to scientific evidence and studies.

The Hon'ble Prime Minister's vision for millets is grounded in science and tradition. Highlighting their importance in Indian civilizational history, millets are renamed as "Shree Anna". Odisha Shree Anna Abhiyan is guided by a mission to revive millets in farms and plates. It is now recognized as one of the best models for the promotion of millets nationally and globally.

Based on a resolution proposed by India, the United Nations declared 2023 as the International Year of Millets. As the celebrations of the International Year of Millets unfolded, the need for a definitive and authenticated foundation guide on nutritional and environmental benefits of the millets emerged. An evidence-based approach on the benefits of Millets was sought by diverse stakeholders such as doctors, educationalists, influencers, celebrities, chef associations, policy makers, and so on and so forth. This was echoed by agencies such as ICAR institutions, CSIR institutions, ICMR institutions, UN-FAO, WFP, IFPRI, ICRISAT and many others.

As a pioneer state in the promotion of millets, the Department of Agriculture & Farmers' Empowerment, Government of Odisha partnered with eminent scientists and experts under the guidance of Asia Pacific Association of Agriculture Research Institutions (APAARI) to develop the Foundation Guide on Millets. The Foundation Guide focussed on three major areas namely Scientific evidence on the health and nutrition claims of millets, Scientific evidence for millet benefits to the environment, Farmers, Women and tribal groups and Market potential of millets. On the health and nutrition, there are significant meta-analysis that has been done on type 2 diabetes and its management, role of millets in reducing blood cholesterol and triacylglycerol levels, potentially reducing the risks of hyperlipidemia, studies indicate that millets may be helpful for managing weight control and reducing obesity, etc. This will help the global community to build consensus on the nutrition related aspects of millets and momentum post International Year of Millets.

I wish to place on record a sincere gratitude to the Hon'ble Chief Minister, Hon'ble Deputy Chief Minister, Director of Agriculture & Food Production and senior officials of Government of Odisha, ICAR- IIMR, WASSAN and NGO partners and everyone involved in this unique project.

Shree Anna Abhiyan thanks all the scientists and experts who played a key role in the development of the Foundation Guide on Millets. We thank the work of all scientists and experts who have spent their significant time and energy undertaking the research which has contributed to this Foundation Guide on Millets.

We hope every stakeholder finds this guide very useful and contribute in taking millets to millions.

(Dr Arabinda Kumar Padhee)

Description of this Guide

The Aim

The **Millet Foundation Guide** aims to be a quick reference guide on the major claims being made about millets and the scientific evidence supporting those claims. It is meant to be a foundation source of scientific information needed to verify claims on the health, nutritional, environmental and agricultural benefits of millets and to discern what has a basis and what does not.

The Need

The need for this Guide on millet claims was identified because a lot is being said about the benefits of these cereals, but all too often without providing the scientific basis. When evidence is indeed provided, it usually is just a few references, without reviewing the studies for their conditions and limitations. This has led to a lot of conflicting information and data circulating in the public discourse on millets.

Target Audiences

As this Guide is aimed at all audiences interested in millets, the scientific evidence presented here is written in an easy-to-understand way. It is useful to consumers in understanding the benefits of millets in their diet; to farmers to understand the value of growing millets under different conditions; to government decision-makers in tuning their policies to best leverage these cereals; to development agents and civil society for identifying where to invest and how best to use millets in attaining the UN Sustainable Development Goals; and to researchers to know what studies already exist and where there are priority research gaps.

Content

The main part of the Guide covers a wide range of benefits attributed to millets and lays out the scientific evidence that can lend clarity to those claims. Such evidence would be useful to confirm the benefits claimed for millets but also to correct any inaccuracies in those claims.

The Guide also goes further to provide case studies illustrating how millets are being popularized through the Shree Anna Abhiyan (formerly known as Odisha Millets Mission). It provides recipe guidance for the various types of millets and their respective nutritional values. The Guide also identifies gaps within the range of scientific evidence it reviews and suggests priorities for future research and policy opportunities to leverage the true benefits of millets.

Section A Scientific evidence on the health and nutrition claims of millets

This section of the Guide analyzes existing studies on how millet consumption impacts diabetes, anemia, hyperlipidemia (excess lipids in the blood), growth (malnutrition) and thyroid issues. As it is commonly claimed that millets have positive effects for people with diabetes, anemia, hyperlipidemia and growth issues, systematic reviews and meta-analyses were undertaken to examine the basis for those claims. On the other hand, thyroid problems are believed by some people to be a negative side-effect of consuming millets; so a systematic review of the few existing studies on the issue was also undertaken.

In addition, this section tackles the confusion arising from widely varying data on the nutrition composition of different types of millets. As a result, a large amount of nutritional data from scientific journal articles was collated and sorted by type of millet and by variety within each type. The data was then subjected to a systematic review to come up with a new and more accurate nutrition composition table for various millets.

Other topics analyzed included the effect of consuming millets on weight control and the bioavailability of nutrients from millets. There were only a few studies that satisfied the stringent scientific requirements of the reviewing team, limiting the conclusions that can be made. The contribution of millets to food safety was also compared to that of other crops.

Further, an innovative research study was undertaken that reviewed, through sensory evaluation by trained evaluators and chefs, nine different types of millets for their suitability and nutritional contribution to each of seven recipes. Through these extensive reviews, data gaps and research priorities were identified and policy priorities were recommended.

Section B Scientific evidence for millet benefits to the environment, farmers, women and tribal groups

This section deals with claims on the value of millets to the environment and farmers, and reviews a wide range of studies conducted on the topic. It deals with the key characteristics of millets and shows how they contribute to the health of the planet, including their role in climate change mitigation and impact on natural resources. Also covered is their overall resilience and strength in adapting to climate change. These are all advantages to farmers with potential to increase yields and afford multiple other benefits.

Case studies from the Shree Anna Abhiyan initiative are also presented, highlighting how millets can be beneficial to tribal groups and women.

Section C Market potential of millets

Exploring the market potential of millets, consumer categories that millets fit well into are identified and market data is collated for each category. The consumer categories explored include gluten-free, ancient grains, superfoods, health and wellness foods and plant-based proteins. This section indicates possible opportunities for developing and branding millet products in each of these categories.

A collation of commercial market reports on millets is also presented. However, these reports rarely indicate the data source and are contradictory; so a need for credible industry market data is identified.

There are many claims about the benefits of millets. During the International Year of Millets, it is particularly important to lay out the scientific basis of each of them so that we understand the best way to use millets for the benefit of consumers, farmers and indeed the planet at large. We also hope this Guide will stimulate more research on these cereals to build up our knowledge and develop guidance on how best to build millet value chains, provide input into policies and guide investments.

We hope the Millet Foundation Guide will be useful in your work and personal journey with millets.

Contents

SECTION A

Scientific evidence on the health and nutrition claims of millets

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Kane-Potaka, J., Anitha, S., Rajendran, A., Upadhyay, S., Tsusaka, T. 2025. Scientific evidence on the health and nutrition claims of millets. In: Padhee, A.K., Chaudhary, P.C., Khetarpal, R. , Balam, D. , and Kane-Potaka, J. (eds). Millet Foundation Guide: Scientific Evidence & Research Priorities. revised edn, Bhubaneswar, India: Department of Agriculture & Farmers' Empowerment, Government of Odisha.

Claim 1: Millets can reduce the risk of developing type 2 diabetes and be useful for managing it

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Scientific evidence and results

To collate evidence for this claim, an analysis of relevant studies on millets was undertaken. This included a systematic review and meta-analysis of published studies on the impact of millet-based diets on the reduction and management of type 2 diabetes. Only studies with control groups were included, i.e., comparing millet consuming groups with those consuming other common staples.

This analysis was based on 12 eligible studies. Of these, 10 were suitable for meta-analysis to assess the effect of a millet-based diet on fasting blood sugar (FBS) levels, 5 to assess the effect on post-prandial blood sugar (PPBS) levels, and 5 to assess the effect on glycated hemoglobin levels (HbA1c).

Key results

- **Millets can contribute to managing and reducing the risks of developing type 2 diabetes.** In this aspect, the millets perform better than the typical staple diets as millets have on average a lower Glycemic Index (GI).

Clinical studies on humans have reported the following results (statistically significant at $p < 0.01$):

- **Reduction of fasting blood sugar levels**: There was an 11.8% reduction in FBS levels in the millet consuming group over 28-180 days whereas the comparator group given diets based on other staple cereals did not show a significant reduction (effect size –0.71; $p = 0.001$).
- **Reduction of post-prandial blood sugar (PPBS) levels**: There was a 15.1% reduction in PPBS levels in the millet consuming group over 28-180 days whereas the comparator group did not show a significant reduction (effect size –0.42; $p = 0.012$).
- **Reduction in glycated hemoglobin (HbA1c) levels**: HbA1c levels decreased 12.0% for millet consuming groups compared to an insignificant decrease for groups consuming other staple cereals. However, this was statistically insignificant ($p = 0.043$), presumably due to the small sample size of two studies undertaken over 90 days. Hence, this requires further research.

Though a total of 80 studies on the impact of millet consumption on diabetes in humans were identified, most of them did not have a control group; so they were not included in this systematic review and meta-analysis. However, they did provide other useful information:

- **Millets have on average a low GI**: The 10 millets that were tested for their GI level had either low or medium GI, with an average on the lower side.
- **Millets have low GI even after cooking**: Though millet GI level tended to rise due to common cooking methods like boiling, steaming and baking, it remained low on average at 52.7 ± 10.3, and lower than the GI levels of major staples such as refined rice, refined wheat and maize.

The decrease in blood sugar levels, PPBS and HbA1c is due to the:

- High fiber content in the millet compared to refined rice [Longvah et al. (2017), as cited in Anitha et al. 2023)]. Fiber content increases the bulk of the food, which delays gastric emptying, leading to slower release of glucose into the blood [Cisse et al. (2018). Hayes et al. (2020), and Hayes et al. (2019), as cited in Anitha et al. (2023)]
- Resistant starch in the millet and the chemical composition (amylose and amylopectin) of the starch, delays starch hydrolysis and thus slows down glucose absorption (Hayes et al. 2019);
- Generally higher protein content in millets compared to refined rice. Higher protein content increases insulin sensitivity, leading to a lowering of blood glucose levels.

These various pathways that reduce blood glucose levels and HbA1C levels also help to manage the blood lipid profile (Anitha et al. 2022b), and decrease the feeling of being hungry.

The studies

The overall study of studies, comprising a systematic review and a meta-analysis, is, titled: Impact of regular consumption of millets on fasting and post-prandial blood glucose level: A systematic review and meta-analysis. (Anitha et al. 2023).

This analysis of the effects of millet consumption on FBS, PPBS and HbA1c levels in comparison to other staple diets was undertaken using the difference-in-differences (DID) method, in which the effects are computed on the Standardized Mean Difference scale.

Studies conducted for a duration less than a week were excluded, as were studies that did not have enough data [Standard Deviation (SD), Standard Error of the Mean (SE) or Mean Change] for meta-analysis, cross-sectional/observational studies, animal studies and review articles.

The studies analyzed are listed in the references and detailed in Table 1A.

Table 1A. A summary of the characteristics of each study that was eligible for the meta-analysis.

Study	Type of millet	Test meal/amount of millet consumed (grams/meal)	Parameter studied
1. Kumari et al. 2020	Finger millet	Porridge/not mentioned	FBS
2. Ugare et al. 2014	Barnyard millet	Porridge/73 g	FBS
3. Geetha et al. 2019	Mixed millet	*Roti*, *dosa* and dumpling/not mentioned	FBS and HbA1c
4. Tiwari and Srivastava 2017	Finger millet	Bun/200 g	FBS and PPBS
5. Thathola et al. 2011	Foxtail millet	Biscuit and *burfi*/100 g	Serum glucose and HbA1c
6. Anushia et al. 2019	Millet	Meal/not mentioned	FBS, PPBS, HbA1c
7. Itagi et al. 2012	Foxtail millet	Meal/80 g	FBS
8. Joshi and Srivastava 2021	Barnyard millet	Cooked with water (similar to rice)/100 g	FBS, PPBS, HbA1c
9. Sobhana et al. 2020	Mixed millets	*Roti*/90 g	FBS, HbA1c
10. Surekha et al. 2013	Barnyard millet	Health food/88 g	FBS, PPBS
11. Geetha and Eswaran 1990	Finger millet, sorghum, little millet	*Idli*, *dosa*, *chapati*, *sevai* and *kozhukattai*/20 g	FBS, PPBS
12. Djaja et al. 2019	Job's tears	Boiled grain mixed with yogurt and prepared as a drink/25 g	FBS

Note: GI = Glycemic Index; FBS = Fasting Blood Sugar; PPBS = Post-Prandial Blood Sugar; HbA1c = Glycated Hemoglobin Level;

Sample size (intervention/ control)	Age group (years)	Study design and duration
18/18	45.6 ± 5.6	Randomized cross-over study. Finger millet porridge given to intervention group for 8 weeks. Control group had a regular diet.
9/9, 6/6	37-40	Intervention group given breakfast, lunch and dinner with 73 g of barnyard millet *upma* or rice (equivalent to 50 g of available carbohydrate) for 28 days. Control group had a regular diet.
30/30	Not indicated	Randomized feeding intervention. Intervention group given *roti*, *dosa* and dumplings (prepared with 50-g mix, equivalent to 50 g of available carbohydrate) for lunch for 120 days. Control group consumed a regular diet.
15/15	40-50	Low-GI finger millet buns fed to intervention group for 60 days.
10/10/10	36-78	Case-control clinical trial conducted for 30 days. Experimental group 1 given biscuits; experimental group 2 fed burfi; and group 3 (control) consumed a regular diet. Carbohydrate equivalent of meal not mentioned. HbA1c measured at 30 days was used in the meta-analysis.
44/44	30-50	Randomized trial. Intervention group counselled to include millet in daily diet and monitored telephonically for 3 months. Control group consumed a regular diet.
9/6	>40	Low-GI foxtail millet diabetic mix fed to intervention group for 4 weeks.
15/15	24-26	Barnyard millet fed to diabetic subjects for 3 months. Control group given a regular diet. HbA1c levels measured at 60 days were used in the meta-analysis as 90-day levels were not available for the control group.
47/47	51.72 ± 1.09	Randomized controlled clinical trial. 90 g of millet flour (55 g equivalent of carbohydrate) was used to prepare *rotis*. Three *rotis* (40-45 g each) were provided to the intervention group over 90 days. Control group consumed a regular diet. As data on HbA1c levels was incomplete, it was not used in the meta-analysis.
7/6	25-45	88 g of millet-based health food (equivalent to 50 g of carbohydrate) provided to intervention group for 28 days. Control group consumed a regular diet.
6/6	40-60	Each group of participants provided a different millet and asked to consume 20 g of it incorporated into their breakfast for a month. Control group consumed a regular diet.
30/30	30-60	Randomized controlled trial for 12 weeks. Intervention group were fed Job's tears mixed with yogurt as a drink every morning. Control group had yogurt.

Low GI = <55; Medium GI = 55-69

Priorities for future research

More studies are needed to test more millet variables and their impacts on diabetes in humans in different settings. Priorities for research include:

1. **A large study covering all the major variables:** It would be valuable to conduct a large study with quality and consistent methodology, covering all the millets, different forms of processing and different consumer age groups, gender and ethnic groups.
2. **Understanding the impacts of poverty on diabetes and vice versa:** These impacts may vary in rural and urban settings and in different cultural contexts.
3. **Understanding the process and benefits of diversifying staples with millets on diabetes:** As staples are a large portion of a diet, diversifying staples can have a major impact on diets and the environment. This requires social and behavioral changes. Understanding how this can happen and the potential scale of impact on diabetes will be important.

Priorities for policy

Recommendations for policy include:

1. **Incentivize diversification of staples and diets with millets:** Diverse diets are healthier for the consumer as well as the planet. Millets are a good candidate for diversifying diets given that they are highly nutritious, hardy, climate-smart and broadly environment-friendly.
2. **Incentivize inclusion of millets in the diet:** This will require full value chain development from fork to farm.
3. **Develop meals especially to reduce the risk of diabetes:** This will require culturally appropriate meals and cooking/processing methods that minimize the GI.

The importance of diabetes

Diabetes is growing globally at a rapid rate. In 2021, 537 million people globally were reported to have diabetes. This is predicted to increase 46% to 783 million by 2045 (IDF, 2021). Diabetes can lead to death and is a major cause of blindness, kidney failure, heart attack, stroke and lower limb amputation (WHO, 2021). Since the year 2000, deaths from diabetes have risen 70% (Mikkelsen, n.d.).

About 75% of all adults with diabetes live in low- and middle-income countries. Diabetes is increasing in all regions of the world, with India, China and USA having the highest number of diabetics. The number of diabetics in Africa is forecast to increase by a massive 143% from 2019 to 2045, the largest increase in any region (IDF 2021).

Nearly 90% of all diabetes cases are type 2 diabetes (IDF 2021). Lifestyle changes are critical to managing type 2 diabetes as there is no medical cure for it. Diet and exercise play a key role in managing the blood glucose level and other risks of diabetes.

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Claim 2: Millets can manage blood cholesterol and triacylglycerol levels and potentially reduce the risks of hyperlipidemia

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Scientific evidence and results

An analysis of relevant studies was undertaken to understand the impacts of millet consumption on hyperlipidemia factors. These studies compared people who had been given a millet-based diet with control groups that consumed other common staples.

Key results

This systematic review and meta-analysis (Anitha et al. 2022) showed that consumption of millets:

- **Reduced total cholesterol**: This reduced 6.6% in the millet-consuming group while there was no significant change in the group that consumed other staples.
- **Reduced low- and very-low-density lipoprotein cholesterol (commonly called bad cholesterol)**: This reduced by 11.7% and 7.9%, respectively, in the millet-consuming group while there was no significant change in the group consuming other staples.
- **Reduced triacylglycerol levels in blood**: This reduced by 8.2% in the millet-consuming group compared to no significant change in the group consuming other staples.
- **Increased high-density lipoprotein cholesterol (commonly known as good cholesterol)**: This increased by 6.1% in the millet-consuming group while there was a 4.6% decrease in the group consuming other staples.

(*Note:* The effect size was -0.44 for total cholesterol; -0.60 for low-density lipoprotein cholesterol (LDL-C); -0.41 for very-low-density lipoprotein cholesterol (VLDL-C); -0.29 for triacylglycerol; and +0.59 for high-density lipoprotein (HDL-C).)

These results are based on the following:

- 12 efficacy studies that included control groups.
- All of these studies were undertaken on adults.
- The gender varied and most studies included males and females.
- Five types of millet-based diets were studied – finger millet, foxtail millet, barnyard millet, sorghum and a mixed millet meal that also included little millet.
- The intervention diets included 40–200 g of millets per day for a duration ranging from 21 to 120 days.

The studies

The overall study of studies, comprising a systematic review and a meta-analysis, is titled: Are millets more effective in managing hyperlipidaemia and obesity than major cereal staples? A systematic review and meta-analysis. (Anitha et al. 2022).

The 12 studies analyzed as part of the systematic review and meta-analysis are listed in the references and detailed in Table 2A.

Priorities for future research

Given the existing scientific evidence, the following priorities for future research are recommended:

1. **More studies on hyperlipidemia covering more variables are needed, including:**
    - **All types of millets and the most popular varieties:** Only five millets were assessed (finger millet, foxtail millet, barnyard millet, sorghum and little millet) in these studies, and none identified the variety of millet.
    - **Effect of different forms of cooking or processing:** Although the studies used a wide range of preparations, no study compared the impact exercised on the blood lipid profile by different types of processing or the level of refinement/polishing of the millet. The millet processing industry is not highly developed. Although the millets used in these studies typically were not polished, some polishing may have occurred. Also, there is a need to analyze results in relation to the level of refinement of the staples as well.
    - **Studies of longer duration:** The duration of studies analyzed varied from 21 days to 4 months. Evidence from studies spanning a year or more will provide useful evidence.
    - **Widen the geographic ambit and diversity of study samples:** Of the 17 studies, 1 was conducted in Sri Lanka, 2 in China and 14 in India, indicating a limited geographical

coverage. The impact of millet-based diets in different geographic locations, among different socioeconomic and ethnic groups with different diets, lifestyles and health concerns should be studied.

- **Variations in age and gender** also require more studies.
- **Consumption of different quantities of millets** also need to be studied.

2. **Health conditions related to hyperlipidemia, like cardiovascular disease and non-alcoholic fatty liver disease (NAFLD) require scientific evidence** in regard to the impact from consuming millets. Since there is strong evidence of a positive impact on hyperlipidemia, it is expected that there may also be a similar impact on related conditions. All types of millets need to be studied for such impacts while also noting any differences due to varieties within each millet.

   It is important also to include all relevant parameters while studying the impact of dietary interventions on hyperlipidemia and other risk markers for cardiovascular disease. A more extensive range of parameters for cardiovascular diseases therefore needs to be incorporated into research, including measures of various vascular functions. Only three out of 6 studies determined the ratio of total cholesterol to HDL cholesterol, which is an important risk marker for cardiovascular disease.

   No published studies were found on NAFLD in relation to millet diets.

Priority for policy

1. **Design millet-based meals and dietary guidelines**, especially where atherosclerotic cardiovascular diseases and lipid and weight management are potential high risks.

The importance of cholesterol and cardiovascular disease

Cardiovascular disease (CVD) is the leading cause of death globally. An estimated 17.9 million people died of CVD in 2019, representing 32% of all deaths.

Three quarters of CVD deaths are in low- and middle-income countries. A majority of these deaths can be avoided by addressing factors such as diet, exercise, alcohol and tobacco use (WHO, n.d.).

High cholesterol levels raise the risk of heart disease and stroke. High cholesterol is estimated to cause 2.6 million deaths annually and 29.7 million disability-adjusted life years (DALYs, the sum of years of life lost due to premature mortality and the years lived with a disability due to a disease or health condition). It is a major health problem in both developed and developing countries (WHO Global Health Observatory, n.d.). Over half the adult population is forecast to have NAFLD by 2040, a tripling since 1990 (Le et al. 2022).

Table 2A. Study characteristics of the eligible studies for hyperlipidemia and weight management.

S.No	Study	Type of millet	Test meal/amount consumed (grams/meal)	Parameters studied
1.	Kumari et al., 2020	Finger millet	Porridge/not mentioned	Total cholesterol
2.	Ugare et al. 2014	Barnyard millet	Porridge/78 g	Total cholesterol, triglycerides, LDL-C, VLDL-C, HDL-C
3.	Geetha et al. 2019	Mixed millets	Dumpling/not mentioned	Total cholesterol, triglycerides, LDL-C, VLDL-C, HDL-C, BMI, weight
4.	Anusha et al. 2018	Foxtail millet	Meal/65 g	Total cholesterol, triglycerides, LDL-C, VLDL-C, HDL-C
5.	Tiwari and Srivastava 2017	Finger millet	Bun/200 g	Total cholesterol, triglycerides, LDL-C, VLDL-C, HDL-C
6.	Thathola et al. 2010	Foxtail millet	Biscuit and *burfi*/100 g	Total cholesterol, triglycerides, LDL-C, VLDL-C, HDL-C
7.	Anushia et al. 2019	Millet	Meal/not mentioned	Total cholesterol, triglycerides, LDL-C, BMI
8.	Itagi et al. 2012	Foxtail millet	Meal/80 g	Total cholesterol, triglycerides, HDL-C
9.	Joshi and Srivastava 2021	Barnyard millet	Cooked by boiling with water (similar to rice)/100 g	Total cholesterol, triglycerides, LDL-C, VLDL-C, HDL-C
10.	Anunciacao et al. 2019	Sorghum	Breakfast cereal and drink made from extruded sorghum/40 g	Weight, BMI
11.	Sobhana et al. 2020	Mixed millets	*Roti*/90 g	Total cholesterol, triglycerides, LDL-C, VLDL-C, HDL-C, weight, BMI, systolic and diastolic blood pressure
12.	Surekha et al. 2013	Barnyard millet	Health food/88 g	Total cholesterol, triglycerides, LDL-C, VLDL-C, HDL-C, weight, TC:HDL ratio, LDL:HDL ratio

Notes: Hyperlipidemia refers to an above-normal level of lipids (fats, cholesterol and triacylglycerol) in the blood.
Triacylglycerol is the main component of animal and vegetable fats in the diet, and the main component of the body's fat stores.
LDL-C and VLDL-C are needed by the body but are commonly above the required level; hence viewed as 'bad cholesterol'.

Sample size (Intervention/ control)	Age group (years) and gender	Study design	Study length
18/18	45.6 ± 5.6	Randomized cross over study conducted by feeding finger millet porridge to intervention group. Control group consumed a regular diet.	8 weeks
9/9, 6/6	37-40 years; gender not given	Breakfast, lunch and dinner comprising barnyard millet *upma* or in rice form were provided.	28 days
30/30	Not indicated; 60 women	Randomized feeding intervention: The intervention group was given millet dumplings for lunch and the control group consumed a regular diet.	120 days
12/12	20-50 years; 12 men and women	Quinoa was given for a month and then after a washout period of 15 days, a foxtail millet diet was given for 30 days in place of rice.	30 days
15/15	40-50 years; 17 men and 13 women	The intervention group was fed a low-GI finger millet bun.	60 days
10/10	36-78 years; 16 men and 14 women	A case-control clinical trial for 30 days where the sample was fed biscuits, followed by a crossover clinical trial for 30 days where the sample was fed *burfi*.	30 days
44/44	30-50 years; 42.24 men, 45.8 women	Randomized trial: The intervention group received _associated_ to include millet in their daily diet and was monitored on the telephone. The control group consumed a regular diet.	3 months
9/6	>40 years; 8 men and 10 women in the intervention group and 4 men and 6 women in the control group	A low-GI foxtail millet diabetic mix was fed to the intervention group.	4 weeks
15/15	24-26 years; all women	Barnyard millet was fed to diabetic subjects and the control group consumed a regular diet.	3 months
24/24	18-40 years; all men	Randomized controlled trial: Sorghum meal and wheat meal were given to overweight men to test the impact on reducing body fat.	8 weeks
47/47	51.72 ± 1.09; both male and female	The intervention group was fed millet-based *roti* and the control group consumed a regular diet.	90 days
7/6	25-45 years; 3 men and 4 women in the intervention group and 2 men and 2 women in the control group	The intervention group was fed millet-based health food as a meal and the control group consumed a regular diet.	28 days

LDL-C normal level is <100 mg/dl, moderately elevated or borderline high level is 130 to 159 mg/dl, and high is >160 mg/dl.
HDL-C is required in the body but can be too low or too high. Typically, the levels are normal or too low, so is viewed as 'good cholesterol'.
HDL-C levels are low if <40 mg/dl, high if >60 mg/dl.

References

Systematic review and meta-analysis

Anitha, S., Tsusaka, T.W., Botha, R., Kane-Potaka, J., Givens, D.I., Rajendran, A., and Bhandari, R.K. 2022. Are millets more effective in managing hyperlipidaemia and obesity than major cereal staples? A systematic review and meta-analysis. *Sustainability* 14. https://doi.org/10.3390/su14116659

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Claim 3: Millets may be helpful in weight control and in reducing obesity but more scientific evidence is needed

Scientific evidence and results

Millets are considered to be good for managing weight and reducing obesity due to their high dietary fiber, low glycemic index (Anitha et al. 2024a), and high protein content (Anitha et al. 2024b), which in effect reduce lipid levels and delay gastric emptying time, thereby extending the feeling of being full.

While there is some evidence indicating that millet consumption may be useful for managing weight and reducing obesity, for the purposes of this systematic review and meta-analysis, no published studies that focused exclusively on weight management could be identified. There were four scientific studies that measured the body mass index (BMI) and compared results with a control group. These were deemed scientifically appropriate for this review.

Comparison of millet-consuming groups with groups consuming other staples showed that:

Key results

- **BMI fell by 2.5%** in people who were overweight and obese.
  However, this was based on a small number of studies and the decrease was not statistically significant.
  *(effect size: -0.21)

The studies

The overall study of studies, comprising a systematic review and a meta-analysis, is titled: Are millets more effective in managing hyperlipidaemia and obesity than major cereal staples? A systematic review and meta-analysis. (Anitha et al. 2022)

The studies analyzed are listed in the references and detailed in Table 3A.

Table 3A. **A summary of the studies analyzed for the systematic review.**

S.No	Study	Type of millet	Test meal/amount consumed (grams/meal)	Parameters studied
1.	Geetha et al. 2019	Mixed millet	Dumpling/not mentioned	Total cholesterol, triglycerides, LDL-C, VLDL-C, HDL-C, BMI, weight
2.	Anushia et al. 2019	Millet	Meal/not mentioned	Total cholesterol, triglycerides, LDL-C, BMI
3.	Anunciacao et al. 2019	Sorghum	Breakfast cereal and drink made of extruded sorghum/40 g	Weight, BMI
4.	Sobhana et al. 2020	Mixed millets	*Roti*/90 g	Total cholesterol, triglycerides, LDL-C, VLDL-C, HDL-C, weight, BMI, systolic and diastolic blood pressure

Note: BMI is calculated taking into account a person's weight relative to height.
BMI <25 = normal; 25-30 = overweight; and >30 = obese.

Sample size (intervention/ control)	Age group (years) and gender	Study design	Study duration
30/30	Not indicated	Randomized feeding intervention in which millet dumpling was given for lunch to the intervention group. The control group consumed a regular diet.	120 days
44/44	30 to 50 years	Randomized trial in which the intervention group received counseling to include millet in the daily diet and was monitored telephonically. The control group consumed a regular diet.	3 months
24/24	18-40 years; All men	Randomized controlled trial to test sorghum meal against wheat meal for its benefit in reducing body fat in overweight men.	8 weeks
47/47	51.72 ± 1.09; both male and female	The intervention group was fed a millet-based roti and the control group consumed a regular diet.	90 days

Priorities for future research

There is a pressing need for more studies on the impact of millets on weight management in particular:

1. **Exclusive studies focusing on the response of weight management and obesity** to millet consumption.
2. More detailed research focusing on weight management and including different **ages, segregating genders** and **cultures**.

These studies should analyze weight management and obesity response in relation to **different types of millets and varieties.**

Importance of weight management

More than one billion people worldwide are obese—650 million adults, 340 million adolescents and 39 million children—and these numbers are increasing (WHO 2022). In 2017, more than 4 million people died as a result of being overweight or obese. Between 1975 and 2016, the number of overweight or obese children and adolescents aged 5–19 years more than quadrupled globally.

Overweight and obesity, which were once considered a problem only in high-income countries, are now dramatically on the rise in low- and middle-income countries. The vast majority of overweight or obese children now live in developing countries (WHO, n.d.).

References

Systematic review and meta-analysis

Anitha, S., Tsusaka, T.W., Botha, R., Kane-Potaka, J., Given, D.I., Rajendran, A., and Bhandari, R.K. 2022. Are millets more effective in managing hyperlipidaemia and obesity than major cereal staples? A systematic review and meta-analysis. *Sustainability* 14(11): 6659. https://doi. Org/10.3390/su14116659

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Claim 4: Millets can increase hemoglobin levels and have a major impact on reducing iron deficiency anemia

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Scientific evidence and results

A study of all the published scientific studies on the impact of millets on anemia in humans was undertaken. This used a systematic review and meta-analysis approach that included 12 studies involving a total of 590 people who were fed meals in which the typical staple of the area was replaced with millets and 549 people in control groups who were fed meals with the standard staples eaten in the area.

Key results

- Across all the studies: **an average of 13.6% increase in hemoglobin level** among the intervention group consuming millet-based foods, while those not eating millet-based meals had an almost negligible change in hemoglobin levels. The intervention group's mean hemoglobin level went from 9.95 ± 1.07 g/dl before treatment to 11.3 ± 1.09 g/dl after consuming the millet-based food while hemoglobin levels in the control group only went from 10.2 ± 0.99 g/dl to 10.6 ± 1.09 g/dl after consuming their regular staple.
- **Mild anemia people shifted to normal status**:In six of the studies, the mild anemia people in the intervention group who consumed millet-based food shifted to normal status.

The studies

The overall study of studies, comprising a systematic review and a meta-analysis, is titled: Can millets increase haemoglobin level and thereby reduce anaemia? – A systematic review and meta-analysis. (Anitha et al. 2023).

Table 4A details the studies included in the systematic review and meta-analysis on the impact of consuming millets on hemoglobin levels.

These studies included the following components:

- Only human studies were included; laboratory (*in vitro*) studies were excluded.
- Only studies with a control group were included.
- The intervention group consisted of 590 adolescents, 268 children and 25 adults while the control group had 260 adolescents, 264 children and 25 adults.
- The studies were all undertaken in India.
- The studies mainly related to pearl millet (5) and finger millet (5); one study used sorghum and one used mixed millets.
- Most studies were conducted over 100 days to 4.5 years, with the exception of one study that was conducted for 25 days and another for 45 days.

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Table 4A. The studies included in the systematic review and meta-analysis on the impact of consuming millets on hemoglobin levels.

Study	Type of food	Study participants/age	Duration	Sample size
1. Devdas et al. 1982	Finger millet-based diet	Pregnant women	9 months	25 intervention (finger millet-based diet); 25 control
2. Devdas et al. 1984a	Finger millet-based diet	2.5-7.5 years	4.5 years	25 intervention (finger millet-based diet); 25 control
3. Devdas et al. 1984b	Finger millet-based diet	6-7.5 years	1.5 years	25 intervention (finger millet-based diet); 25 control
4. Devdas et al. 1984c	Finger millet-based diet	3.5-6.5 years	3 years	25 intervention (finger millet-based diet); 25 control
5. Durairaj et al. 2019	Mixed millets health mix	< 5 years	6 months	30 intervention; 30 control
6. Karkada et al. 2018	Finger millet porridge (4 tablespoons or 60 g/day)	13-14 years	45 days	30 intervention; 30 control
7. Moharana 2020	Pearl millet *laddoo* (sweet)	17-19 years	28 days	60 intervention; 60 control
8. Singh et al. 2014	Pearl millet *laddoo* (sweet)	16-19 years	45 days	10 intervention; 10 control
9. Rajendra Prasad et al. 2015	Sorghum *upma/khichdi, roti*	9-12 years	8 months	80 intervention; 80 control
10. Finkelstein et al. 2015	Pearl millet *bhakri* (flat bread)	12-16 years	6 months	109 intervention; 108 control
11. Scott et al. 2018	Pearl millet *bhakri* (flat bread) and *sev* (snack)	12-16 years	6 months	88 intervention; 52 control
12. Arokiyamary et al. 2020	Pearl millet (100 g/day)	5-6 years	100 days	30 intervention; 30 control

Parameters studied	Study design
Weight, hemoglobin	Feeding intervention: A finger millet-based meal was provided to the intervention group. Another group which served as control was not fed any supplementation diet. Another intervention group that was fed a rice-based diet was not included for the meta-analysis as the aim was to study the efficacy of a finger millet-based diet.
Height, weight, chest circumference, hemoglobin, serum protein	Feeding intervention: A finger millet-based meal was provided to one intervention group. Another group that served as the control was not given any supplementation diet. Yet another intervention group was fed a rice-based diet which was not included for the meta-analysis as the aim was to study the efficacy of a finger millet-based diet.
Height, weight, chest circumference, hemoglobin	A finger millet-based meal was provided to one intervention group. Another group that served as the control was not given any supplementation diet. Yet another intervention group was fed a rice-based diet which was not included for the meta-analysis as the aim was to study the efficacy of a finger millet-based diet.
Weight, height, chest circumference, arm circumference, hemoglobin	A finger millet-based meal was provided to one intervention group. Another group that served as the control was not given any supplementation diet. Yet another intervention group was fed a rice-based diet that was not included for the meta-analysis as the aim was to study the efficacy of a finger millet-based diet.
Hemoglobin, height and weight	Feeding intervention
Hemoglobin	Quasi-experimental design using two-stage cluster sampling method
Hemoglobin	Quasi-experimental pre-test-post-test design
Hemoglobin	Randomized clinical trial
Hemoglobin, serum ferritin, anthropometry	Feeding intervention (there was attrition in the sample by the end of the study)
Hemoglobin, serum ferritin	Double blind randomized efficacy trial
Hemoglobin, serum ferritin, transferin, body iron	Double blind randomized intervention
Hemoglobin	Feeding intervention

Claim 5: Bioavailability of iron from millets is similar to that from other plant-based foods, increases with cooking/processing and can provide the daily physiological iron requirement of an average person

There have been comments made in mass media that the iron in millets has minimal absorption due to antinutrient levels. Some studies have tested and measured the absorption of iron in millets and the antinutrient levels along with the impact of different forms of cooking and processing on antinutrients and iron absorption.

The key findings indicate the following sub-claims.

Claim 5A: Variations in the range of phytates (antinutrients) in millets are similar to those in common staples and legumes

Scientific evidence and results

Phytates were recorded for five of the millets in the Indian Food Composition Tables – pearl millet, finger millet, little millet, kodo millet and sorghum – as well as for all major staples and legumes (Longvah et al. 2017). These are listed in Table 5A.

Key results

Phytates in millets were similar to common staples and legumes where the phytates ranged from:

- 265 to 549 mg/100 g of millets;
- 266 to 742 mg/100 g in common staples; and
- 277 to 604 mg/100 g in legumes.

Table 5A. Phytate content in millets, common staples and legumes.

Cereal/legumes	Phytates (mg/100 g)
Sorghum	549 ± 27.2
Pearl millet	485 ± 12.1
Finger millet	306 ± 6.9
Little millet	265 ± 20.1
Kodo millet	452 ± 6.5
Brown rice	742 ± 14.5
Raw rice (milled)	266 ± 9.6
Whole wheat flour	632 ± 15.9
Maize dry	646 ± 19.4
Split pigeonpea	277 ± 23.4
Whole pigeonpea	604 ± 10.8
Soybean (white)	460
Soybean (brown)	443 ± 24.6
Split chickpea	450 ± 23.2
Whole chickpea	11.2

(Extracted from Longvah et al. 2017)

Reference

Longvah, T., Ananthan, R., Bhaskarachary, K., and Venkaiah, K. 2017. Indian food composition table. Hyderabad, India: National Institute of Nutrition. pp. 1–578.

Claim 5B: Absorption of iron from pearl millet is comparable to that from typical plant-based foods, with iron bioavailability percentages for pearl millet being 7.5 ± 1.6

Scientific evidence and results

Iron bioavailability in plant-based foods approximately ranges from 1-10% (ICMR 2020). There were only two human studies (listed in the references below) pertaining to millets with all the data and measurements of bioavailable iron.

Key results

- Pearl millet had an average iron bioavailability of 7.5% ±1.6. This was the average bioavailability across both studies for high-iron pearl millet (8.2 mg /100 g of iron).

Since these related only to pearl millet, it should be noted that other millets have not been analyzed.

References

Studies assessed

Cercamondi, C.I., Egli, I.M., Mitchikpe, E., Tossou, F., Zeder, C., Hounhouigan, J.D., and Hurrell, R.F. 2013. Total iron absorption by young women from iron-biofortified pearl millet composite meals is double that from regular millet meals but less than that from post- harvest iron-fortified millet meals. *J. Nutr.* 143:1376–1382. doi: 10.3945/ jn.113.17682645.

Kodkany, B.S., Bellad, R.M., Mahantshetti, N.S., Westcott, J.E., Krebs, N.F., and Kemp, J.F. 2013. Biofortification of pearl millet with iron and zinc in a randomized controlled trial increases absorption of these minerals above physiologic requirements in young children. *J. Nutr.* 143:1489–1493. doi: 10.3945/jn.113.1 76677

Claim 5C: Processing can significantly increase the amount of bioavailable iron in millets (based only on laboratory testing)

Scientific evidence and results

A variety of processing methods were tested in 7 studies (listed below in the References); however, they were all laboratory tests, which can only be considered indicative, as methodologies can vary significantly. One additional laboratory study and two studies on humans were excluded as they tested full meals.

Key results

Apart from soaking (Mamiro et al. 2001), all processing methods resulted in increased bioavailable iron (indicative amounts only) compared to the raw/unprocessed grain (see Figure 5A), as shown below:

- The highest increase in iron bioavailability was through extrusion (expansion) at 5.4 times, for finger millet. (Krishnan et al., 2012)
- Bioavailable iron more than tripled with fermentation, popping and malting. This included 3.4 times for fermentation in finger millet, pearl millet and sorghum (Gabaza et al. 2018; Sripriya et al, 1997), 3.4 times for popping in finger millet (Krishnan, et al. 2012) and 3.5 times for malting (Krishnan, et al. 2012) in finger millet.
- Bioavailability of iron more than doubled (2.2 times) with germination (sprouting) (Mamiro et al. 2001; Sripriya et al, 1997; Suma et al. 2014) in finger millet and pearl millet and by 2.6 times with decortication (dehulling) (Krishnan, et al. 2012) in finger millet.
- Dephytinization (Lestienne et al. 2005) increased bioavailable iron by 1.4 times in pearl millet.

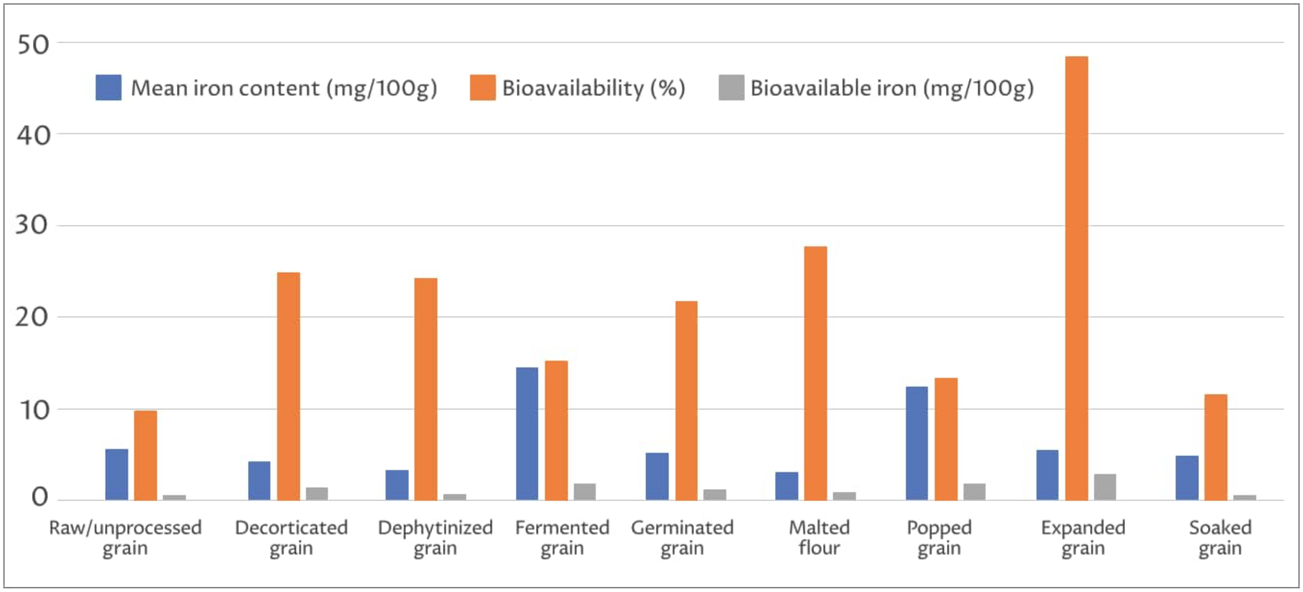

Figure 5A. The effect of processing on the availability of iron in millets.

References

Studies assessed

Afify, AE-M.M.R., El-Beltagi, H.S., Abd El-Salam, S. M., and Omran, A.A. 2011. Bioavailability of iron, zinc, phytate and phytase activity during soaking and germination of white sorghum varieties. PLoS ONE. 6:e25512. Doi: 10.1371/ journal.pone.0025512 *Frontiers in Nutrition* | www.frontiersin.org 13 October 2021 | Volume 8 | Article 725529

Gabaza, M., Abraha, H.S., Muchuweti, M., Vandamme, P., and Raes, K. 2018. Iron and zinc bioaccessibility of fermented maize, sorghum and millets from five locations in Zimbabwe. *Food Res Int.* 103:361–370. doi: 10.1016/j.foodres.2017.10.047

Krishnan, R., Dharmaraj, U., and Malleshi, N.G. 2012. Influence of decortication, popping and malting on bioaccessibility of calcium, iron, and zinc in finger millet. *Food science and technology* 48(2):169–174. doi: 10.1016/j. lwt.2012.03.003

Lestienne, I., Besanc, P., Caporiccio, B., Lullien-peallerin, V., and Treache, S. 2005. Iron and zinc in vitro availability in pearl millet flours (*Pennisetum glaucum*) with varying phytate, tannin, and fiber contents. *J. Agri. Food Chem.* 53:3240–3247. doi: 10.1021/jf0480593

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Sripriya, G., Antony, U., and Chandra, T.S. 1997. Changes in carbohydrate, free amino acids, organic acids, phytate and HCl extractability of minerals during germination and fermentation of finger millet (*Eleusine coracana*). *Food Chem.* 58:345–350. doi: 10.1016/S0308-8146(96)00206-3

Suma, P.F., and Urooj, A. 2014. Influence of germination on bioaccessible iron and calcium in pearl millet (*Pennisetum typhoideum*). *J. Food Sci. Technol.* 51:976–981. doi: 10.1007/ s13197-011-0585-8

Claim 5D: All or most of the daily physiological iron requirement can be provided through millets in the diet (based only on laboratory studies)

Scientific evidence and results

Given the mean iron content in different millets, different forms of processing and bioavailability, the iron absorbed can be calculated and compared with physiological requirements of millets for different genders and age groups. This is shown in Figure 5B based on the 7 studies listed in the references.

Key results

- **Calculations show that all or a significant portion of the physiological iron requirement can be provided through millets,** including in different processed forms, and for different ages and genders.

It is important to note that:

- Since the studies included were only laboratory based, the figures can only be indicative. Human studies are required for more accurate data.
- Numerous variables impact iron levels in millets and its absorption, such as the type of millet, variety of millet, where it is grown, the form of cooking and processing it goes through, and other foods in the diet.

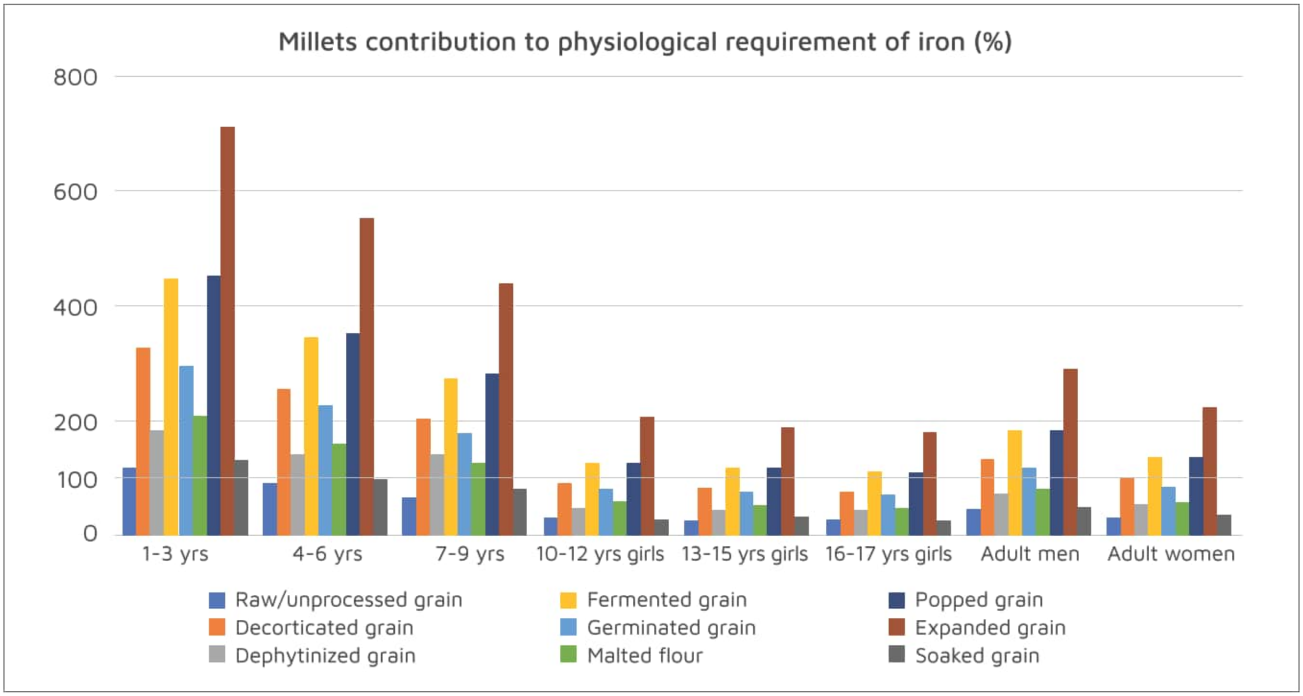

Figure 5B. Millets' contribution to physiological requirements of iron (%) in different genders and ages.
(Source: All 7 studies listed in claim 5C and ICMR (2020))

Priorities for future research

Based on the existing studies and recognized gaps, the recommended priorities for future research are:

1. **More human studies on iron bioavailability in all types of millets**: Only two human studies exist on the bioavailability of iron from millets and these are only on pearl millet.

2. **More studies on the impact of different types of processing on iron bioavailability in millets**: Only laboratory studies exist that test millets alone (not a full meal), which used different study methods. A laboratory study encompassing all the millets and different forms of processing using a uniform methodology will be valuable. Human studies are also needed to strengthen data.

3. **Studies on the impact of millets on reducing iron deficiency anemia covering different types of millet, different meals/ diets and a wider range of age groups, gender, ethnic groups, and health conditions, especially high-risk groups**: Only pearl millet was used in human studies for its impact on reducing anemia, while proso millet, barnyard millet, browntop millet, fonio, teff, Job's tears and guinea millet have not been included in studies on their impact on reducing anemia, and kodo millet, little millet and foxtail millet were studied only as part of mixed millet meals.

Priorities for policy

Two overall priorities are recommended for policy:

1. **Incorporate millets into existing meal programs, especially for high-risk groups of anemia:** This involves designing meals that are tasty, culturally acceptable and maximizing nutritional benefits through the selection of appropriate millets, varieties and complementary food and processing that maximize bioavailability.

2. **Provide incentives to diversify staples with millets:** Common staples across Asia and Africa are low in iron and constitute a large proportion of the meal, making it difficult for people to consume enough iron. Diversifying staples with high-iron millets can be a solution to iron-induced anemia, adding to the many other benefits of millets in terms of nutrition, health and the environment. Diversifying agriculture and food systems and drawing consumer attention to diversifying diets are key.

The importance of iron and the need to tackle anemia

A quarter of the world's population is believed to be anemic and the condition is growing rapidly among vulnerable groups such as women, expectant mothers, young girls and children under 5 years (IHME 2023). In 2021, some 1.92 billion people were reported to be anemic (IHME 2023).

Some facts:

- Half a billion women, i.e., 30% of women in the main reproductive ages of 15-49 are anemic (WHO 2023).
- 37% of pregnant women are anemic (WHO 2023)
- 40% of children from the age of 6 months to under 6 years are anemic (WHO 2023).

Low- and middle-income countries bear the highest burden of anemia, especially Africa and South East Asia (WHO 2023).

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Studies assessed

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Gabaza, M., Abraha, H.S., Muchuweti, M., Vandamme, P., and Raes, K. 2018. Iron and zinc bioaccessibility of fermented maize, sorghum and millets from five locations in Zimbabwe. *Food Res Int.* 103:361–370. doi: 10.1016/j.foodres.2017.10.047

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Other references

ICMR (Indian Council of Medical Research). 2020. Nutrient requirements for Indians Recommended Dietary Allowances estimated average requirements – A report of the expert group. Hyderabad, India: National Institute of Nutrition.

IHME (The Institute for Health Metrics and Evaluation). 2023. The Lancet: New study reveals global anemia cases remain persistently high among women and children. Anemia rates decline for men. Available at https://www.healthdata.org/news-events/newsroom/news-releases/lancet-new-study-reveals-global- anemia-cases-remain-persistently

Longvah, T., Ananthan, R., Bhaskarachary, K., and Venkaiah, K. 2017. Indian food composition table. Hyderabad, India: National Institute of Nutrition. pp. 1–578.

WHO (World Health Organization). 2023. Anaemia. May 2023. Available at www.who.int/news-room/fact-sheets/detail/anaemia (accessed 29 Aug 2023)

Claim 6: A millet-based diet can improve growth in children and help overcome malnutrition and stunting

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Scientific evidence and results

The scientific evidence supporting this claim is based on a study of all existing relevant published scientific studies. This was undertaken as a systematic review and meta-analysis of published studies on the impact of millets on growth in children, as well as the results of randomized control experiments (including comparison of millet interventions with control treatments).

Key results

The results of this study of studies indicate that diversifying standard diets with millets can have a significant impact on growth in children and help overcome malnutrition and stunting.

- **Children and adolescents fed millet-based diets had significantly more growth (28-37%) compared to those given regular refined rice-based diets.**

Other results included:

- 28.2% greater increase in mean height (based on 8 studies)
- 26% greater increase in weight (9 studies)
- 39% greater increase in mid upper arm circumference (5 studies)
- 37% greater increase in chest circumference (5 studies)

(*Note:* These results were all statistically significant at $p < 0.05$.)

Given that the diets fed to the intervention group and control group differed only in respect of the staple cereal (millet or refined rice), this positive impact on growth is attributed to the naturally high nutrient content of millets, which have high amounts of growth-promoting nutrients (especially sulfur amino acids, total protein and extremely high levels of calcium in the case of finger millet).

However, when regular diets were greatly enhanced with more diverse and nutritious foods, replacing refined rice with millets led to only very minimal growth improvement—with a chest circumference increase of only 2% ($p < 0.05$). This is a reasonable result given that the enhanced control diet has a diverse range and good quantities of nutritious foods, and so replacing one food item is likely to have less effect.

These results indicate that there is value in including millets as a staple in the diets of communities whose normal meals are not diverse or highly nutritious.

The studies

The overall study of studies, comprising a systematic review and a meta-analysis, is titled: Can feeding a millet-based diet improve the growth of children? —A systematic review and meta-analysis. (Anitha et al. 2022).

The studies analyzed are listed in the references and detailed in Table 6A and include the following components:

- **Age groups** studied: Infants, preschool and school-age children and adolescents.
- **Number of eligible studies**: 11 for the systematic review; 9 for the meta-analysis in randomized feeding trials; and 8 for the meta-analysis. All studies were undertaken in India.
- **Types of millets** included in the studies: Finger millet in the majority of studies (9 studies in total); sorghum in 1 study; a mixture of millets (finger, pearl, foxtail, little and kodo millets) in 2 studies.
- **Duration of study**: From 3 months to 4.5 years. The majority of studies (9) were carried out for longer periods of time (ranging from 8 months to 4.5 years); and 2 studies were carried out for shorter periods (3 months and 6 months).
- **Diet comparisons** included: Refined rice was substituted for millets in regular as well as enhanced diverse diets. The enhanced diets based on finger millet had higher quantities of each food group compared to the regular diet: 45% more finger millet, 270% more pulses, 59% more dairy products, 140% more green leafy vegetables and 64% more fruits. The enhanced refined rice-based diet had 35% more refined rice, 327% more pulses, 59% more dairy products, 194% more green leafy vegetables and 70% more fruit.

Priorities for future research

The analysis provides strong evidence for millet consumption improving growth. However, more detailed studies are needed with greater variation of different variables, not just about adding millets to diets but analyzing different ways to incorporate millets. Specific recommendations for these variations follow.

1. **Study more types of millets and varieties**: The studies considered for the meta-analysis researched finger millet, sorghum and multiple millets (finger millet, pearl millet and little millet). Broadening this approach to study other types of millets will help in determining which ones have the most positive impact on growth and hence should be included in nutrition programs and nutrition-sensitive agriculture interventions. In particular, it would be very useful to compare finger millet, which has very high calcium content, with other millets and understand how it impacts growth.

   None of the studies analyzed identified the specific varieties of millet used or the effect of specific nutritional content. Future studies addressing these aspects will help in identifying how important a particular type of millet and its varieties can be in increasing growth.

2. **Study more ethnic groups**: The studies included in the meta-analysis were all limited to India. More such studies are needed in other countries, especially in Africa where millets are a traditional crop and there is high malnutrition.

3. **Include all the growth measurements**: Only two of the studies measured body mass index (BMI). The others measured only height and weight without estimating BMI, height-for-age (HAZ) and/or weight-for-age (WAZ). Including all aspects of growth in future studies will lead to a better understanding of millet impact on stunting and underweight status.

4. **Measure all major growth promoters**: For instance, methionine is an essential sulfur-containing amino acid and a major growth promoter. However, none of the studies measured it in the intervention and control diets. Also, total protein, calcium and zinc, very important as growth promoters, were not measured.

5. **Analyze different types of cooking/ processing** of millets to ascertain their impact on growth. That can lead to more detailed recommendations on diet design.

6. **More studies on adolescents needed.** Only one study was designed to assess the impact of millet-based diets on adolescent growth. Adolescence being the third critical stage of rapid growth and bone mineralization in humans, millet impact on nutrition during that stage would be a good policy input to have.

7. **Newer studies are needed on the impact of millets.** Except two studies included in this analysis, all others were conducted in the 1980s and by one research team.

8. **Studies designed with more accuracy to standardize meals** for both the intervention and control groups. In the studies, the diets were similar and just the staple cereal was changed for the intervention group; however, there should be more accuracy to standardize all food groups so that both intervention and control diets are the same except the selected staple.

New studies should, wherever possible, incorporate the research priorities mentioned above. Also, high research standards should be followed.

Table 6A. A summary of each study that was analyzed for the systematic review.

Study	Country	Type of millet	Form consumed	Study participants	Duration
1. Devdas et al. 1982	India	Finger millet	Meal	Pregnant women	9 months
2. Devdas et al. 1984a	India	Finger millet	Finger millet malted, finger millet porridge, cooked with pulses, *idli, adai*	Infants	0-18 months
3. Devdas et al. 1984b	India	Finger millet	Meal	Preschool children	0-4 years
4. Devdas et al. 1984c	India	Finger millet	Meal	School children	2.5-4.5 years
5. Devdas et al. 1984d	India	Finger millet	Meal	School children	6-7.5 years
6. Devdas et al. 1984e	India	Finger millet	Meal	Preschool children	0 to 3 years
7. Devdas et al. 1984f	India	Finger millet	Meal	Preschool children	3.5-6.5 years
8. Durairaj et al. 2019	India	Kodo, little, foxtail millets	Health drink	Primary school children	6 months
9. Rajendra Prasad et al. 2015	India	Sorghum	Sorghum *roti* (flat bread), cooked with water, *khichdi/upma*	School going children	8 months
10. Anitha et al. 2019	India	Finger millet, pearl millet, little millet	*Khichdi, ragi idli, bisibele bath,* little millet cooked with water	Adolescents	3 months

Sample size	Parameters studied	Study design and remarks
25 intervention (finger millet-based diet); 25 control	Weight, hemoglobin	Controlled feeding trial. This study was not included in the meta-analysis as it was focused on pregnant women.
25 intervention (finger millet-based diet); 25 control	Weight, height, chest circumference, mid upper arm circumference	Controlled feeding trial: Millet-based diet fed to one group; enhanced refined rice-based diet to another group and control group given regular refined rice-based diet.
25 intervention (finger-millet-based diet); 25 control	Weight, height, chest circumference, mid upper arm circumference	Controlled feeding trial: Millet-based diet to one group; enhanced refined rice-based diet to another group and regular refined rice-based diet to the control group.
25 intervention (finger millet-based diet); 25 control	Height, weight, chest circumference, hemoglobin, serum protein level	Controlled feeding trial: Millet-based diet to one group; enhanced refined rice-based diet to another group and regular refined rice-based diet to the control group.
25 intervention (finger millet-based diet); 25 control	Height, weight, chest circumference, hemoglobin	Controlled feeding trial: Millet-based diet to one group; enhanced refined rice-based diet to another group and regular refined rice-based diet to the control group.
25 intervention (finger millet based diet); 25 control	Weight, height, chest circumference, arm circumference, hemoglobin	Controlled feeding trial: Millet-based diet to one group; enhanced refined rice-based diet to another group and regular refined rice-based diet to the control group.
25 intervention (finger millet-based diet); 25 control	Height, weight, chest circumference, hemoglobin	Controlled feeding trial: This study was not included in the meta-analysis as baseline values were not available to calculate mean differences.
30 intervention; 30 control	Height and weight	Controlled feeding trial: Standard Deviation (SD) change was calculated using t value provided in the paper as per the Cochrane handbook (Higgins et al. 2019).
78 intervention	Height, weight, hemoglobin, BMI	Controlled feeding trial: Sorghum-based diet given to intervention group and compared with enhanced refined rice-based diet given to the control group. This study was included for the weight parameter. For the height parameter, the boys group's value was not included as it was presented in different ways in two papers by the same author. This was influencing the entire study, so it was excluded.
136 intervention; 107 control	Height for age; BMI for age	Controlled feeding trial: Millet-based diet (intervention) compared with enhanced refined rice-based diet (control). Height and weight values obtained from the author.

Priorities for policy

To tackle child malnutrition and achieve sustainable nutritional security, government support is needed to bring about a level playing field for millets and to drive demand for millets in order to attract investments across the whole value chain. There is a need to drive demand from fork to farm — from consumer to farmer. It is imperative to work with influencers.

There is a need for awareness raising, capacity building and advocacy, all supported by scientific evidence. Policy-making should incentivize whole-grain millets and promote healthy product development to ensure that their nutritional value is retained as the industry develops.

Priority recommendations:

1. Governments develop programs to **diversify staples** to include millets.
2. **Meal programs** be designed to include millets. These can be designed for different ages and as culturally sensitive and tasty recipes, and incorporated into school meal programs and mother and child programs.
3. **Meal programs complemented with awareness and marketing campaigns** to change the image of millets and generate popular interest in them.
4. Provide **incentives to grow and invest** in millets, and to develop at minimum a level playing field for millets in countries where subsidies or support programs exist.

The importance of growth and malnutrition

Undernutrition (stunting, underweight and wasting) are a major global crisis. Currently, stunting affects 149 million children and wasting affects 45 million children under 5 years (WHO 2021). Undernutrition renders children highly vulnerable to infections, increases the frequency and severity of infections and delays recovery.

Of the global deaths of children under 5 years, approximately 45% are linked to undernutrition (WHO 2021). They are more prevalent in low- and middle-income countries. Wasting is prevalent among more than half of the stunted children under 5 in Asia and in more than one-third in Africa. More than two-thirds of all wasted children live in Asia and more than a quarter in Africa (UNICEF/WHO/World Bank 2019). Child malnutrition is a very sensitive indicator of the overall levels of food security and hunger.

Diversifying staples

In the developing countries of Asia and Africa, more than 70% of energy intake comes from the Big 3: Rice, wheat and maize-based foods (Awika 2011; Anitha et al. 2019). Traditional crops such as millets are rich in nutrients, including protein, iron and zinc as well as calcium (in the case of finger millet), which are generally lacking in staples such as milled rice and maize (Longvah et al. 2017).

Given the high nutrient content of millets, understanding their role in growth should be a high priority for policymakers striving to achieve sustainable nutritional security.

References

Systematic review and meta-analysis

Anitha, S., Givens, D.I., Subramaniam, K., Upadhyay, S., Kane-Potaka, J., Vogtschmidt, Y.D., Botha, R., Tsusaka, T.W., Nedumaran, S., Rajkumar, H., Rajendran, A., Parasannanavar, D.J., Vetriventhan, M., and Bhandari, R.K. 2022. Can feeding a millet-based diet improve the growth of children? —A systematic review and meta-analysis. *Nutrients* 14:225. https://doi.org/10.3390/nu14010225

Studies qualifying for the systematic review and meta-analysis

Devdas, R.P., Chandrasekhar, U., and Bhooma, N. 1982. Nutritional outcomes of a rural diet supplemented with low cost locally available foods—I. Impact on expectant women. *Indian J. Nutr. Dietet.* 19: 111–116. [Google Scholar]

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Claim 7: Millets can keep you feeling full longer compared to a variety of other grains – Analyzing hunger index, satiety score and glycemic response

Scientific evidence and results

Existing studies evaluating the impact of consuming millets on hunger index, satiety score and glycemic response were collated and reviewed.

Six studies were identified that fulfilled the scientific criteria, including that of having control groups. These consisted of 5 randomized studies conducted on humans and 1 laboratory study based on a simulation method that is equivalent to human studies. Studies conducted on animals were excluded.

The control groups were fed a variety of foods including oats, rye, refined rice, potato, barley and buckwheat.

Key results

The available evidence shows that:

- **Millets have very high fiber content, almost double of what is considered 'high'.** Fiber content is considered high when there are at least 6 g of fiber per 100 g. Pearl millet, finger millet and sorghum have on average almost double this level of fiber. Table 7A lists the fiber content in millets compared to that in other common grains.
- Millets can **increase satiety** and **delay gastric emptying time,** leading to a **feeling of fullness for long.**

These properties of millets have multiple benefits such as **reducing blood glucose level** and **reducing lipid profile level.**

This means that with a holistic approach, millets can contribute to reducing chronic health issues like obesity, diabetes and cardiovascular disease.

This is supported by other studies (based on systematic reviews and meta-analyses) on weight control and obesity (Anitha et al. 2022a), diabetes (Anitha et al. 2023) and hyperlipidemia (Anitha et al. 2022b).

Table 7A. Fiber content in various grains (Longvah et al. 2017).

Grain	Fiber content (g/100 g)		
	Total fiber	Insoluble fiber	Soluble fiber
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
Refined rice	2.81 ± 0.42	1.99 ± 0.39	0.82 ± 0.22
Refined wheat flour	2.76 ± 0.29	2.14 ± 0.30	0.62 ± 0.14
Dry maize	12.24 ± 0.93	11.29 ± 0.85	0.94 ± 0.18
Whole wheat flour	11.36 ± 0.29	9.73 ± 0.47	1.63 ± 0.64
Barley	15.64 ± 0.64	9.98 ± 0.62	5.66 ± 0.68

The studies

The overall study that analyzed the existing studies is titled: Millets have potential to increase the satiety value and reduce the feeling of hunger (Anitha et al., submitted).

Table 7B summarizes the studies analyzed. The millets tested included major millets – pearl millet, finger millet and sorghum. The controls included oats and rye breakfast porridge, refined rice, potato and wheat pasta, wheat couscous, pearl barley groats, buckwheat groats and oat groats and grits.

Table 7B. A 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	Of the 16 participants (10 female and 6 male), 15 were given oats and rye, 9 were given finger millet and 12 were given pearl millet.	21	Randomized four-way crossover study	Periodical MRI scan to measure gastric volume; fasting and post-prandial blood glucose levels	Pearl millet induced lower post-prandial blood glucose levels and appetite scores. The 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 reduces 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 female, 9 male)	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 the porridges.	GIP is a hormone that is linked to triacylglycerol absorption. The lower GIP response with pearl millet porridge is an added advantage.

(Continued)

Author	Location	Food tested	Sample size	Age (years)	Study design	Parameters	Results	Remarks
Cisse et al. 2018	Bamako, Mali	Sorghum, millet, refined rice, potato and wheat pasta	14 healthy participants (12 men and 2 women) were included in the main study and 6 individuals (3 men and 3 women) were included in the validation study.	20 -50	Crossover study for 16 consecutive days and validation after one year	Gastric emptying time, visual analogue scale to measure satiety value	Millets and sorghum as thick porridge and millet couscous have a slow gastric emptying time of 2.5 hours compared to other starchy foods such as refined rice (1.3 hours), boiled potato (1.5 hours) and wheat pasta (1.2 hours) in normalweighing individuals.	There is a significant difference between millet and sorghum in slowing gastric emptying time.
Hayes et al. 2019	West Africa	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 that is densely packed; therefore, the hydrolysis in millet was slow, which could account for the slow gastric emptying rate.
Hayes et al. 2020	USA	Thick millet porridge, 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 (commercially available) (n=14), wheat couscous (n=15) and white rice (n=15)	18 -50	Crossover study with a 5-7 day washout period	Continuous glucose monitoring for glycemic response, visual analogue 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 foods tested (<3 hours). Glycemic response in all millet-based foods and wheat was lower compared to that in refined rice.	Millet-based products give 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)

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. However, oat and barley groats had the highest satiety value which was associated with the dietary fiber and hydration degree. Millet groat was found to have less fiber compared to oats and barley groats.	The study suggests that oats groats and barley groats could be a good dietary option for people who areoverweight.

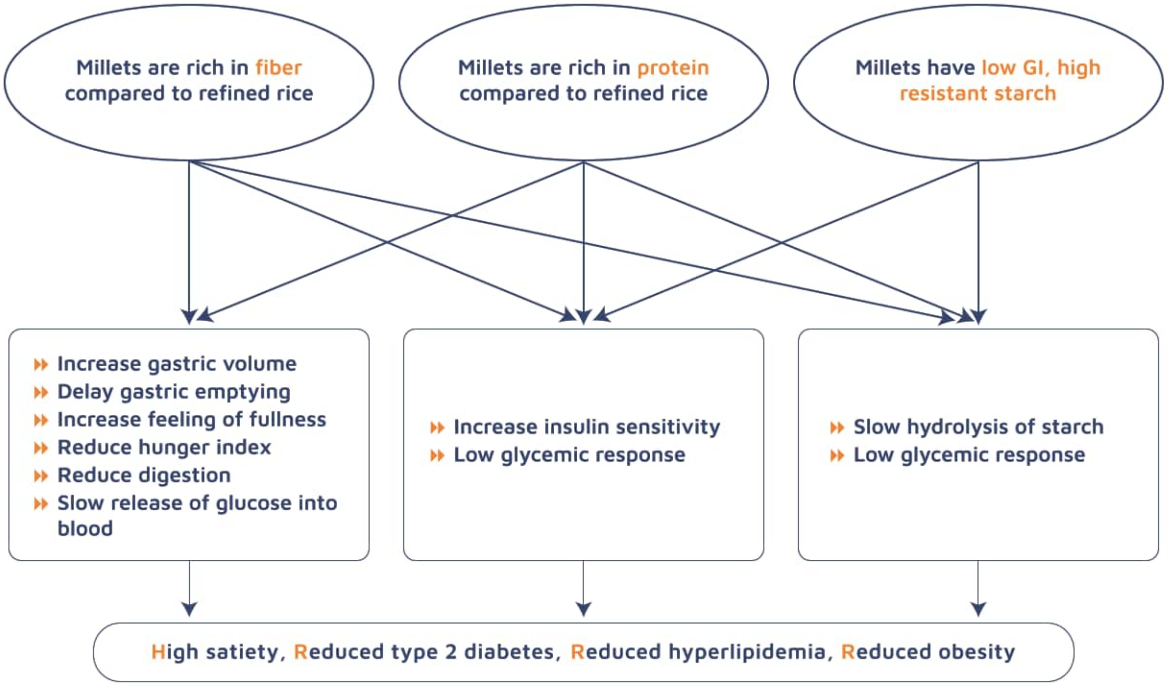

Figure 7A. Interconnections of millets action on satiety and other health issues. (Anitha, et al. 2024)

Priorities for future research

1. More studies and replications are needed that include the following variables:
   - All minor millets need to be tested for their effects on satiety, as only studies on major millets (pearl millet, finger millet and sorghum) were identified. Moreover, some millets were not specified by type.
   - Different age groups need to be studied, especially the very young (babies and young children) and the elderly, to understand how the feeling of fullness due to millets can impact those with sensitive digestive systems.
   - The impacts of different types of cooking and processing on millets should be studied to assess their impact on feeling of fullness.
   - A wider range of ethnic groups need to be studied. The studies chosen were undertaken in Asia, where a large number of millets are grown and eaten.
2. Studies focussed on endurance can provide specific data and insights into how and when millets can be beneficial to those undertaking physical work and sports.
3. Studies should extend to understanding the impact of millets on gut health.

Priority for policy

1. Millets should be appropriately integrated into public health policies and plans for overnutrition, diabetes and hyperlipidemia.

References

Overall study

Anitha, S., Upadhyay, S., and Kane-Potaka, J. 2024. Millets have the potential to increase satiety and reduce the feeling of hunger: a systematic review. *Frontiers in Sustainable Food Systems - Nutrition and Sustainable Diets.* Vol. 8. https://doi.org/10.3389/fsufs.2024.1348068

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Claim 8: Nutrient levels of millets vary significantly by variety

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The need

Millets are frequently claimed to be nutritionally superior compared to common staples like refined rice, wheat and maize and foods made out of the refined grains. However, nutrition tables listing the nutrient contents of millets often do not reference the study the data was sourced from nor the methodology of determining the contents. Additionally, millet nutrient tables rarely specify which variety (or cultivar) the data pertains to or whether those nutrient contents are present in commonly available millet varieties. Since nutrient contents vary across varieties, this can give rise to confusion. There is a need therefore to relate millet nutrition data to specific varieties.

Scientific evidence and results

To address this need, a study was undertaken to organize the nutrient levels of millets by variety. Only data published in English scientific journals was assessed for this purpose. Ninety full-length research papers, book chapters and food composition tables were selected for variety- wise nutrition data on 12 most commonly grown millets: barnyard millet, browntop millet, finger millet, fonio, foxtail millet, Job's tears, kodo millet, little millet, pearl millet, proso millet, sorghum, and teff. Data from the 90 studies covered 61 countries.

Key results

- Nutrient levels of millets vary significantly by variety.
- The newly collated nutrition table (Table 8A) is believed to be the most representative of nutrient levels of grown millets.

There are limitations of this data and an important recommendation arising from this review is that nutrition tables should be designed in accordance with the specific millet variety used or available.

Table 8A. Nutrient composition of millets

(mean levels with standard deviation and range).

	Barnyard millet	Browntop millet	Finger millet	Fonio	Foxtail millet
Iron mg/100g	10.06 ± 7 (2.28–22.98)	–	12.21 ± 13.69 (2.64–53.39)	2.42 ± 2.81 (0.80-10.00)	5.15 ± 4.06 (1.92-12.90)
Zinc mg/100g	2.03 ± 1.85 (0.44-5.92)	–	2.49 ± 0.81 (0.97-3.93)	2.31 ± 0.52 (1.9-3.8)	–
Calcium mg/100g	23.83 ± 7.72 (5.81-36.13)	–	331.29 ± 103 (29-523)	–	70.07 ± 49.48 (31-155)
Protein g/100g	12.05 ± 1.77 (10.05–14.75)	11.64 –	9.32 ± 2.60 (5.80–16.87)	8.52 ± 0.62 (7.40-9.50)	10.4 5± 1.05 (9.50-12.30)
Fiber g/100g	27.48 ± 3.59 (23.25–31.70)	16.08 –	8.19 ± 5.51 (2.22–18.06)	18.20 ± 1.56 (15.70-20.70)	2.01 ± 0.43 (1.52-2.38)
Magnesium mg/100g	195.42 ± 16.33 (169–221)	–	168.67 ± 36.14 (78–201)	–	–
Fat g/100g	5.65 ± 1.10 (3.01–6.90)	5.28 –	1.86 ± 1.56 (0.10–4.50)	4.16 ± 0.31 (3.60-4.50)	4.29 ± 0.33 (3.84-4.58)
Carbohydrate g/100g	–	–	68.72 ± 5.23 (56.32–75.30)	65.99 ± 1.83 (62.20-68.70)	–
Ash g/100g	–	8.62 –	2.35 ± 0.78 (0.73–4.00)	3.07 ± 1.54 (2.10-7.40)	1.81 ± 0.27 (1.54-2.17)

(Source: Extracted from Table 6 in the systematic review by Anitha et al. 2024)

Note: Where there is a gap in data in the table, it means that no studies were identified that satisfied the requirement for recoding of data.

Job's tears	Kodo millet	Little millet	Pearl millet	Proso millet	Sorghum	Teff
–	2.34 (2.34-2.34)	1.26 (1.26-1.26)	6.14 ± 1.78 (2.18-13.41)	3.4 ± 0.56 (3-.380)	6.60 ± 8.08 (2.43-55.26)	11.09 ± 8.35 (3.74-34.69)
–	1.65 (1.65-1.65)	1.82 (1.82-1.82)	8.73 ± 11.55 (1.70-134)	–	3.44 ± 4.45 (0.8-26.99)	2.91 ± 0.68 (2.36-4.43)
–	15.27 (15.27-15.27)	16.06 (16.06-16.06)	21.85 ± 14.18 (3.17-72.87)	15.50 ± 10.61 (8-23)	35.49 ± 40.95 (5-241)	183.41 ± 29.45 (148-232)
12.66 –	8.92 (8.92-8.92)	10.13 (10.13-10.13)	9.02 ± 2.75 (4.50-17.10)	12.42 ± 1.99 (9.37-15.20)	10.74 ± 2.66 (4.28-17.00)	9. 5± 1.82 (6.76-13.30)
3.8 –	–	–	10.68 ± 3.18 (2.07-17.60)	2.33 ± 0.04 (2.30-2.35)	4.20 ± 2.12 (1.64-9.12)	1.75 ± 0.51 (0.79-2.25)
–	–	–	156.04 ± 70.54 (34.02-477)	–	157.48 ± 34.33 (83.4-238)	142.70 ± 16.29 (118-168)
4.26 –	–	–	7.52 ± 1.20 (5.14-10.20)	3.21 ± 0.16 (3.09-3.32)	3.13 ± 0.96 (1.21-5.60)	3.27 ± 0.16 (3.04-3.48)
–	–	–	69.97 ± 8.36 (55.50-81.00)	–	67.01 ± 5.27 (56.39-74.21)	74.07 ± 1.43 (71.9676.48)
1.38 –	–	–	1.90 ± 0.31 (1.47-2.17)	2.22 ± 0.06 (2.17-2.26)	2.09 ± 0.53 (1.30-3.45)	2.49 ± 0.32 (2.13-3.22)

The studies

The systematic review conducted on the 90 studies is titled: Variation in the nutrient content of different genotypes and varieties of millets, studied globally: A systematic review (Anitha et al. 2024).

Results in detail

The systematic review showed:

- Some millets were consistently high or low in the measured nutrient while others varied widely.
- ***Calcium*** levels are consistently very high in finger millet (331.29 ± 103 grams/100 grams) and teff (183.41 ± 29.45 g/100 g) varieties. These two millets, respectively, can provide 33% and 18% of the recommended daily allowance (RDA) of calcium for a female adult consuming 100 g per day. However, some finger millet varieties were outliers with very low calcium content; so programs requiring high calcium levels from finger millet should check the variety they are working with.
- ***Iron*** content was highest in finger millet (12.21 ± 13.69 g/100 g) followed by teff (11.09 ± 8.35 g/100 g), barnyard millet (10.06 ± 7 g/100 g), sorghum (6.60 ± 8.08 g/100 g), pearl millet (6.14 ± 1.78 g/100 g) and foxtail millet (5.15 ± 4.06 g/100 g). These millets can provide between 41% and 17% of the RDA of iron for a female adult consuming 100 g per day. (*)
- ***Zinc*** levels are good in all the millets with pearl millet (8.73 ± 11.55 g/100 g) followed by sorghum (3.44 ± 4.45 g/100 g) and teff (2.91 ± 0.68 g/100 g). These millets can provide between 67% and 22% of the RDA of zinc for a female adult consuming 100 g per day.(*)

(*) A serving may be up to about 300 g and vary depending on the individual.

- ***Protein*** was high in nearly all the millets, within the range of 4.25-17.10%, with the highest being in Job’s tears (12.66%), followed closely by proso millet (12.42% ± 1.99), barnyard millet (12.05% ± 1.77), browntop millet (11.64%), sorghum (10.74% ± 2.66), foxtail millet (10.45% ± 1.05), little millet (10.13%), teff (9.5% ± 1.82), finger millet (9.32% ± 2.60), pearl millet (9.02% ± 2.75), kodo millet (8.92%) and fonio (8.52% ± 0.62). Note that only one of the reports analyzed for this review reported on protein levels in Job’s tears.
- ***Dietary fiber*** was high overall in the majority of millets. Exceptionally high total dietary fiber content was reported in barnyard millet varieties (27.48 ± 3.59 g/100 g) which can meet 100% of the fiber requirement of the body based on consuming 100 g per day (ICMR 2020). This was followed by browntop millet (27.48 ± 3.59 g/100 g), fonio (18.20 ± 1.56 g/100 g), pearl millet (10.68 ± 3.18 g/100 g) and finger millet (8.19 ± 5.51 g/100 g).
- ***Magnesium*** levels were high too in the millets for which data was available. This included barnyard millet (195.42 ± 16.33 g/100 g), finger millet (168.67 ± 36.14 g/100 g), sorghum (157.48 ± 34.33 g/100 g), pearl millet (156.04 ± 70.54 g/100 g) and teff (142.70 ± 16.29 g/100 g). This can typically provide between 52% and 38% of the RDA for a female adult.

Additional analysis was undertaken using heat maps to identify correlation between different nutrients. Most of the genotypes and varieties of millets showed:

- ***a positive relation between grain iron and zinc content.*** This is expected given that both nutrients share the same physiological mechanism of absorption from soil and assimilation into the grains.
- ***a positive relation between protein and most of the minerals.*** This is expected because they act as cofactors for most of the protein enzymes.

Priorities for future research

Table 8A accompanying this analysis is believed to be the most accurate of the existing millet nutrient tables. However, there are limitations, and future research priorities include:

1. **Nutrition tables should be collated by variety** to reflect the nutrition levels in millet varieties available in specific markets.
2. **The tables should show the range of the nutrients** (based on available varieties).
3. **A new regional and worldwide nutrition collation study should be undertaken using one consistent methodology.**
4. **Future research should state clearly what level of processing was undertaken when nutrient levels were recorded and also cover the different types of processing** and how this impacts bioavailability.
5. **More nutrients should be included in future studies,** and data for all the main 12 millets should be collected. This includes breaking down data by the type of fat and carbohydrates.
6. **Other factors like growing conditions should also be studied** to understand the impact on nutrient levels in millets.

Policy recommendation

It is highly recommended that:

1. **Nutrition programs and product development using millets should take the variety of the millet into account.**

References

Systematic review

Anitha, S., Rajendran, A., Botha, A., Baruah, C., Mer, P., Sebastian, J., Updhyay, S., and Kane-Potaka, J. 2024. Variation in the nutrient content of different genotypes and varieties of millets, studied globally: a systematic review. *Frontiers in Sustainable Food Systems - Nutrition and Sustainable Diets.* Vol. 8. https://doi.org/10.3389/fsufs.2024.1324046

Other reference

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Claim 9: In general, millets contribute to food safety better than other staple crops; they are less susceptible to major mycotoxins aflatoxin and fumonisin; and are gluten- and lactose-free and thus low in allergens

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Scientific evidence and results

Existing studies on food safety challenges in millets, including food allergens, were reviewed and analyzed (Anitha et al. 2023). The overall results of this analysis are summarized below:

Key results

- If handled well after harvest, millets have a lower food safety risk overall than most commodities.
- Millets are less susceptible to aflatoxin and fumonisin contamination than maize and many other popularly grown crops across Asia and Africa.
- Even when contaminated, millets accumulate lower aflatoxin levels since they have less oil content and have less exposure to soil contaminants as they are grown above the ground.
- Overall aflatoxin contamination in millets is less compared to maize, groundnut, sesame and bambara nut.
- Millets were occasionally found to be contaminated with toxigenic strains of *Aspergillus flavus*. However, under conditions of extreme temperature, aflatoxin contamination in millets can be high, particularly during droughts and floods.
- Millets have a high nutritional value. When combined with high food safety standards, they can potentially be important in boosting immunity (Villena et al. 2020; Fung et al. 2018), and possibly contribute to consumers' coping capacity against harmful bacteria and viruses.
- Millets are low in allergens as they are gluten-free and lactose-free.

Results in detail

The studies analyzed support the fact that millets tend to accumulate lower aflatoxin levels even when contaminated with toxigenic *A. flavus*. Note that many of the studies did not specify which millet they studied. The type of millet is listed below when recorded in the study.

- A study in Nigeria (Ezekiela et al. 2014) showed that *Aspergillus*-contaminated fonio had less aflatoxin than toxigenic fungi isolated on laboratory medium even though 68% of the fonio had *Aspergillus* contamination.
- A study conducted in Kenya (Sirma et al. 2016) showed that millets (including sorghum) had comparatively lower levels of aflatoxin than maize. Aflatoxin B1 contamination was found to be
  - 76% in maize
  - 64% in millets (excluding sorghum)
  - 60% in sorghum.

Aflatoxin levels exceeded the Kenya Bureau of Standards limit of 5 parts per billion (ppb) by

- 26% in maize;
- 11% in sorghum; and
- 10% in millets.

- Achaglinkame et al. (2017) found millets to be less susceptible to aflatoxin compared to maize.
- Testing of aflatoxin and fumonisin contamination in crop samples (Akello et al. 2021) showed that maize was generally more affected with fumonisin and *Aspergillus* fungus.
- 10% of maize, 3.3% of sorghum, 1.7% of pearl millet and 0% finger millet had the level of aflatoxin that exceeded the EU limits.
- Fumonisin levels exceeded EU limits by
  - >53.9% in maize
  - >10% in sorghum
  - >1.9% in finger millet
  - >0% in pearl millet.
- Sorghum generally had less aflatoxin contamination compared to groundnut and bambara nut (Anitha et al. 2017). This is so because unlike the legumes, millets are not contaminated from soil during growth as they produce grain above the ground.
- A study by Apeh et al. (2016) in Nigeria found that a high percentage of crop samples were contaminated with aflatoxin but in relatively low concentrations. Less contamination was observed in millets as they have less oil content compared to sesame.

  Aflatoxin was found in:
  - 50% of sesame samples
  - 54% of sorghum samples
  - 61% of millet samples.

  Mean aflatoxin contamination was:
  - 5.31 ppb in sorghum (with a range of 0.96-21.74 ppb)
  - 5.99 ppb in millets (with a range of 1.05-14.96 ppb)
  - 13.67 ppb in sesame (with a range of 0.79-60.05 ppb).

- Anitha et al. (2019) in Malawi and Sirma et al. (2016) in Kenya showed that temperature variations during extreme drought and flood conditions can aggravate aflatoxin concentration in millets.
- The lower aflatoxin contamination in millets is based on their lower moisture and oil content (Anitha et al. 2017):
    - *Low moisture levels in millets reduce the risk of contamination:* Although millets varyin physical and chemical composition, in general they have a lower moisture content compared to other staples, including maize, as they are harvested as dry grain. Though dried maize does contain <20% moisture, a significant quantity of maize is sold in a fresh state which has >60% moisture. The high moisture level in fresh maize makes it prone to fungal infestation if not dried adequately (Longvah et al. 2017).
    - *Low oil content in millets reduces the risk of contamination:* High oil content in sesame and groundnut can be the cause of high aflatoxin contamination (Anitha et al. 2017). As groundnut and bambara nut grow underground, they are more exposed to soil fungi and hence are highly vulnerable to contamination. Millets, in contrast, have low oil content and produce grain above ground, thereby naturally reducing exposure to fungi.

The study of studies

The results presented here are based on the following review of a wide range of food safety studies, titled: Do millets contribute to food safety better than maize and other staple crops and commodities? (Anitha et al. 2023).

Priorities for future research

While the many nutritional and environmental benefits of millets are well-recognized and reported, investigation into their food safety aspect has received minimal attention. It is clear millets have the advantage of having a lower risk of toxins like aflatoxin and fumonisin; however these still exist in millets.

As a result, it is recommended that:

1. **Any research on food safety topics include millets, especially giving priority to research on aflatoxin and fumonisin** when identifying appropriate solutions, including practices that can prevent contamination; and
2. **Research on food safety be analyzed for different types of millets and by variety.**

Priority for policy

1. **Policies should include monitoring and support for solutions for contaminants in millets, especially aflatoxin and fumonisin,** to ensure safe food for consumers and protect farmer and industry trade opportunities.

The importance of food safety

Food safety shortcomings can contribute to illness and malnutrition. Among food safety concerns, aflatoxin contamination is very prominent in the drylands of Africa and Asia where millets are commonly grown.

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Review study

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Claim 10: Millets can be a grain substitute in many common dishes and enhance their nutritional value

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Scientific evidence and results

This claim is based on scientific evidence from a study that tested the suitability of nine types of millets as a boiled grain and in six Indian rice-based dishes. Two analyses were undertaken:

1. Scientific research was undertaken to determine which millets can substitute some common refined rice dishes. This was achieved using both chef and institutional sensory panels and by undertaking sensory evaluations following which the data was statistically analyzed.
2. The nutritional value of millets in the dishes was analyzed through laboratory testing.

In total, 53 cooked millet dishes were tested based on 7 recipes which included each millet and refined rice in each selected dish:

- 9 millets (finger millet, pearl millet, sorghum (red and white), little millet, barnyard millet, proso millet, kodo millet and browntop millet) and refined (non-sticky) rice
- 7 dishes: Boiled grain, and 6 Indian dishes – *dosa* (thin crepe made of fermented rice and black lentil), *idli* (savory rice cake), *bisi bele bath* (spicy dish made of rice, lentils and vegetables), *pulao* (single-pot dish made of rice and vegetables), *puttu* (made of coarse rice flour and grated coconut) and *pongal* (made of rice and split green gram).

Key results

- Most millets suited most dishes.
- Flour and batter-based dishes suited all the millets.
- Refined rice scored slightly higher than the millets on sensory characteristics most of the time, but the millets sometimes scored higher on some of the sensory characteristics. There were instances when millets scored the highest, depending on the dish. This further emphasized that the millets identified as suitable for the dishes were suitable substitutes for refined rice.
- Overall, the millet-based dishes were higher in nutrition than the refined rice-based dishes in terms of fiber, protein, iron, zinc, calcium and magnesium, but there were variations. It is noted that only one sample of each millet was tested and not a range of varieties.

The study

This review is based on the study titled: Sensory and nutritional evaluation of nine types of millets in selected Indian dishes (Anitha et al. 2023).

The analysis included:

1. A first-level screening by a chef's panel to assess the suitability of the nine types of millet for the selected dishes based on characteristics including grain size, cooking quality, time taken for cooking, and appearance.
2. Standardizing the recipes to suit the millets instead of refined rice. This included, e.g., modifying the cooking time and quantity of water and millet.
3. Two panels of 12 members each were recruited for the sensory evaluation of each millet in each dish, to compare it to the same dish using refined rice and analyze the taste, texture, aroma, appearance and overall ranking. Each dish was evaluated by one panel. Panel members were aged between 25 and 50 years, female and male, and had an education level sufficient to understand the questions in English or the vernacular language.

   The data was collected using a 9-point hedonic score of each recipe and analyzed using a biplot, radar plot and ANOVA. Also, correlations for each of the millets in a recipe against the sensory characteristics was undertaken using a biplot two-dimensional exploratory graph, after conducting PCA to describe the relatedness of samples or data points in the first and second principal components.
4. Laboratory testing of the nutrition levels of each cooked dish.

Sensory evaluation

The sensory characteristics of each of the millets in the recipes is given in Figures 9A-G. This data was analyzed by statistical significance, further supporting the claim that the selected millets are suitable for the dishes.

Key results

- Overall, all the millets selected for dishes scored similar to refined rice in terms of sensory characteristics.
- Refined rice had the highest or close to highest score on most of the sensory characteristics, although most millets scored well too.
- The exception was *dosa* where the majority of millets scored higher than refined rice. Pearl millet, however, scored lower than refined rice.
- The greatest variation in sensory scores was for boiled grain with millets, mostly ranging from 'like slightly' to between 'like moderately' and 'like very much', while refined rice's sensory scores mostly ranged between 'like moderately' and 'like very much'.
- The sensory scores were almost similar for all the millets and refined rice for *bisi belle bath*, with sensory scores being close to 'like very much'.

Nutritional evaluation

Nutritional values

Overall, millet-based dishes were more nutritious than refined rice-based dishes.

However, there were variations, and it should be noted that nutrients in millets can vary significantly based on the type of millet, the variety, as well as growing conditions. As a result, nutrient levels of specific cooked millet dishes may also vary significantly. Only one source of each millet was used in the study.

A comparison of the nutrition levels of each millet-based dish compared to the refined rice- based dish is summarized in Table 10A.

Quantity of grain in each dish

The quantity of millets or rice grain required for each dish and typical adult portions eaten were calculated. This is important to understand the nutritional value that each millet can contribute and to calculate servings and their contribution to daily nutritional requirements.

The results are based on 100 g of cooked food, which is a small serving size. Depending on the increase in serving size, the nutrient value may multiply by many times. For example, if typical consumption is 350 g, then these results can be multiplied by 3.5 times.

Key results

- *Boiled grain*: 32 g of raw grain make approximately 100 g of boiled grain.*
- *Dosa*: 40 g of raw grain is used to make approximately 100 g of *dosa*, and one *dosa* weighs approximately 180 g. Two *dosas* may be a typical serving.
- *Idli*: 100 g of grain makes approximately 2.5 *idlis*, with each *idli* weighing 40 g. A typical serving could be 4 to 6 *idlis*.
- *Bisi belle bath*: 10 g of grain is used to cook 100 g of *bisi belle bath*.*
- *Pulao*: 20 g of grain can produce 100 g of *pulao*.*
- *Puttu*: 44 g of grain is used to make approximately 100 g of *puttu*.*
- *Pongal*: 10 g of grain is used to make 100 g of *pongal*.*

* Typical adult consumption may be about 350 g.

Figures 10A-G. Sensory characteristics of different dishes prepared using different types of millet and compared to refined rice-based dishes as control. The dishes were scored by institutional sensory panelists based on a 9-point hedonic scale for appearance, taste, texture, aroma and overall acceptability, where 9 = like extremely, 8 = like very much, 7 = like moderately, 6 = like slightly, 5 = neither like nor dislike, 4 = dislike slightly, 3 = dislike moderately, 2 = dislike very much and 1 = dislike extremely.

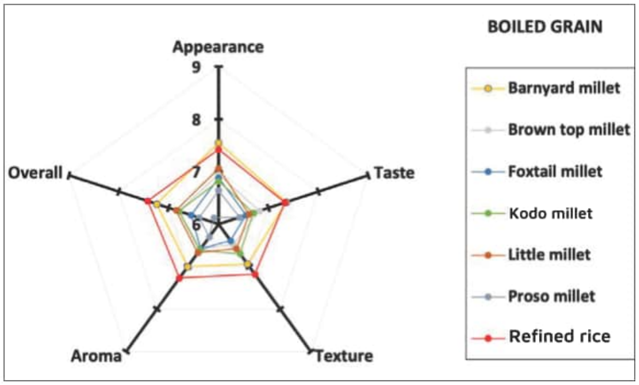

Figure 10A. Sensory characteristics of boiled grain of six types of millets compared to refined rice-based dish as the control.

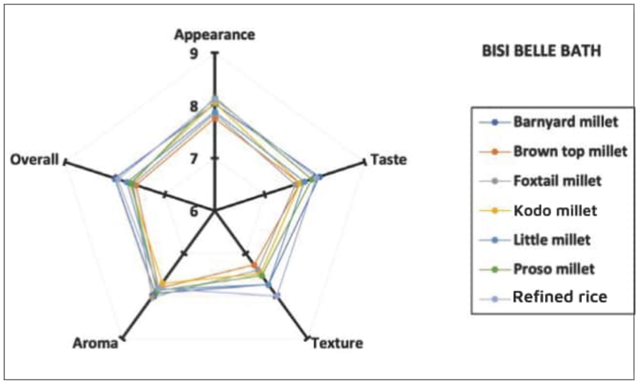

Figure 10B: Sensory characteristics of *bisi belle bath* prepared with six types of millets compared to refined rice-based dish as the control.

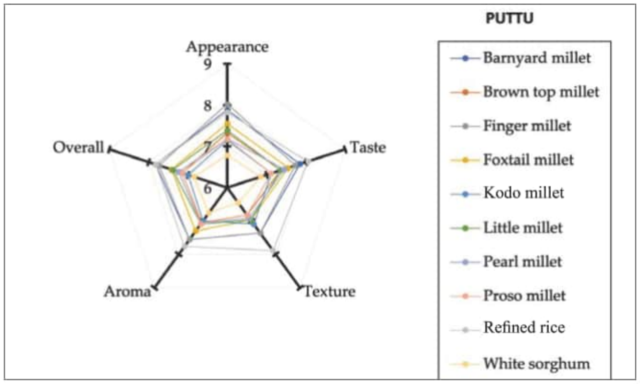

Figure 10C. Sensory characteristics of *puttu* prepared with nine types of millets compared to refined rice-based dish as the control.

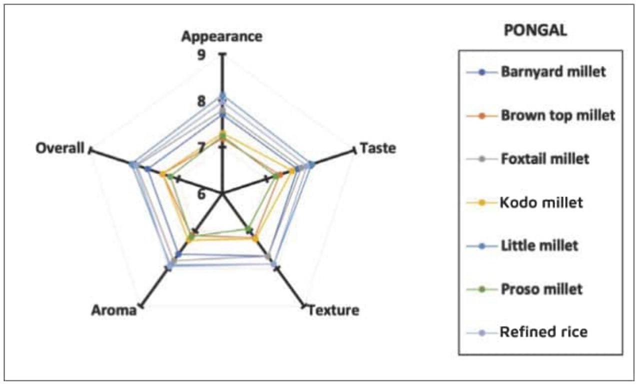

Figure 10D. Sensory characteristics of *pongal* prepared with six types of millets compared to refined rice-based dish as the control.

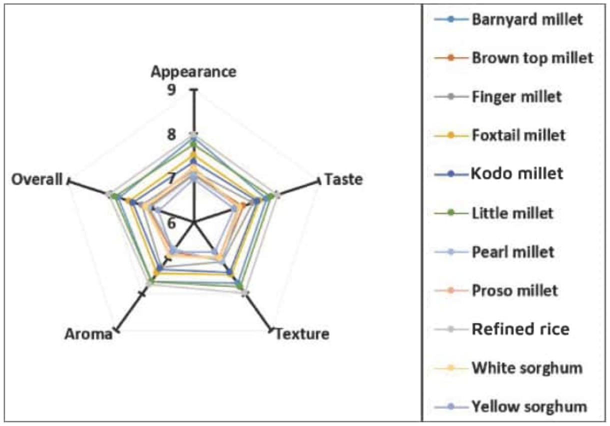

Figure 10E. Sensory characteristics of *idli* prepared with nine types of millets compared to refined rice-based dish as control.

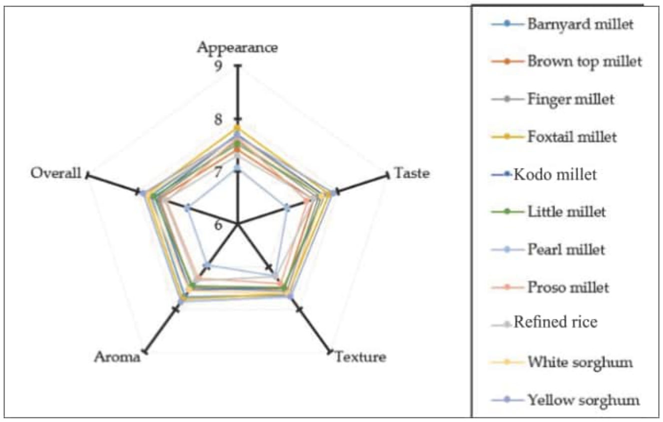

Figure 10F. Sensory characteristics of *dosa* prepared with nine types of millets compared to refined rice-based dish as the control.

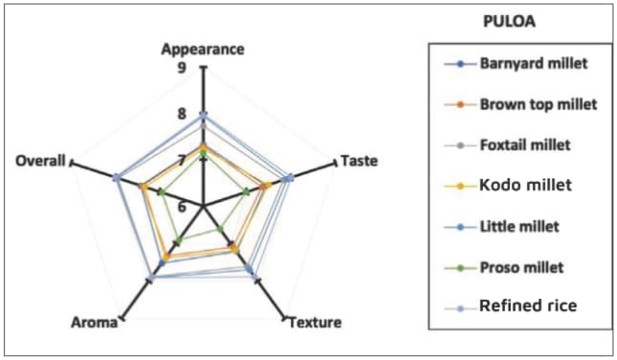

Figure 10G. Sensory characteristics of *pulao* prepared with six types of millets compared to the refined rice-based dish as control.

Table 10A. A summary comparison of nutrient levels in millet-based dishes and refined rice-based dishes.

Dish	Nutrient	Nutrient levels in millet-based dishes (compared to refined rice-based dishes)
Puttu	Protein	The majority of millet-based dishes had high protein and some had up to double the protein
	Fiber	Fiber content varied in millet-based *puttu*, some had less and some more
	Iron, zinc, calcium and magnesium	Millet-based *puttu* had more of these nutrients and finger millet-based *puttu* had significantly higher calcium
Pongal	Protein	Millet-based *pongals* had similar or higher protein levels
	Fiber	The level varied, with some millet-based *pongal* dishes having less and some more fiber
	Zinc and iron	All millet-based *pongals* had higher zinc and iron
	Calcium	The level varied partially but most millet-based *pongals* had similar levels of calcium
	Magnesium	All millet-based *pongals* had higher magnesium levels
Boiled grain	Protein	Overall, boiled millets had higher protein
	Fiber	All boiled millets had higher fiber
	Iron, zinc and calcium	The levels varied, but overall boiled millets were reasonably similar or slightly higher in iron, zinc and calcium; however, the levels were not high
	Magnesium	All boiled millets had higher magnesium
Pulao	Protein	All millet-based *pulaos* had lower protein
	Fiber and magnesium	The levels varied (lower and higher), but overall millet-based *pulaos* had similar fiber levels
	Iron and zinc	The levels varied (lower and higher)
	Calcium	All millet-based *pulaos* had lower levels of calcium, but overall millets and refined rice had low levels

(Continued)

Dish	Nutrient	Nutrient levels in millet-based dishes (compared to refined rice-based dishes)
Dosa	Protein	The level varied (lower and higher), but overall millet-based *dosas* had similar reasonable levels of protein (ranging from 4.1 ± 0.04% to 6.39 ± 0.35%)
	Fiber	The level varied (lower and higher), but overall millet-based *dosas* had similar levels of fiber
	Iron and zinc	The levels varied, with overall low levels in millet- and refined rice-based *dosas*
	Magnesium	The overall level was higher in millet-based *dosas*
	Calcium	The level was higher in all millet-based dosas and very high in finger millet-based *dosa*
Idli	Protein	All millet and refined rice-based *idlis* had very similar levels (ranging from 4.37 ± 0.07% to 5.15 ± 0.04%)
	Fiber	Overall, millet-based *idlis* had higher fiber
	Iron, zinc, magnesium and calcium	All millet-based *idlis* had higher levels
Bisi belle bath	Protein	Almost all millet-based *bisi belle baths* had higher protein
	Fiber	Overall, millet-based *bisi belle baths* hade lower fiber
	Iron and calcium	The levels varied (lower and higher), and overall all millets and refined rice-based *bisi belle baths* had low levels
	Zinc and magnesium	All millet-based *bisi belle baths* had higher levels, but the overall level was low

Priorities for future research

This is the first known scientific study combining sensory and nutrition analyses of millet-based dishes and comparing them to dishes made with a popular staple. As a result, replication and more studies are highly recommended, especially:

1. Analyzing a wider variety of dishes;
2. Using national dishes from different geographical regions;
3. Assessing how sensory and nutritional levels can vary if high-nutrient millet varieties are selected;
5. A comparison with other staples like wheat and maize as well as wholegrain staples; and
6. Targeting specific social programs based on local millet types and varieties and local dishes.

Priority for policy

It is recommended that:

1. **Social programs incorporating millets are designed using sensory and nutrition analyses** to ensure maximum impact.

Reference

Anitha S., Arjun, P., Palli, N.C., Sreekanth N., Miruthika Devi S.A., Pandey, S., Krishnan, S., Prasad, S., Sharma, S., Murthy, K.C., Botha, R., Upadhyay, S., and Kane-Potaka, J. 2024. Sensory and nutritional evaluation of nine types of millet substituted for polished white rice in select Indian meal preparations. *Frontiers in Sustainable Food Systems - Nutrition and Sustainable Diets.* Vol. 8 https://doi.org/10.3389/fsufs.2024.1331260

Claim 11: There is not enough scientific evidence to assert that millets consumed as part of a balanced diet can negatively impact thyroid functioning or lead to goiter

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Background

Concerns have been raised that consumption of some millets can interfere with thyroid functioning and cause goiter. Millets are an integral part of traditional diets in many countries in Africa and Asia [Vetriventhan et al. 2020; APEDA, 2023]. It is estimated that more than 90 million people in about 30 countries depend on millets for food and income [CGIAR 2019]. Though no mass concerns over thyroid issues due to consumption of millets have been reported or verified, despite millets being widespread, it is important to analyze scientifically if millets can indeed impact thyroid functioning.

Scientific evidence and results

A systematic review of existing studies on the association between millet consumption, thyroid functioning and goiter was undertaken to evaluate the available evidence on the influence of millet consumption on goiter and its clinical implications relating to the thyroid gland.

Key findings

The findings of the review indicate that there is not enough scientific evidence to assert that millets consumed as part of a balanced diet can lead to goiter in the general population. Additionally, the studies included in the review had numerous limitations and did not stand up to scientific rigor. For example:

- Only three studies were on humans; the rest were on rats, pigs and goats fed raw millet and 100% millet diets, which is not a realistic diet for any animal or human.
- The three human studies had no control groups, were cross-sectional, had insufficient evidence on complete dietary habits and were not undertaken on healthy humans as malnutrition was reported.
- There were no *in vivo* studies on humans. The studies involved only pearl millet and were done *in vitro* or *ex vivo*.
- Deductions were made without any proven cause-effect on humans.
- The role of variables such as iodine deficiency was not clarified.
- The very wide variations in flavanols in millets were not taken into account.

The studies

The systematic review that is the basis of this analysis is titled: Does millet have a goitrogenic component? If yes, does the goitrogenic component of millet cause goiter? – A systematic review of existing evidence (Anitha et al. 2024)

The nine studies published in peer-reviewed scientific journals that were analyzed are listed in the references and detailed in Table 11A.

Limitations of the studies in more detail

1. Majority were animal studies: As six of the nine studies were animal experiments, it is a contentious issue whether speculation derived from animal experimentation on the goitrogenic effect of millets can be used to predict the human response (Ram, 2019; Shanks et al. 2009).
2. The 3 human studies were cross-sectional surveys: The human studies did not examine the cause-effect relationship. They were observational research that analyzed data across a sample population at a specific point in time. Also, since there was limited data on the prevalence of iodine deficiency in the humans studied, it cannot be categorically said that it was the millet that was causing goiter in the endemic region.
3. Lack of studies on variability of flavone content across types and varieties of millets: It was observed that incidence of goiter was high in the millet-consuming population of Sudan but not in the millet-consuming populations of Nigeria or India. This disparity could be due to the high variability of flavone content in millets. Factors such as soil conditions, weather, growing location, use of plant growth regulators or pesticides, pathogen challenges, as well as date of harvest and storage time can all impact goitrogenic content in millets (Conaway et al. 2000; Fahey et al. 2001).

None of the studies, human or animal, took into account literature showing that there is a marked variability in C-glycosylflavanol content in different cultivars and different fractions of millets. For instance, Gaitan et al. (1989) reported that the bran fraction contained greater amounts of C-glycosylflavanol (C-GF) than the endosperm. Akingbala (1991) found that 70% of the C-glycosylflavanol was in the pericarp and germ fractions. Similarly, Boncompagni et al. (2018) detected and quantified vitexin, glucosylvitexin, and orientin in 97 pearl millet grain samples originating from Indian and West and Central African landraces with substantial variability in goitrogenic polyphenols (C-GFs) across the landraces.

4. The animal studies were conducted on raw millets or bran, with millets fed as 100% of the diet, which is not typical for either animals or humans. It is worth noting that Goldie et al. (2016) observed hyperplasia in rats fed a 100% millet diet, while rats that received 60% and 30% millet diets were less affected. Similarly, in the study by Gaitan et al. (1989), the bran fraction that contained maximum glucosylflavone content exhibited detrimental effects while the whole millet fraction did not show any anti-thyroid activity. In the study by Osman and Fatah (1981), millets were the staple food of the population and provided 70% of the dietary energy, indicating that the diets were predominantly based on millets and lacked diversity. So it is not clear if thedetrimental effects were due to the goitrogenic factors present in a pure millet diet or due to an imbalance of nutrients that may occur as a result of relying only on millet. Therefore, it is not certain whether these compounds would be as harmful when eaten along with other foods or as part of a balanced diet as they might seem to be in isolation.

5. There were multiple etiological factors like preexisting iodine deficiency and malnutrition in the studied subjects: The relevance of studies on goitrogens in iodine-deficient participants is debatable. Multiple environmental and nutritional factors play an important role in thyroid dysfunction (Babiker et al. 2020; Rayman, 2019). For instance, Osman and Fatah (1981) claimed an association between millet consumption and incidence of goiter but also reported a marked deficit in all anthropometric measures of the surveyed children. Moreover, the study region was mentioned as being iodine-deficient. A subclinical or clinical thyroid dysfunction or insufficient iodine intake might have an influence on the effects mediated by flavones and, therefore, such factors need to be analyzed and considered (Huser et al. 2018).

Similarly, the study by Elnour et al. (2000) conducted in Sudan found that urinary excretion of iodine was normal in a population with 22% prevalence of goiter, indicating that the population probably consumed normal levels of iodine. So, it was assumed that the goiter observed may be associated with inappropriate metabolism of iodine in the body and that consumption of millets with low dietary diversity could have been the reason for the inappropriate metabolism. However, the researchers could not explain the sources of iodine in a region of severe iodine deficiency where iodized salt was not produced. The high prevalence of protein-energy malnutrition along with multiple vitamin deficiencies in this population could also potentially explain the derangement in thyroid hormone metabolism.

Human studies on the effects of millet consumption on thyroid functions in healthy individuals are lacking. More research that considers additional factors that influence thyroid function is needed before arriving at a conclusion regarding the effects of millets.

6. There are beneficial effects of flavones on human health: Based on available evidence, it is noted that millets may exhibit goitrogenic properties in concentrated, isolated or raw form. However, processing and cooking and consuming a diversified diet can substantially reduce any damaging effects.

   A few studies have implicated flavonoids in millets to cause goiter, while several others have shown a wide range of protective health effects. Vitexin and its isomer isovitexin have been proven to be good radical scavengers and natural antioxidants (Bai et al. 2016; Girish et al. 2016; Babaei et al. 2020), with anti-inflammatory (Maleki et al. 2019; González-Gallego et al. 2007), anticancer (Liu et al. 2019; Ninfali et al. 2017), hepatoprotective (Alzahrani et al. 2017), cardioprotective (Nambiar et al. 2022; Azubuike-Osu et al. 2021), and neuroprotective effects (Li et al. 2020). The health benefits of eating flavonoids could potentially far outweigh any potential negative nutritional effects.

7. Processing of millets, even dehulling, can substantially reduce flavanol content: Millet grains are dehulled (except finger millet, pearl millet and sorghum that are naked grain – without hulls) before being processed for human consumption (Boncompagni et al. 2018). As C-glycosylflavanols are mostly concentrated in the pericarp and germ, any milling or polishing process that removes these fractions substantially reduces the C-glycosylflavanol content.

   Malting and thermal processing dramatically reduce the number of phenolics present in millets.Simple household processing techniques such as heating, convert the goitrogenic compounds into metabolites that are less likely to be harmful. Gaitan et al. (1989) reported that after heating, the antithyroid activity of millet bran increased and then when the boiled extract was left to stand in the same boiled water, it further increased. Akingbala (1991) showed that C-glycosylflavanol content in millet flour decreased after cooking, decortication, and steeping decorticated grain in water for a short time and discarding the water. Thus, levels of C-glycosylflavanol in millet foods and beverages are usually considerably lower than in the raw grains. No studies have been done on how changes in C-GFs before and after processing affect the goitrogenic content of millets.

   The only proven information in these studies is that the millets studied had C-glycosylflavones, however flavones exist in a variety of fruits and vegetables (e.g., cabbage and cauliflower) and are widely consumed without any cause for concern. Further, flavones have demonstrated numerous potential beneficial activities in animal studies and human trials.

Priority for future research

It is highly recommended to:

1. **Further analyze the effects of millets on goitrogens and overall thyroid functioning,** and to understand any underlying mechanisms at work. This should include population-level and clinical studies and all the different types of millets.

Priority for policy

No policy recommendations are given due to the paucity of scientifically credible data. Further studies are required.

Importance of the thyroid gland

The thyroid gland is a vital hormone-producing gland that regulates the body's metabolism, growth and development.

It constantly releases thyroid hormones into the bloodstream depending on the needs of the body. This can impact, for example, pulse rate and heartbeat, brain maturity in children, growth in children, and can activate the nervous system to improved concentration and faster reflexes, the digestive function and body temperature (National Library of Medicine, 2023).

Table 11A. Summary of studies on goitrogenic properties of millets.

Author and year	Location	Type of millet	Study sample	Methodology
1. Osman and Fatah, 1981	Sudan	Pearl millet *(Pennisteum typhoides)*	Children and households	Cross-sectional: Anthropometry and goiter survey in children 72- hour recall household dietary survey
2. Osman et al. 1983	Sudan	Pearl millet *(P. typhoides)*	School girls (8-9 years old)	Mixed method included a cross-sectional survey and experimental analysis of millet content
3. Osman, 1981	Sudan	Pearl millet (*Pennisteum typhoides*)	Rats	Experimental (*in vivo*)
4. Gaitan et al. 1989	Pearl millet grain from Dakar, Senegal	Pearl millet (*Pennisetum americanum* (L.) Leeke)	Female Sprague-Dawley rats, and porcine thyroid slices	Experimental (*in vivo* in rats and *in vitro* in porcine thyroid slices)
5. Elnour et al. 1997	Sudan	Pearl millet (*Pennisetum americanum* (L.) Leeke) cultivars: 1. Balady 2. Bayoda	Male Sprague-Dawley rats	Experimental (*in vivo*)
6. Elnour et al. 2000	Sudan	Pearl millet	Pre-school children	Cross-sectional survey
7. Goldie et al. 2014	Nigeria	Pearl millet *(P. americanum)*	Rats	Experimental (*in vivo*)
8. Abdel Gadir and Adam, 2007	Sudan	Pearl millet (*P. typhoides*)	Male goat	Experimental (*in vivo*)
9. Sartelet et al. 1996	Fonio millet sample from Guinea	Fonio millet (*Digitaria exilis*)	Porcine slices	Experimental (*in vitro*)

Sample size	Results
1,583 children 73 rural and 70 urban households	Goiter was more prevalent in rural areas where as much as 74% of dietary energy is derived from millets, compared to 37% in the urban areas.
34 school girls	1. Thiocyanate concentration was significantly elevated and that of thyroxine significantly lower in girls with goiter grades 1, 2, or 3 compared to those with grade 0. 2. A thionamide-like substance was isolated in the millets meal and suspected to be a goitrogenic factor present in millets.
Five rats each in the experimental and control groups	1. Feeding millets to rats produced histological changes in their thyroid gland and distorted the thyroid hormone pattern. 2. The response of the thyroid gland to a millet diet depends on the duration of the experimental diet.
Group of four rats for experimental and control diets	1. *In vivo* feeding of bran fraction for 30 days led to a significant increase in the thyroid gland of rats. 2. A marked (~85%; $p < 0.05$) inhibition of TPO was observed in the case of extracts of bran fraction in porcine thyroid slices. 3. C-glycosylflavones are active antithyroid agents in millet. Major C-glycosylflavones (glucosylvitexin, glucosylorientin and vitexin) showed antithyroid activity in the porcine thyroid slice system. They are also inhibitors of TPO. 4. Anti-TPO activity of extract of millet bran fraction increased severalfold after 1-4 hours of boiling and increased further after allowing the boiled extract to stand for as long as 1 week.
5-8 rats in each group of experimental and control diets	1. Two pearl millet cultivars (Balady and Bayoda) affected thyroid function in different ways. Only Balady cultivar was associated with significant enlargement of the thyroid gland ($p < 0.05$). 2. Supplementation of millet diets with iodine to dietary requirement did not compensate for the goitrogenic effect of millet in rats. 3. The thyroid gland showed significant enlargement in rats that were fed fermented Balady cultivar compared to those that were fed the nonfermented Balady cultivar.
984 children for anthropometry 191 children for urinary iodine excretion	Goitrogenic substances in millets play an instrumental role in the etiology of endemic goiter.
60 rats	Histopathological analysis of the thyroid gland revealed hyperplasia in rats with a 100% millet diet, while those on 60% and 30% millet diets were less affected.
12 animals (3 animals in each group)	Pearl millet incorporated in the diet at 1g/kg/day caused goiter in male goat kids and incorporating potassium iodate at 50 ppm did not protect animals against pearl millet goitrogenesis.
---	Two flavonoids (apigenin and luteolin) extracted from fonio millet caused thyroid dysfunction by altering both the TPO and the cyclic nucleotide phosphodiesterase systems.

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SECTION B

Scientific evidence for millet benefits to the environment, farmers, tribal groups, and women

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K.S. Varaprasad, Namuduri, S., Gemeder, N., Pavagadhi, S., Sivaraj, N., Vinutha, K.S., Sandhya Kumari, C., Sahithi, S., Bhamidipati, P., Parida, T. and Riyazuddin, S. 2025. Scientific evidence for millet benefits to the environment, farmers, tribal groups and women. In: Padhee, A.K., Chaudhary, P.C., Khetarpal, R., Balam, D. and Kane-Potaka, J. (eds). Millet Foundation Guide: Scientific Evidence & Research Priorities. revised edn, Bhubaneswar, India: Department of Agriculture & Farmers' Empowerment, Government of Odisha.

Claim 1: Millet cultivation has a low carbon and energy footprints

Adopting millets in mainstream agriculture could potentially minimize carbon emissions and reduce the energy burden and input costs for agri-food ecosystems.

Summary

Cultivation of millets supported by farm management practices such as mulching and intercropping with staples and pulses/legumes could significantly reduce the current global agricultural burden on account of energy inputs, greenhouse gas emissions and other environmental externalities. Bringing millets into mainstream agriculture will diversify diets, strengthen global food security and at the same time reduce the carbon footprint of agricultural systems. This analysis summarizes some key studies on the impact of millet cultivation on the carbon and energy footprints while Table 1A provides a holistic, state-of-the-art overview of research conducted in this domain.

Scientific evidence

Claim 1A: Millets emit fewer greenhouse gases compared to other crops

Millet cultivation has received attention in India since the Green Revolution. Belonging to the C_4 family, millets have the capacity to convert more carbon dioxide into oxygen and reportedly have a smaller carbon footprint with respect to the greenhouse gas (GHG) emission inventory of agricultural systems compared to other cereals. Among the millets, proso millet has been shown to have a high efficiency of C_4 photosynthesis (Goron and Raizada 2015); and a low transpiration ratio; it can efficiently fix carbon even under climatic adversities (drought, high temperatures, and limited nitrogen and CO_2) (Habiyaremye et al. 2017). Interestingly, millets are also less vulnerable to pests. This quality minimizes the need for intensive pesticide use and thus contributes to reducing energy dependence and carbon emissions (Ceasar and Maharajan 2022). In particular, broomcorn millet has shown, in a longitudinal experiment conducted over three years by Shi et al. (2022), promising results under elevated

CO_2 conditions. The results indicate that proso millet has the potential to fix carbon despite its physiological behavior.

Cultivation of fine cereals such as rice and wheat require more agricultural inputs and therefore emits more greenhouse gases compared to coarse grains such as sorghum, pearl millet and finger millet (Rao et al. 2019). Millets have a considerably lower carbon dioxide equivalent per hectare (3,218 kg) compared to cereals (rice 3,968 kg; wheat 3,401 kg) (Tiwari et al. 2022). The global warming potential (kg CO_2 equivalent per hectare) of rice (2,890-17,000) and wheat (2,000-18,000) is reported to be high compared to millets (3,218) and sorghum (3,358) (Jain et al. 2016; Wang et al. 2018; Dayakar et al. 2021).

According to a meta-analysis by Sah and Devakumar (2018), emissions contributed by the cultivation of rice (23.75 teragrams of CO_2 equivalent per hectare, teragrams carbon emission/hectare (Tg CE/ha) are four times that of sorghum (5.94 Tg CE/ha), finger millet (2.99 Tg CE/ha), and pearl millet (3.43 Tg CE/ha). Ullah et al. (2017) and Clemens et al. (2023) suggested millets are the best alternative to rice as they meet all nutritional needs and yet require fewer resources, thereby contributing to reduction of the energy and carbon footprints (Ullah et al. 2017; Clemens et al. 2023). A study by Maitra et al. (2022) reported similar findings for small millets, which are underrated due to their lesser popularity in cultivation systems. These authors reported that small millets have lower carbon and energy footprints as compared to major cereals. They also found small millets to be more climate adaptive than cereals such as rice and maize (Maitra et al. 2022).

Claim 1B: The morphological characteristics of millets help in reducing carbon and nitrogen inputs

Millets are known to have deep root systems compared to fine cereals. The root-shoot ratios of sorghum, millet, wheat and barley are 5:9, 2:8, 7:4 and 6:3, respectively (Gelaw et al. 2014). A meta-analysis comparing cereals (wheat, maize, rice) with millets revealed a notable competitive advantage for millets due to their deep root system, which reduces the need for external supplementation of nitrogen, phosphorus and other nutrients, leading to lower fertilizer usage and enhanced sustainability. In a nutshell, millets make an ideal case for feed-to-biomass conversion: We obtain more from less, leading to reduced GHG emissions, making millets a suitable choice for inclusion in future agrifood ecosystems (Wang et al. 2018).

Some millets are also reported to have higher levels of phytoliths [phytolith occluded carbon (phytOC)], which are microscopic silica particles in plant tissue that persist after the decay of the plant and perform functions like promoting epidermal stiffness and toughness. Specialized plant structures are known to play a role in long-term carbon sequestration. Vidhya and Pragasan (2022) explored the potential of carbon sequestration among millet crops such as pearl millet, sorghum, little millet, finger millet and foxtail millet at three different growth stages (30, 60 and 90 days). They reported finger millet to have higher phytolith content than other millets. The phytOC available in finger millet contributes to long-term terrestrial carbon sequestration when released into the soil after the crop is harvested and the soil is mulched in preparation for the next cropping cycle. Practices such as managing soil nutrients and regularly adding silicon fertilizer to agricultural lands can improve phytolith production, increase phytOC accumulation to contribute to terrestrial carbon sequestration, and thus assist in mitigating climate change.

Claim 1C: Inclusion of millets in diversified cropping systems helps to minimize the carbon and energy footprints

Cereal/millet and legume intercropping systems have been widely adopted in semi-arid and arid regions, which helps in irrigation management. It has been reported that millets have higher nitrogen accumulation within intercropping systems as compared to monocultures. These intercropping systems often require less nitrogen and carbon, which reduces volume of agricultural inputs; thereby minimizing the energy and carbon footprints (Liu et al. 2023) and leading to increased millet yields (Dang et al. 2020). Recent research findings have shown that millet and legume intercropping facilitated by biofertilizer such as arbuscular mycorrhizal fungi and plant-growth-promoting rhizobacteria is a promising innovative tool in reducing chemical inputs that can pave the way to integrated farm management and regenerative agriculture (Mathimaran et al. 2021).

Intercropping systems with wheat and millets have been shown to have lower carbon emissions in small land management units (LMUs) than large and medium LMUs. The role of sustainable practices is more important in the conservation of resources and decreasing the ecological footprint (Kumar et al. 2022). Kumar et al. (2021) reported that in intercropping practice, the carbon sustainability index (10.3) and carbon efficiency (11.3) performed better in the case of millet-based systems due to their lower carbon input than other cereal-based systems. This process is very effective for farm management with millets.

Intercropping of pearl millet with moth bean or cluster bean reduces growth and dry matter of weeds, which is an advantage over sole cropping. Consumption of phosphorus and nitrogen by weed is high in solo cropping whereas less uptake is noticed in intercropping (Kiroriwal and Yadav 2013). A combination of pulses and millets is a good approach to increase production per unit area, stabilize the crop and reduce the density of weeds (Sharmili et al. 2021). Legumes with bajra–Napier hybrid has high biomass with low carbon and energy footprints and can be managed as fodder to fix climate change (Manoj et al. 2022). Teff varieties such as Kora and DZ-Cr-387 are the most efficient varieties to reduce weed bulk with minimal loss of productivity. Gebrehiwot et al. (2020) reported 18% higher grain yield and 6% biomass reduction from Kora and 21% higher grain yield and 17% biomass reduction from DZ-Cr-387.

Claim 1D: Traditional farm management practices further impact the carbon and energy footprints

Choudhary et al. (2017) studied millet cultivation in semi-arid regions in both conventional and unconventional intercropping systems and concluded that intercropping pearl millet with mustard improved productivity and energy efficiency if the post-harvest crop residue was judiciously used. While maintaining the crop residue cover on soil resulted in higher productivity and profitability in a pearl millet-mustard intercropping system, it also needed higher energy inputs including labor costs for farm management, resulting in reduced energy/carbon efficiency. This study suggested that farmers have to strike a balance by using crop residue for different end-uses such as mulching, fodder for livestock and other industrial purposes. Fodder and feed for livestock is a particular consideration as millets are cultivated in subsistence farming systems in semi-arid regions where livestock primarily depend on crop residue for feed. Hence, farmers would have to adopt a balanced approach to efficiently utilize crop residue (Choudhary et al. 2017).

A study comparing energy-use patterns in millet cultivation in India and Nigeria revealed that energy input in Nigeria (3,283 MJ ha^{-1}) was almost half lower than in India (7,000 MJ ha^{-1}). Yet, the energy output in the two countries was similar, with Nigeria at 69,269 MJ ha^{-1} and India at 69,269 MJ ha^{-1}. A pilot study in India showed that the lowest input and output of energy was seen in the case of no-tillage farming, where two intercultural operations with low tillage enhanced the ratio. These findings underline the importance of weed management and moisture reserve during cultivation time (Kargwal et al. 2022).

A socioeconomic survey on 5 LMUs found that landholding capacity (small, marginal and large) and the intercropping system do have an impact on the environment; large holdings increased energy efficiency (9.8%) with an energy return of 243,989 MJ ha^{-1} (Kumar et al. 2022).

A field experiment based on energy distribution patterns in pearl millet cultivation by small, medium, and large farmers (Kargwal et al. 2023) found that yielding energy was high from the input energy in all categories. Further, indirect energy use was more than direct energy in the form of fertilizer (urea). The highest indirect energy consumption was in the form of fertilizer by small and large farmers and less in the form of seed. In contrast, medium farmers reported less fertilizer consumption and high use of direct energy in the form of diesel. Large and medium farmers did not use pesticides, while small farmers used less quantity. This indicates that pearl millet is a pest-resistant plant. It is a worthy choice to replace primary cereals.

In a comparative field study of biofuel production from sorghum and pearl millet biomass varieties versus native varieties, it was found that energy content was more in the biomass varieties than the native ones. On other hand, carbon emissions were greater in the biomass varieties (sorghum 48.97 kg CO_2 eq/MT; pearl millet 74.53 kg CO_2 eq/MT) than the native ones (sorghum 92.42 kg CO_2eq/MT; pearl millet 138.18 kg CO_2 eq/MT) (Patel et al. 2020).

Table 1A. A summary of research studies, reviews and opinion articles on the energy and carbon footprints of millet cultivation.

S.No.	Reference	Segment	Article type	Origin
1.	Choudhary et al. 2017	Energy and carbon footprint	Field research	India
2.	Kumar et al. 2022	Energy and carbon footprint	Analytical paper	India
3.	Patel et al. 2020	GHG (CO_2)	Field research	India
4.	Shi et al. 2022	GHG (CO_2)	Laboratory experiment	China
5.	Kumar et al. 2021	Energy and carbon footprints	Field research	India
6.	Sah and Devakumar 2018	GHGs	Meta-analysis	India
7.	Kargwal et al. 2023	Energy	Field research	India
8.	Wang et al. 2018	GHGs	Analytical paper	Worldwide
9.	Kargwal et al. 2022	Energy	Analytical paper	Worldwide
10.	Manoj et al. 2022	Energy and GHG (CO_2)	Field research article	India

Method and type of millet	Insights/Results
Intercropping (pearl millet and mustard) field experiment	Intercropping improved the productivity and judicious use of crop residue improves, energy footprint, and carbon footprint.
Intercropping of pearl millet and wheat in rainfed, semi-arid area	Pearl millet and wheat were a good fit in these intercropping systems and suitable for sustainable agriculture. Large land management units increased the net energy return (243,989 MJ ha^{-1}), carbon efficiency (11.9), and energy-use efficiency (9.8).
Solo cropping of pearl millet, bamboo and sorghum in the field	Native varieties of millets have more potential for lower CO_2 emission than biomass varieties.
Solo cropping of proso millet in pots	Under elevated CO_2 conditions, protein content decreased in seed compared to other nutrients and agri production (13.6-34.2%).
Intercropping systems in the field with pearl, finger, sorghum, foxtail millet, rice, wheat, soybean, chickpea, cob-pigeon pea, Brassica campestris L, mustard	Millet-based cropping systems had lower energy and carbon input (914 kg CO_2 ha^{-1}) than other grain-based systems (6,271 kg CE ha^{-1}).
Pearl millet, finger millet, rice	Rice varieties need more fertilizer (nitrogen); so they release more CO_2 and other GHG gases. Millet varieties do not require fertilizer, hence GHG emissions are less.
Mono cropping of pearl millet in field	In this study of the energy distribution (direct and indirect) pattern in pearl millet farming by large, medium and small farmers, 2% of energy was consumed in the form of fertilizer and less in seed form (2%). The fertilizer required was less for medium farmers (1,115.04 MJ ha^{-1}) compared to small (1,533.02 MJ ha^{-1}) and large farmers (2,206 MJ ha^{-1}).
Meta-analysis on millets	Millets are self-sufficient to survive in any type of climate. They need less in terms of inputs and care, which indirectly decreases the ecological footprint. They have the lowest CO_2 equivalent emission (878 kg C ha^{-1}), global warming potential (3,218 kg CO_2 eq. ha^{-1}).
Meta-analysis on overall millets	India had higher and Nigeria lower energy consumption in millet production.
Monocropping and intercropping with maize, sorghum, oats, pearl millet, cowpea, lucerne, desmanthus, sesbania, bajra-Napier hybrid	Intercropping of bajra-Napier hybrid and legume proved efficient to manage carbon and energy.

(Continued)

S.No.	Reference	Segment	Article type	Origin
11.	Jain et al. 2016	GHGs	Field research	India
12.	Dayakar Rao et al. 2021	Energy and carbon footprints	Book chapter	India
13.	Ceasar and Maharajan 2022	Energy	Review paper	Worldwide
14.	Ullah et al. 2017	GHG (Nitrogen)	Analytical paper	Pakistan
15.	Gelaw et al. 2014	GHG (CO_2)	Analytical paper	Ethiopia
16.	Clemens et al. 2023	GHG (CO_2)	Review paper	Worldwide
17.	Maitra et al. 2022	GHG (CO_2)	Review paper	Worldwide
18.	Habiyaremye et al. 2017	GHG	Review paper	Worldwide
19.	Goron and Raizada 2015	GHG	Review paper	Worldwide
20.	Kiroriwal and Yadav 2013	Land management	Analytical paper	Worldwide
21.	Sharmili et al. 2021	Land management	Review paper	Worldwide
22.	Gebrehiwot et al. 2020	Land management	Field research article	Ethiopia
23.	Rao et al. 2019	GHGs	Analytical paper	Worldwide
24.	Tiwari et al. 2022	GHG (CO_2)	Review paper	Worldwide
25.	Vidhya and Arul 2022	GHGs	Field research	India

Method and type of millet	Insights/Results
Mono cropping of pigeonpea, wheat, pearl millet and sorghum, oil seeds (groundnut, soybean and mustard)	The input and output of a set of GHGs were estimated in the field.
Crops overall	Promotion of millets in every aspect is needed to counter climate change and hunger India.
Millets overall	This paper is based on the characteristics and pest resistance of millets.
Meta-analysis on pearl millet	Pearl millet provides an answer to hunger by taking less energy from surroundings in the context of climate change.
Meta-analysis on pearl millet, maize, wheat, barley, sorghum, teff	C input and output of six major crops increased twice from 1994 to 2010-11; livestock of smallholder farmers accounted for greater CO_2 emissions.
Overall millet	Advanced technologies for reduction of the carbon footprint in farm practices can add more value to millet cultivation.
Millets overall	Small millets intake less inputs and emit less CO_2 than other cereals.
Proso millet	As proso millet is from the C_4 family, it can regulate carbon in harsh conditions.
Millets overall	Small millets are known as orphan cereals because they are less popular in agricultural systems. However, they have a high yielding capacity with minimum inputs in a reciprocal climate.
Meta analysis of intercropping with pearl millet, moth bean, cluster bean	Unlike solo cropping, intercropping minimizes weed density. N and P absorption by weeds in solo cropping goes up to 16.29 kg N ha^{-1} and 2.38 kg P ha^{-1}.
Intercropping of millet and pulses in field	Intercropping of pulses and millets provides the best option to reduce weeds and stabilize the crop.
Solo cropping of teff millet in field	Teff reduces weed growth without compromising yield and biomass production.
Meta-analysis on solo cropping of wheat, rice, finger millet, pearl millet, maize, sorghum in field	GHG emissions from millets are significantly less than for other cereals, which makes millets a good option for a sustainable environment.
Comparison of millets are cereals	The carbon footprint of millets (3,218 kg) is less than for rice (3,401 kg) and wheat (3,968 kg).
Monocropping of pearl, sorghum, little, finger and foxtail millet	Finger millet accumulated the highest phytOC among all millet.

Research priorities

Carbon and energy budgeting is a complex task as it requires a thorough understanding of the farm-to-fork ecosystem to be able to draw inferences on the total cumulative carbon emissions and sequestration potential. Most studies have reported emissions and energy costs for production and crop residue management; but, for a more holistic view, it is imperative to include postharvest processing and other processes in the calculation. We also find that certain types of millet are popular amongst the scientific community and there are more articles published on them. However, millets are diverse in terms of their nutritional and morphological profiles. Therefore, it will be more beneficial to adopt an inclusive approach to assessing the carbon trade-offs for different varieties of millets. Similarly, for intercropping systems, more research is needed to compare diverse systems to include and reflect a major proportion of current global dietary staples, pseudocereals, legumes, pulses and oilseeds.

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Claim 2: Millets can grow and survive with less water, leading to less depletion of natural resources

Millets are known for their hardiness and adaptability to diverse environmental conditions. A growing body of literature (Table 2A) supports the claim that millets can be cultivated with less water, which slows down the depletion of natural resources compared to other crops.

Summary

Millets are considered highly efficient in utilizing water resources for crop production. They have a lower water requirement compared to major cereals like maize and wheat. This efficiency makes them particularly well-suited for cultivation in regions with limited access to water. Scientific studies have provided evidence to support the claim that millets can significantly reduce water usage compared to other cereals. Precision irrigation techniques, including drip irrigation and other modern methods, can play a crucial role in enhancing millet yields. While there are a limited number of specific studies on finger millet, research has also shown that precision irrigation can boost the yield of pearl millet, an important millet. These techniques help optimize millet production by delivering the right amount of water to plants at the right time. This improves yields and enhances water-use efficiency and overall irrigation management.

Millets are ideal crops for cultivation in arid and semi-arid regions where other cereals often struggle due to water scarcity and harsh environmental conditions. Millets' drought- tolerant nature and lower water requirement allow them to thrive in these challenging climates. They can even grow on marginal lands that may not be suitable for other crops. As a result, millets serve as reliable sources of food in regions prone to water shortages and food insecurity. Millets have the advantage of extended seed shelf life: the seeds can be stored for longer periods without significant deterioration in quality. This characteristic is particularly valuable in regions where food scarcity is a frequent occurrence. Farmers can store millet seeds for sustenance during times of crop failure or scarcity.

Scientific evidence

Claim 2A: Millets require less water for survival than cereals

Millets are considered to be water-efficient crops, as they can produce a substantial yield with limited water resources. Finger millet, pearl millet and sorghum are among the most important drought-tolerant crops worldwide that can be cultivated in areas with water deficits due to their lower water requirement during growth. These crops are primary food sources in the drylands, where their production dates back to over 5,000 years (Ruiz-Giralt et al. 2023).

Sorghum is known for its ability to thrive in arid and semi-arid regions with limited water resources, showcasing its water-efficient characteristics. Pearl millet, on the other hand, is recognized for its drought tolerance and efficient water use, enabling reasonable yields with less water (Bidinger et al. 1987; Shrestha et al. 2023). It is cultivated extensively across 30 million hectares in the arid and semi-arid tropical regions of Asia and Africa, serving as a primary food source for 90 million poor people. Furthermore, it plays a crucial role in providing feed and fodder, contributing substantially to nearly half of the global millet production (Srivastava et al. 2020). This resilient crop thrives predominantly on marginal lands, relying on rainfed conditions for growth. It can yield a significant grain harvest even in regions prone to drought, where average annual precipitation remains below 250 mm (Nambiar et al. 2011).

Finger millet is well-suited to agroecological zones with erratic rainfall, where its water-efficient traits contribute to its resilience (Habiyaremye et al. 2022; Mukami et al. 2019). Small millets collectively refer to a group of millet species that are known for their adaptability to diverse agroclimatic conditions, often requiring less water than major cereals (Vetriventhan et al. 2021). Barnyard millet's short growth cycle and adaptability to different agroclimatic conditions contribute to its reputation as a water-efficient crop (Sood et al. 2015).

The cultivation of millets can contribute to water conservation and help alleviate the pressure on freshwater resources. Foxtail millet requires 257 g of water to produce 1 g of dry biomass, whereas maize and wheat require 470 g and 510 g, respectively (Li and Brutnell 2011). Pearl millet can grow in areas with limited annual rainfall (300-500 mm) whereas crops such as maize and sorghum are very likely to fail in most years (Vadez et al. 2012). Irrigation water demand in India stands at 0.1, 0.5, 0.1 km^3 for finger millet, pearl millet and sorghum respectively, while for rice it is about 76.7 km^3 (98%) (Davis et al. 2019).

Millets on an average require 300-400 mm of water, whereas rice requires 1,250 mm, about four times that much. This is particularly important across Asia and Africa, where a major part of agriculture is rainfed. About 50% of cultivated land in India is rainfed (Department of Agriculture & Farmers Welfare, n.d.) and about 95% of African agriculture is rainfed (Abrams 2018). In a study by Davis et al. (2018), replacing the area grown to rice with finger millet, pearl millet, sorghum and maize resulted in reduced irrigation water demand by 33%.

Claim 2B: Precision irrigation techniques increase the yield of millets

Precision irrigation techniques can help increase the yield of millets. Precision irrigation involves the application of water to crops in a precise and controlled manner, ensuring that the right amount of water is delivered to the right place at the right time, which can help optimize crop growth and increase yield. Precision agriculture techniques have been studied in millets such as sorghum, pearl millet, finger millet and other small millets.

There are no specific studies on the effect of precision irrigation on the yield of finger millet. However, research articles suggest that precision irrigation techniques such as drip irrigation can be used to deliver water directly to the roots of pearl millet plants, which can increase their yield, productivity, and irrigation water-use efficiency in arid regions. Using such techniques could also increase the yield of finger millet.

González Perea et al. (2018) developed an integrated modeling approach involving the coupling of a water application model with a biophysical crop simulation model (Aquacrop) to evaluate the in-field impacts of precision irrigation on crop yield and soil water management. The approach allowed for a comparison between conventional irrigation management practices against a range of alternate so-called 'precision irrigation' strategies (including variable rate irrigation, VRI). It also provided a valuable framework to evaluate the agronomic (yield), water resource (irrigation use and water-use efficiency), energy (consumption, costs, footprint) and environmental (nitrate leaching, drainage) impacts under contrasting irrigation management scenarios.

Another study (Ismail 2012) tried to achieve the greatest above-ground biomass production of pearl millet per unit of water by two methods — precision irrigation to add the required amount of water when and where needed and the evaluation of production per unit of water for each cut of pearl millet.

Roy et al. (2017) highlight the potential of millets as next-generation crops for climate-smart agriculture. They suggest that research should explore the climate-resilient traits of millets and non-millet crops to facilitate crop improvement. Although they do not specifically mention precision agriculture techniques, the importance of developing sustainable agricultural practices to address climate change is emphasized.

A study on the dynamics of spatial variability of millet growth and yields at three sites in Niger, West Africa and its implications for precision agriculture research (Gandah et al. 2000) focuses on the use of a simple scoring technique to estimate millet yield and define spatial variability of millet growth. The study suggests that precision agriculture techniques can be used to optimize millet production in dryland areas.

In a study on mainstreaming orphan millets to promote climate-smart agriculture to secure nutrition and health, Babele et al. (2022) summarize the benefits of millets and major barriers/bottlenecks to their improvement. It discusses pre-and post-harvest technologies and changing consumer behavior with suitable programs and incentives. Although it does not specifically mention precision agriculture techniques, it emphasizes the importance of developing climate-smart agriculture practices to secure nutrition and health.

In a study on how genome-wide association studies (GWAS), microbiome-wide association studies (MWAS) and microbiome genome-wide association studies (mGWAS) provide insights into precision agriculture based on genotype-dependent microbial effects in foxtail millet, Wang et al. (2022) suggest that microbial-mediated growth effects on foxtail millet are dependent on the host genotype, indicating that precision microbiome management could be used to engineer high-yielding cultivars in agriculture systems. Although the study focuses on foxtail millet, the findings could be applicable to other millets.

In a study on new models for resilient practices in millet and sorghum cultivation (Ruiz-Giralt et al. 2023), the extent of sorghum, finger millet and pearl millet cultivation in areas with limited rainfall was analyzed. The authors suggest that small-scale farmers in the drylands can use precision agriculture techniques such as irrigation to optimize millet production and increase resilience to climate change.

Although the focus is on different aspects of millet cultivation, overall scientific evidence suggests that precision agriculture techniques can be used to optimize millet production in dryland areas, increase resilience to climate change and reduce the depletion of natural resources.

Claim 2C: Millets are the crops of choice for cultivation in arid and semi-arid regions of the world and their seeds can be stored for years

There is research evidence that millets are climate-resilient crops that can survive in a wide range of ecological conditions under water scarcity and are less reliant on chemical fertilizers. Pearl millet [*Pennisetum glaucum* (L.) R. Br.] is cultivated in dry regions of the arid and semi-arid tropics where no other cereal can be successfully grown (Sanjana Reddy et al. 2021). It is mainly grown on marginal lands under rainfed conditions and can produce a significant amount of grain even in drought-prone areas that receive an average annual precipitation of <250 mm. Millets can be stored for long periods of time without spoilage. This makes them an ideal crop for drought-prone areas, where food security can be a major concern. The seeds of millets can be stored for years, providing a reliable source of food even in times of scarcity. Thus, millets are considered to be sustainable and resilient crops. Sorghum and pearl millet are among the six major cereal crops that are a staple food for about 250 million people in the semi-arid tropics and drylands of south Asia and Africa. They are also regarded as climate-smart crops because of their extreme tolerance to heat (up to 42°C air temperature), drought and salinity (Chaturvedi et al. 2022).

Dwelling on nutricereals, Satyavati et al. (2021) highlight that pearl millet's attributes of being drought-tolerant, having a short growing season, and requiring less water than other cereal crops make it a crop of choice for cultivation in arid and semi-arid regions of the world and an ideal crop for farmers in regions with water scarcity.

Analyzing the extent of sorghum, finger millet and pearl millet cultivation in areas with limited rainfall, Ruiz-Giralt et al. (2023) suggest that small-scale farmers in the drylands can use millets and sorghum as crops of choice for cultivation in arid and semi-arid regions, with seeds that can be stored for years.

A review of the nutritional use of millet grain for food and feed (Hassan et al. 2021) highlights that millets are considered one of the oldest cultivated crops and are well-suited to marginal lands, where soils are poor and dry.

Table 2A. A summary of research studies, reviews and opinion articles on the claim that millets can be grown and survive with less water, leading to less depletion of natural resources.

S. No.	Reference	Segment	Article type	Origin	Method and type of millet
1	Abrams, L. 2018.	Food and nutrition security	Report	Sweden	Analytical report
2	Babele et al. 2022.	Climate Smart Agriculture	Review Article	India	All major millets
3	Bandyopadhyay et al. 2017	Climate Smart Agriculture	Opinion article	India	All millets
4	Bidinger et al. 1987.	Plant physiology	Research Article	India	Evaluated the performance of 20 pearl millet genotypes under drought stress conditions and non-stress conditions. Multiple regression analysis to fit the response of genotypes to drought stress.
5	Chaturvedi et al.2022	Crop improvement	Editorial article		
6	Davis et al. 2018	Sustainable food system	Analytical review article	USA	Finger millet, pearl millet and Sorghum
7	Davis et al. 2019	Food production	Research article	USA	Finger millet, pearl millet and Sorghum
8	Dwivedi et al. 2012	Sustainable agriculture and food systems	Review article	India	Small millets
9	Gandah et al. 2000	Geospatial applications	Research article	Niger, Africa	Pearl milet

Insights/results
Over 95% of African food production is rainfed, yet only 5% of public agricultural water investments support rainfed agriculture. Enhanced rainfed agriculture can be financed through various sources.
Discusses the potential of orphan millets to improve food security and nutrition in the face of climate change. Millets have a C_4 photosynthetic system that is highly advantageous for survival in high temperatures and low moisture. The paper suggests that improving breeding practices and developing genetic and other "omics" resources for orphan millets could help improve their yield under stress conditions.
Deals with the importance of exploiting the beneficial attributes of millets for the improvement of millets. Availability of genome sequence information of foxtail millet has facilitated the development of several high-throughput genome-wide molecular markers.
Provides a basis for selecting pearl millet genotypes with improved drought resistance for cultivation in drought-prone areas.
It highlights the importance of exploiting the beneficial attributes of sorghum and pearl millet for the improvement of these crops per se as well as other related grass species.
Quantitatively assesses outcomes of alternative production decisions across multiple objectives using India's rice-dominated monsoon cereal production as an example.
It demonstrates that replacing rice with other cereals, such as maize, finger millet, pearl millet, or sorghum, can improve water use and nutrient supply in India. The research shows that these alternative cereals require less irrigation water than rice and can improve the production of protein, iron, and zinc.
Provides a roadmap for accelerating the improvement of small millets through the use of genetic and genomic resources.
Highlights the importance of understanding the spatial variability of millet growth and yield for developing effective precision agriculture strategies.

(Continued)

S. No.	Reference	Segment	Article type	Origin	Method and type of millet
10	González Perea et al. 2018	Precision Agriculture	Research article	Spain	The research involves the coupling of a water application model with a biophysical crop simulation model (Aquacrop) to compare conventional irrigation management practices against a range of alternate precision irrigation strategies, including variable rate irrigation (VRI)
11	Hassan et al. 2021	Nutrition	Review article	South Africa	Pearl millet and finger millet
12	Habiyaremye et al. 2022	Sustainable agriculture	Research article	USA	The study tested 20 quinoa and 14 millet cultivars for grain yield, emergence, days to heading, flowering, maturity, and plant height in 2016 and 2017 in Musanze, a highland region, and Kirehe, in the Eastern lowlands of Rwanda
13	Ismail et al. 2012	Water use efficiency and productivity	Research article	Saudi Arabia	Investigating the effects of different irrigation methods and stress on the productivity and water use efficiency of pearl millet as a forage crop in arid regions.
14	Li et al.2012	Model genetic systems	Review article	USA	Describes the attributes of Setaria viridis and Setaria italica species that make them attractive as model systems, including their small genomes, rapid life cycle, and morphological similarity to most of the Panicoideae grasses. Italian millet and wild species.
15	Mukami et al. 2019	Plant physiology and biochemistry	Research article	Kenya	The physiological and biochemical responses of finger millet varieties to drought stress were characterized.
16	Nambiar et al. 2011	Health and nutrition	Review article	India	Pearl millet
17	Roy et al. 2017	Remote sensing	Research article	USA	It investigates the use of daily, quasi-global satellite-based estimates of actual evapotranspiration at 0.25° spatial resolution generated by the Global Land Evaporation Amsterdam Model (GLEAM) to improve the performance of the model.

Insights/results
Describes the development of an integrated modeling approach to evaluate the in-field impacts of precision irrigation on crop yield and soil water management.
Provides important updates on the utilization of pearl and finger millets in diets for humans and animals and highlights the potential of millet grain for food and feed applications.
It suggests that adding quinoa and millet into the cropping systems of these regions should play a vital role in fostering sustainable crop intensification and diversification efforts fostering socio-economic growth and food and nutrition security.
Provides important insights into the effects of different irrigation methods and stress on the productivity and water use efficiency of pearl millet as a forage crop in arid regions.
Provides important insights into the potential of Setaria viridis and Setaria italica as model genetic systems for the Panicoid grasses and highlights the importance of understanding the genetic basis of domestication and improvement in these crops.
Increased levels of drought stress significantly decreased germination and early seedling growth of finger millet varieties. It highlights the importance of understanding the physiological and biochemical responses of finger millet to drought stress to develop drought-tolerant varieties.
Discusses the potential health benefits of pearl millet. Pearl millet is a highly nutritious grain that is rich in several nutrients as well as non-nutrients such as phenols. It has high energy, less starch, high fiber, low glycemic index, and is gluten-free. The protein content ranges from 8 to 19%, and it is low in lysine, tryptophan, threonine, and the sulfur-containing amino acids. Pearl millet can be recommended in the treatment of celiac diseases, constipation, and several non-communicable diseases.
Discusses the use of satellite-based evapotranspiration estimates to improve the performance of a simple lumped catchment-scale hydrologic model driven by satellite-based precipitation estimates to generate streamflow simulations for a poorly gauged basin in Africa.

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S. No.	Reference	Segment	Article type	Origin	Method and type of millet
18	Ruiz-Giralt et al.2023	Dryland agriculture	Research article	Spain	Presents new models that focus on the ecological factors driving finger millet, pearl millet, and sorghum traditional cultivation, with a global perspective.
19	Sanjana Reddy et al. 2021	Crop production	Research article	India	Providing valuable information on the performance and stability of pearl millet varieties in arid and semi-arid regions of India
20	Satyavathi et al. 2021	Food and nutritional security	Review article	India	Pearl millet
21	Srivastava et al. 2020	Nutritional security	Review article	India	Genomic selection (a breeding approach that uses high-density DNA markers distributed across the genome to facilitate the rapid selection of desirable traits) – Pearl millet
22	Shrestha et al. 2023	Drought tolerance	Review article	USA	Analyzes the characteristics of pearl millet that foster drought resistance, including both short- and longer-term responses to drought
23	Sood et al. 2015	Plant breeding	Review article	India	Barnyard millet: Compilation of information available on crop history, evolution, crop breeding and present status to make the crop competitive and revamp its cultivation.
24	Taylor et al. 2014	Agricultural sustainability and food security	Review article	India	Discusses the potential of millets as a solution to agricultural sustainability and food security
25	Roy et al. 2017	Remote sensing	Research article	Kenya and Tanzania	Modelling
26	Vadez et al. 2012	Abiotic stress	Methods article	India	Developing a new approach to pearl millet breeding for drought tolerance based on the fact that post-flowering drought tolerance is a highly complex trait.
27	Vetriventhan et al. 2021	Genetic resources	Research	India	200 diverse little millet landraces were characterized to assess variability for agronomic and nutritional traits and identify promising accessions.
28	Wang et al. 2022	Precision agriculture	Article	China	Discusses the use of GWAS, MWAS, and mGWAS to provide insights into precision agriculture based on genotype-dependent microbial effects in foxtail millet.

Insights/results
Mapping the possible cultivation areas of finger millet, pearl millet, and sorghum on a global level. It highlights the potential of these crops as a response to the recent increase of aridity levels worldwide and their role in the resilience and sustainability of dryland agriculture.
Provides valuable information for the development of pearl millet varieties that can help to improve food security in arid and semi-arid regions of India.
Pearl millet can be exploited for improving nutritional quality and combating malnutrition, and the focus should be laid towards the development of food products from pearl millet to make it more accessible.
The study concludes that the use of genomic selection and GWAS in pearl millet breeding can lead to the development of improved cultivars with desirable traits.
Several pearl millet accessions have been found from even drier regions, including areas in the Mauritania and Mali regions with average rainfall less than 50 mm.
A multi-purpose crop that is grown for human consumption as well as fodder. It is generally cultivated in areas where climatic and edaphic conditions are not suitable for major cereals.
The article concludes that millets can be a solution to agrarian and nutritional challenges and can contribute to sustainable food systems.
The use of satellite-based evapotranspiration estimates to improve the structure of a simple conceptual rainfall-runoff model. Making diagnostic structural improvements to hydrologic models can significantly improve the simulation of actual evapotranspiration.
Provides valuable information for the development of drought-tolerant pearl millet varieties, which can help to improve food security in regions affected by drought.
Significant variability observed for grain yield and nutritional traits, including protein, iron, and zinc content, among the landraces. The authors identified several accessions with high grain yield and nutritional traits, suggesting that these accessions could be used for breeding programs to develop improved little millet varieties.
The article concludes that the use of GWAS, MWAS, and mGWAS can provide insights into precision agriculture based on genotype-dependent microbial effects in foxtail millet.

Priorities for future research

Despite the progress made on research into millets and sustainable cultivation practices to address the challenges of water scarcity and resource depletion, research gaps exist in the following areas:

- Drought-resistant millet varieties
- Precision irrigation techniques
- Climate-resilient agricultural practices
- Soil health and nutrient management
- Water-efficient postharvest technologies
- Policy and market support

Addressing these research gaps will play a significant role in promoting millet cultivation which requires less water and minimizes the depletion of natural resources, thus contributing to sustainable agricultural practices and food security.

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Claim 3: Millets grow faster, putting less stress on the environment

Summary

Millets, including sorghum, pearl millet, finger millet, foxtail millet, little millet, and barnyard millet possess a short life cycle, typically around 10-12 weeks, compared to wheat and rice (C_3 plants) which require 20-24 weeks. This short life cycle is advantageous for stress mitigation and efficient resource utilization. Millets, as C_4 plants, exhibit improved photosynthetic rates in warm conditions and excel in water- and nitrogen-use efficiency compared to C_3 plants. For instance, foxtail millet (*Setaria italica*) requires significantly less water to yield dry biomass compared to maize and wheat. Various studies demonstrate the short growth cycle and stress tolerance of millets, making them suitable for marginal environments.

Scientific evidence

Claim 3A: Millets have a shorter lifecycle than other major crops

The short life cycle of millets (10-12 weeks), compared to other major crops (20-24 weeks), supports them in stress mitigation. Sorghum, pearl millet, finger millet, foxtail millet, barnyard millet and other millets have a shorter life cycle than other major crops such as wheat, rye, barley and oats which grow best in cool weather conditions, while millets are warm-season plants that do best in the heat of summer (Goron and Raizada 2015). Millets are C_4 crops which grow between 20-100% faster than C_3 crops, as confirmed by Shrestha et al. (2023). Millets exhibit improved photosynthetic rates in warm conditions, offering immediate water- and nitrogen-use efficiencies that surpass C_3 photosynthesis approximately 1.5 to 4-fold (Bandyopadhyay et al. 2017). For instance, finger millet requires only 257 grams of water to yield 1 gram of dry biomass, whereas maize and wheat demand 470 and 510 grams of water, respectively (Nadeem et al. 2020). Furthermore, C_4 photosynthesis provides millets with additional advantages, such as thriving and performing well in warmer temperatures, displaying more flexible biomass allocation patterns and reducing hydraulic conductivity per unit leaf area (Lundgren et al. 2014).

Sorghum is known for its short growth duration and ability to thrive in arid and semi-arid regions, making it an ideal choice for sustainable agriculture (Yahaya et al. 2023). Pearl millet is a fast-growing cereal crop suitable for regions with limited water resources, contributing to sustainable agriculture (Bidinger et al. 1987). Finger millet has a relatively short growth duration and can be cultivated in diverse agroecological zones, reducing environmental stress (Habiyaremye et al. 2022; Mukami et al. 2019). Foxtail millet is known for its quick growth, particularly in areas with limited water availability (Li and Brutnell 2011). Small millets collectively refer to a group of fast-growing millet species.Research on their short crop duration and suitability for sustainable agriculture is well documented (Padulosi et al. 2013). Barnyard millet is known for its short growth cycle and adaptability to diverse agroclimatic conditions.

Rebecca et al. (2016) report that C_4 photosynthesis boosts growth by altering the size and structure of plant leaves and roots. C_4 plants grow 20-100% faster than C_3 plants; they also make 'cheaper' quality leaves, allowing them to produce 50% more roots. As roots take up water and nutrients from the soil, C_4 plants have important advantages in dry and infertile soils across the world's savannas and grasslands, a quality that could help the crops use soil resources more sustainably, as well as produce larger yields.

Muchow (1989) conducted a study to compare the productivity of high-yielding hybrids of maize, sorghum and pearl millet under fully irrigated and high fertility conditions at three planting dates in a semi-arid tropical environment. Pearl millet was always the earliest, in both flowering and maturity, while maize was always the latest in maturity. Pearl millet reached maturity in about 70 to 80 days, sorghum in 85 to 105 days and maize in 100 to 110 days.

Baltensperger (1996) reports that millets have shorter growing seasons, which helps them either to tolerate or avoid drought and intense heat and grow quickly to attain maturity. According to Mula et al. (2009), early-maturing pearl millet cultivars (80-90 days) grow well under declining soil moisture and poor rainfall. Vadez et al. (2012) indicate that even under favorable conditions, pearl millet tends to have a shorter crop cycle than other cereals because it has early flowering as a 'built in' drought escape mechanism, inherited from its wild progenitors, having evolved in semi-desert environments.

In a literature review, Goron and Raizada (2015) report that proso millet might be the earliest dryland farming crop in East Asia, maturing within 60-90 days and still providing a reasonable and assured harvest even under adverse conditions.

Anecdotal evidence (Earth 360, n.d.) indicates that millets can develop from planted seeds to mature, ready to harvest plants in as little as 65 days.

Claim 3B: Millets have the potential to increase productivity in marginal environments and will help in overcoming future climate change

Millets, including sorghum, pearl millet, finger millet and other small millets hold immense promise in bolstering agricultural productivity in marginal environments, while also serving as a strategic tool in the battle against the challenges posed by climate change. These resilient crops have adapted to diverse agroclimatic conditions, often thriving in regions where other cereals struggle. Their capacity to withstand water scarcity, heat stress and low fertility soils makes them well-suited for cultivation in arid and semi-arid areas. Millets' rapid growth, shorter growing season and efficient use of resources not only only ensure food security but also contribute to sustainable agriculture. As climate change increasingly disrupts traditional cropping patterns, millets' versatility, combined with their nutritional value, positions them as a vital component of future agricultural strategies, helping to enhance resilience, mitigate climate impacts and secure food supplies for vulnerable communities worldwide. Millets have a short crop duration; hence are less exposed to the weather and climate while also providing an option for crop rotation, which is especially important for smallholder farmers.

Growth and production of sorghum and millets in marginal environments have been studied, highlighting their potential for stress mitigation and increased productivity (Saxena et al. 2018). A study assessing climate change impacts on pearl millet under arid and semi-arid environments using the CSM-CERES-Millet model found that pearl millet is a climate-smart crop with inherent genetic potential for stress tolerance and yield improvement (Numan et al. 2021).Finger millet has been recognized for its genetic potential as a climate-smart crop and its ability to tolerate drought and heat stress (Numan et al. 2021).

There are limited research articles on foxtail millet, but as a type of millet, it is expected to share similar characteristics and potential for productivity in marginal environments.Small millets can be grown in adverse climatic and soil conditions, making them suitable for marginal environments and climate change mitigation (Saxena et al. 2018). Barnyard millet is a climate-resilient crop that can be grown in marginal environments and has the potential to contribute to increased productivity in such areas.

The increasing global population will inevitably lead to a rising demand for food. Although maize, rice, and wheat have emerged as the dominant staple cereals, millets and other lesser-known crops have yet to gain comparable recognition. With expanding drylands, deteriorating soil quality and diminishing groundwater resources posing significant challenges worldwide (Bisoffi et al. 2021), the prospects for enhancing the production of major staple cereals appear limited. Millets offer a promising solution, thriving in shallow, less fertile soils with a pH range of 4.5 to 8.0 (Babele et al. 2022). The diverse array of small millets, including finger, foxtail, proso, barnyard, kodo, little, guinea, browntop, teff, fonio and Job's tears are a readily viable replacement for wheat and rice.Additionally, millets such as pearl and finger millet exhibit robust growth even in soils with salinity levels as high as 11–12 dS/m, in stark contrast to rice's poor adaptability beyond a soil salinity of 3 dS/m. Millets have the potential to increase productivity in marginal environments and help in overcoming future climate change.

Priorities for future research

Although research has shown that millets have the potential to increase productivity in marginal environments and help in overcoming future climate change, the following research gaps need to be addressed to fully understand their potential:

- There is scant and scattered information on the growing duration of different millets in comparison with other C_4 crops (mainly maize) and their effect on soil and other natural resources.
- More research is needed on responses to elevated CO_2 in C_4 plants, particularly millets.
- Limited research on specific millet types: Research on the potential of millets is limited to specific millet types, such as foxtail millet, limiting our understanding of their potential for productivity in marginal environments. This calls for widening the research to other types of millets.
- Lack of research on specific stressors: There are studies focused on the effects of drought and heat stress on millets. The impact of other stressors such as flooding or soil salinity have not been fully explored.
- Limited understanding of genetic potential: While research has highlighted the genetic potential of millets as climate-smart crops, the specific genes and molecular mechanisms involved in their stress tolerance and productivity need to be studied in detail.
- Limited research on practical implementation: Though the potential of millets has been researched, there is limited research on the practical implementation of millet cultivation in marginal environments, such as best farming practices or the economic viability of millet cultivation.
- Insufficient research on market demand: While millets have the potential to increase productivity in marginal environments, the limited research on market demand for these crops could limit their adoption and impact.

Table 3A. A summary of research studies, reviews and opinion articles on the claim that millets grow faster, putting less stress on the environment.

S. No.	Reference	Segment	Article type	Origin	Method and type of millet
1.	Babele et al. 2022.	Climate Smart Agriculture	Review Article	India	All major millets
2.	Bandyopadhyay et al. 2017	Climate Smart Agriculture	Opinion article	India	All millets
3.	Baltensperger, 1996	Crop resources	Book chapter	USA	Discusses the agronomic practices for foxtail and proso millet cultivation, including planting dates, seeding rates, and fertilizer requirements
4.	Bidinger et al. 1987.	Plant physiology	Research Article	India	Evaluated the performance of 20 pearl millet genotypes under drought stress conditions and non-stress conditions. Multiple regression analysis to fit the response of genotypes to drought stress.
5.	Bisoffi et al. 2021	Sustainable food system	Review article	Italy	Discusses the impact of COVID-19 on sustainable food systems and the lessons that can be learned for future emergencies
6.	Habiyaremye et al. 2022	Sustainable agriculture	Research article	USA	The study tested 20 quinoa and 14 millet cultivars for grain yield, emergence, days to heading, flowering, maturity, and plant height in 2016 and 2017 in Musanze, a highland region, and Kirehe, in the Eastern lowlands of Rwanda
7.	Goron and Raizada, 2015.	Crop improvement	Review article	Canada	Highlights the importance of understanding the genetic diversity of small millets, which can help to identify traits that are important for crop improvement, such as drought tolerance, disease resistance, and nutritional quality
8.	Li et al.2012	Model genetic systems	Review article	USA	Describes the attributes of Setaria viridis and Setaria italica species that make them attractive as model systems, including their small genomes, rapid life cycle, and morphological similarity to most of the Panicoideae grasses. Italian millet and wild species.
9.	Lundgren et al. 2014	Plany physiology	Review article	United Kingdom	Discusses the evolution of C_4 photosynthesis and the role of Kranz anatomy in this process.

Insights/results
Discusses the potential of orphan millets to improve food security and nutrition in the face of climate change. Millets have a C_4 photosynthetic system that is highly advantageous for survival in high temperatures and low moisture. The paper suggests that improving breeding practices and developing genetic and other “omics” resources for orphan millets could help improve their yield under stress conditions.
Deals with the importance of exploiting the beneficial attributes of millets for the improvement of millets. Availability of genome sequence information of foxtail millet has facilitated the development of several high-throughput genome-wide molecular markers.
Provides a comprehensive overview of foxtail and proso millet, highlighting their importance as crops for food and feed, and their potential for sustainable agriculture in dry and marginal growing environments.
Provides a basis for selecting pearl millet genotypes with improved drought resistance for cultivation in drought-prone areas.
Highlights the importance of sustainable and resilient food systems in the context of emergencies such as the COVID-19 pandemic, and emphasizes the need for continued research and investment in sustainable agriculture and food systems.
It suggests that adding quinoa and millets in the cropping systems of these regions should play a vital role in fostering sustainable crop intensification and diversification efforts fostering socioeconomic growth and food and nutrition security.
Discusses the genetic diversity and genomic resources available for small millet crops, which could be used to accelerate a new green revolution.
Provides important insights into the potential of *Setaria viridis* and *Setaria italica* as model genetic systems for the Panicoid grasses and highlights the importance of understanding the genetic basis of domestication and improvement in these crops.
Provides a comprehensive overview of Kranz anatomy and its role in the evolution of C_4 photosynthesis, highlighting the importance of understanding the variation and distribution of anatomical traits across C_3 and C_4 taxa

(Continued)

S. No.	Reference	Segment	Article type	Origin	Method and type of millet
10.	Mukami et al. 2019	Plant physiology and biochemistry	Research article	Kenya	The physiological and biochemical responses of finger millet varieties to drought stress were characterized.
11.	Muchow, 1989	Crop production	Research article	Australia	Emphasizes the importance of water management and crop breeding for increasing crop productivity in semi-arid environments (crop: pearl millet)
12.	Mula, et al. 2009	Crop production	Case study article	India	Presents case studies from Gujarat and Maharashtra, India, on the cultivation of pearl millet as a postrainy cool season crop
13.	Nadeem et al. 2020	Abiotic stress	Review article	China	Focuses on the adaptation of foxtail millet to abiotic stresses, with a special perspective on its responses to nitrogen and phosphate limitations
14.	Numan et al. 2021	Abiotic stress	Review article	USA	Discusses alternative strategies for multi-stress tolerance and yield improvement in millets
15.	Padulosi et al. 2013	On-farm conservation	Review article	Europe	Discusses novel approaches to cope with climate change, including the use of Neglected underutilized crops as climate-resilient crops
16.	Rebecca et al. 2016	Plant physiology	Article	United Kingdom	Highlights the importance of understanding the molecular mechanisms underlying C_4 photosynthesis, which can act as a basis for further research and crop improvement.
17.	Saxena et al. 2018	Climate change	Review article	Canada	Provides a review of the potential of millets for food security in the context of climate change.
18.	Shrestha et al. 2023	Drought tolerance	Review article	USA	Analyzes the characteristics of pearl millet that foster drought resistance, including both short- and longer-term responses to drought
19.	Vadez et al. 2012	Abiotic stress	Methods article	India	Developing a new approach to pearl millet breeding for drought tolerance based on the fact that post-flowering drought tolerance is a highly complex trait.
20.	Yahaya et al., 2023	Agronomy	Research article	Africa	Aims to evaluate drought tolerance and the effect of genotype-environment interaction (GEI) on grain yield of a population of African sorghum genotypes. The authors seek to identify high-yielding and drought-adapted genotypes for direct production and also for use in breeding programs.

Insights/results
Increased levels of drought stress significantly decreased germination and early seedling growth of finger millet varieties. It highlights the importance of understanding the physiological and biochemical responses of finger millet to drought stress to develop drought-tolerant varieties.
The study found that maize had the highest yield potential, with an average grain yield of 9.2 t ha^{-1} over three sowing dates. Sorghum had an average grain yield of 5.6 t ha^{-1}, while pearl millet had an average grain yield of 2.9 t ha^{-1}.
Provides evidence that pearl millet can be successfully grown as a postrainy cool season crop in Gujarat and Maharashtra, India, and highlights the importance of pearl millet as a food and feed crop in regions with low rainfall and poor soil fertility. The article emphasizes the potential of pearl millet as a climate-resilient crop, and the need for continued research and investment in crop breeding and genetic improvement to increase crop productivity and resilience.
The article provides evidence that foxtail millet has unique responses to abiotic stresses such as low nitrogen and low phosphate, which make it a promising crop for sustainable agriculture in nutrient-poor soils. The article emphasizes the need for continued research and investment in crop breeding and genetic improvement to increase crop productivity and resilience in foxtail millet and other crops.
The article provides evidence that alternative strategies such as conventional breeding, the use of PGPRs, and genome editing can be used to improve stress tolerance and yield in millets.
The article provides evidence that neglected and underutilized species have the potential to contribute to sustainable agriculture and food systems, particularly in the context of climate change.
Discusses the impact of C_4 photosynthesis on plant growth by altering physiology, allocation, and size.
Millets have the potential to contribute to food security in the context of climate change, as they are well-adapted to dry and marginal growing environments. They require less water and fertilizer than other major cereals, and can be grown on poor soils with low fertility.
Several pearl millet accessions have been found from even drier regions, including areas in the Mauritania and Mali regions with average rainfall less than 50 mm.
Provides valuable information for the development of drought-tolerant pearl millet varieties, which can help to improve food security in regions affected by drought.
Sorghum genotypes are recommended for production in dry agro-ecologies of sub-Saharan Africa characterized by pre-and-post anthesis drought stress.

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Claim 4: Millets have traits that make them resilient to climate stress

Unique morphological traits and genetic features confer upon millets high resilience against climate adversities, making them highly climate-adaptive and tolerant crops.

Summary

Millets possess numerous climate-resilient features, including adaptation to ecological and environmental conditions such as water and heat stress, and insect/pest incidence. Owing to a unique suite of properties, they can grow in nutrient-limited conditions with minimal inputs. Thus, they offer a sustainable, nutritious and economical option to meet growing global food demand.

Scientific evidence

Claim 4A: Salient morphological features enable millets to tolerate and survive climatic adversities

There is growing scientific recognition of the climate-adaptive features of millets, such as a short growth cycle, high photosynthetic and nitrogen-use efficiency and adaptation to ecological conditions such as low nutrient and water conditions. Studies have shown (Table 4A) that most millets have low vulnerability to environmental stresses and can thrive with minimal dependence on fertilizer (Singh et al. 2021; Dayakar Rao et al. 2021; Wilson and VanBuren 2022). Ceasar and Maharajan (2022) highlighted the potential of millets for attaining Sustainable Development Goals (in particular SDG 2, Zero Hunger) in the context of climate change. They attributed this potential to millets' unique ability to thrive with minimal reliance on fertilizers compared to mainstream cereals. The short growth cycle allows millets to mature quickly, and thus avoid drought and other environmental stresses. Their high photosynthetic efficiency enables them to produce more biomass using less water and nutrients. Their superior nutrient content, including high levels of protein, fiber and minerals, makes them more resilient to nutrient stress. Their high nitrogen-use efficiency enables them to grow well even in low-nitrogen soils. Furthermore, under favorable conditions, millets produce more tillers and thereby more grain (Choudhary et al. 2023).

Certain types of millets such as finger millet, pearl millet and sorghum have been shown to have excellent climate-adaptive properties, especially tolerance to water stress (Ruiz-Giralt 2023). Hegde and Linge Gowda (1989) enumerated the unique morphological features that enable finger millet to adjust to different agroclimatic conditions and make it drought-tolerant. The ability to survive in harsh climatic conditions (especially drought and limited nutrients) has been attributed to the morphology of millets: A deep, fibrous root system coupled with C_4 physiology that can survive in various ecological conditions (Wilson and VanBuren 2022). Studies have highlighted the role of the root system and high photosynthetic efficiency which make pearl millet highly climate-resilient (Azare et al. 2020; Satyavathi et al. 2021) and therefore a crop of choice for cultivation in arid and semi-arid regions of the world. Several hybrids and varieties of pearl millet have been developed in India over the past 50 years in public and private sectors (Yadav and Rai 2013). However, few efforts have been made to study the climate-resilient features of pearl millet in comparison with major cereals (Bandyopadhyay et al. 2017).

Claim 4B: Millets can survive and grow even under several biotic and abiotic stressors

Millets have evolved to survive in extremely harsh conditions without human intervention. While some millets (foxtail, pearl and finger millet and sorghum) have been domesticated more than others such as kodo and browntop millets (Aggarwal et al. 2022), most varieties thus developed have preserved this characteristic, which adapts them to thrive in fairly diverse environments. In the current context of worsening conditions due to climate change, such features have brought millets back into the focus of researchers and policymakers seeking to develop more sustainable food systems (Saxena et al. 2018). Being rainfed crops, millets do not require standing water in the field; so there is no need to fell forests to make place for big dams, reservoirs and elaborate canal systems to bring water to farms. They do not also need any fertility enhancement or pesticide application to grow well and yield a good harvest (Tiwari 2023). Essentially, the environmental footprint of millets is a fraction of that of rice or wheat.

Millets also play an important role in nurturing soils and improving their fertility and texture, thereby increasing yields and ensuring better returns to farmers. Once their root system is established, millets can survive several dry weeks. When it starts raining, the plants resume growth and produce a yield by the end of the season (Kumar et al. 2018). Millets are thus environmentally, ecologically and economically friendly sources of food and nutrition for about a third of the world's population. They show exceptional tolerance to abiotic stresses such as drought, heat, cold, nutrient deficiency and excess salt. Millets are C_4 plants well-adapted to marginal, dryland and semi-arid environments having scanty rainfall and low-fertility soils (Saleem et al. 2021).

Biotic stresses like fungal, bacterial, and viral diseases do affect crop production in millets. Downy mildew, blast, rust and ergot, for instance, are major constraints to productivity in pearl millet. However, millets have developed various defensive processes against biotic stresses (Sharma et al. 2020). During a pathogen attack, signal transduction pathways activate stress-related regulatory elements to respond to the pathogen efficiently (Chanwala et al. 2022). Biotic stress resistance in millets is an important factor to consider in overcoming disease and pest-related challenges faced by vital food and feed crops, including sorghum, pearl millet, finger millet, foxtail millet and other minor millets (Das and Padmaja 2016). Furthermore, problems such as diseases, pests, and weeds are likely to be aggravated due to changing climate patterns. Management of these stresses, therefore, is becoming increasingly challenging (Kumar et al. 2022). Current strategies are mainly oriented toward developing resistant cultivars rather than using chemicals, which is a cost-prohibitive option in developing countries (Fatondji et al. 2012).

Claim 4C: Genetic breeding and technological advancements further enhance climate resilience in millets

Conventional breeding to enhance biotic and abiotic stress resistance in pearl millet has achieved considerable success. In the past few years, various novel approaches including functional genomics and molecular breeding have also been attempted in this crop to augment yields under adverse environmental conditions, and there is a lot of scope for further improvement using such tools (Shivhare and Lata 2017). The discovery and use of various DNA-based markers such as EST-SSRs, DArT, CISP and SSCP-SNP in pearl millet have not only helped in determining population structure and genetic diversity but also proved to be important for developing crop improvement strategies at a faster rate and with greater precision (Shivhare and Lata 2017). Molecular marker-based genetic linkage maps and identification of genomic regions that determine yield under abiotic stresses, particularly terminal drought, have paved the way for marker-assisted selection and breeding of pearl millet cultivars.

Against the backdrop of increasing pressure on natural resources due to high population growth, farmers are constrained to cultivate marginal lands, thereby compounding the problem of land degradation. Additionally, there are regional differences in sensitivity to climate change and in the resilience of traditional cultivars (Fatondji et al. 2012). While traditional cultivars are more resilient to climatic adversities, modern varieties do have the potential to yield more under optimal conditions (Acevedo et al. 2020). The challenge of feeding an ever-growing population with a healthy and balanced diet and the threat posed to crops by changing climate conditions make it imperative to exploit the beneficial attributes of millets and develop varieties with desirable characteristics (Bandyopadhyay et al. 2017).

Recent studies have examined genes related to drought resistance that were identified through individual transcriptomic studies. Ninety-four genes were identified that were differentially expressed in both vegetative and reproductive stages under drought stress. Among them is a tight cluster of genes directly related to biotic and abiotic stresses, carbon metabolism and hormonal pathways. Much remains to be learned about how pearl millet's unique combination of genetic and physiological mechanisms allows it to achieve such high drought tolerance. The answer to this question may be useful for crops other than pearl millet (Shrestha et al. 2023).

Claim 4D: Amidst climate change, population growth and dwindling resources, millets offer a sustainable solution to feed the future

Millets constitute a significant proportion of underutilized grasses and are known for their climate resilience and excellent nutritional profiles. Among the millets, foxtail millet (*Setaria italica*) and its wild relative, green foxtail millet (*S. viridis*), are collectively regarded as models for studying broad-spectrum traits, including abiotic stress tolerance, C_4 photosynthesis, biofuel and nutritional characteristics. Similarly, sorghum and pearl millet serve as major sources of food, feed and fodder in the semi-arid tropical regions of the developing world. Furthermore, it has been shown by DeFries et al. (2023) that the increase in the water footprint of sorghum will be a third of that of wheat by 2024, which would make it a crop of choice in the era of climatic vagaries. They concluded that sorghum provides a climate-resilient alternative to wheat and other staples, which are more sensitive to climate change. Further, Mude et al. (2020) enumerated that cultivation of millets (sorghum) can maintain calorie production, improve nutritional supply (+1% to 5% protein; +5 to +49% iron), reduce the demand for water (-3% to -21%), inputs and GHGs (-2% to -13%) compared to other cereal crops.

Despite the considerable potential of these neglected and underutilized crops with regard to climate resilience, food security and nutrition, their widespread adoption remains a challenge. Uptake of millet cultivation is inhibited by poor economic performance due to low yields, compounded by various social factors. Using farm survey data and aggregated time-series data from four states in southern India, a research study examined factors influencing productivity in finger millet cultivation. A farm-level yield-gap analysis was complemented by an analysis of total factor productivity (TFP) growth between 1999 and 2014 to better understand the role of research and innovation. The results of this study suggested that there was considerable potential that could be unlocked through improved growing practices to achieve better yields. However, technical support emerges as a crucial factor in the effort to boost finger millet productivity. The TFP analysis indicated a moderate level of growth with high variability and conflicting trends between states, suggesting a need to invest more in research and development, extension and infrastructure. Sustained productivity gains will require research efforts that respond to needs expressed by farmers. Finger millet can be part of an overall strategy for sustainable intensification (Grovermann et al. 2018).

Innovative solutions are necessary to minimize the influence of climate change on crop productivity. These include breeding to obtain cereals that are more tolerant to environmental conditions caused by climate change, increased production of those new cultivars, improved irrigation, and more effective use of fertilizer (Ullah et al. 2017).

Furthermore, different predictive models have inferred that climate change would reduce the production of major cereal crops, but millets are an exception due to their ability to grow in variable climatic conditions and dry areas on account of their strong root system. Moreover, millets are not resource-intensive crops and release fewer greenhouse gases than other cereals. Therefore, in addition to addressing food security, millets have an enormous potential for reducing the impact of agriculture on global warming. They should be grown worldwide as an alternative to major cereals and grains. Given these features, only low investment will be needed to produce millets and provide a sustainable income source to farmers (Hassan et al. 2021).

Priorities for future research

Climate change influences biophysical factors such as the growth of plants and animals along with associated food processing and distribution. Hence, a systematic assessment of the effects of climate change on crops, specifically temperature-tolerant species such as millets, will help increase crop productivity and minimize food insecurity by implementing 'anticipate and adopt farming techniques' (Ruiz-Giralt et al. 2023).

Understanding the mechanism and upregulation of stress-related transcriptional factors, signaling genes, etc., which induce/develop stress tolerance in species, will help identify the genotypes and their tolerance to environmental conditions. The lack of genetic resources is hampering improvement of millets. In addition, identification and characterization of the genes responsible for nutritionally rich, stress-tolerant and gluten-free species need to be developed to improve millet resilience to climate change.

Biotic and abiotic stresses cause morpho-physiological and biochemical changes during various phenological stages in millet genotypes. Understanding the mechanism of different biochemical parameters such as pigments, accumulation of proline, antioxidant enzymes, etc., which induce/develop stress tolerance in species, will lead to the development of millet resilience to climate change.

Research results suggest there is considerable potential for improved growing practices to achieve better millet yields. To achieve sustained productivity gains, it will require research efforts that respond to needs expressed by farmers to develop an overall strategy for sustainable intensification. Further development of stress-tolerant millet species should be encouraged to withstand future environmental pressures, besides exploiting their excellent nutritional value over other conventional crops (Shivhare and Lata 2017).

Table 4A. Summary of research outcomes and insights from key studies conducted around the world in the past 10 years to document the climate-resilient potential of millets.

S.No.	Reference	Segment	Article type	Study area
1.	Bandyopadhyay et al. 2017	Abiotic stress tolerance	Opinion	Specific study area not mentioned
2.	Wilson and VanBuren 2022	Abiotic stress tolerance	Review	Asia and Africa (based on land and climate)
3.	Bose 2018	Abiotic stress (water use)	News article in LEISA India	India
4.	Saxena et al. 2018	Abiotic stress (water use)	Review article	India; China; western, middle and southern Africa; parts of South America and USA
5.	Gebrehiwot et al. 2020	Weed control and management	Research article	Ethiopia
6.	Shabbir et al. 2022	Biotic stress (weed control andmanagement)	Research article	Australia
7.	Ruiz-Giralt et al. 2023	Sustainable Development Goals (climate change)	Research article	World region classifying aridity index value
8.	Antony and Maharajan 2022	Sustainable Development Goals (climate change)	Brief report	Across the world

Method and type of millet	Highlights/results
Study of millet gene varieties focused on foxtail, finger, and pearl millet	Summary of genes identified and characterized in different millets for their role in conferring abiotic stress tolerance.
Exploration of genome editing and advanced breeding methods to develop nutritious, climate-resilient millets for the future	Despite low yield and agronomic issues, millets have exceptional adaptability and climate resilience, with potential to improve food security and preserve cultural traditions.
Meta data analysis covering all varieties of millets	Farmers' perception: Compared to rice, climate-friendly millets use less water. They can grow in a less rainfall area, and under high temperature and drought conditions.
Study of the availability of resources like water and soil invarious regions through modeling scenarios; focused on pearl, proso, foxtail, barnyard, and kodo millets	The conditions needed for different millets to be grown globally; millet in various parts of the world; impact of climate change on agricultural productivity by 2050; an overview of future water supplies based on chosen studies.
Over two consecutive seasons, 10 teff varieties were evaluated for weed competitiveness in two locations using a split plot design, hand weeding, and non-weeded treatments.	With an explanation of the abiotic conditions in the study area, the study used cultural control methods to control weeds in the teff variety. Teff varieties Kora and DZ-Cr-387 were discovered to have the highest weed competitive ability, which reduced weed density, dry weight, and cover and led to the least amount of yield loss.
Field experiments at University of Sydney's Bringelly and Lansdowne farms evaluated the weed-suppressive ability of summer cover crop species, analyzing data using GenStat and ANOVA on transformed data.	In weed suppression tests conducted on three species, teff showed high potential in terms of fast establishment, high biomass production and weed suppression.
Using published ethnographic material, novel data was collected through questionnaire on finger millet, pearl millet, sorghum.	The study reveals that factors like plant growth, cycle, length, soil water holding capacity, and nutrient availability are crucial for millet and sorghum agriculture, despite the assumption that total annual precipitation is the most important. This suggests that traditional methods could be crucial for the sustainability and resilience of dryland agriculture.
A study on millet physiological historical climate resilience, based on meta-analysis, encompassing all typesof millets.	Millets can help in attaining ustainable Development Goals and meeting key challenges in millet research.

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S.No.	Reference	Segment	Article type	Study area
9.	Abdullah et al., 2022	Climate resilience	Research article	No particular region
10.	Babele et al. 2022	Climate resilience (abiotic stress)	Review	No particular region
11.	Chaturvedi et al. 2022	Climate resilience	Research article	South Asia and sub-Saharan Africa
12.	Xiao et al. 2021	Climate resilience	Research article	China
13.	Adamou et al. 2012	Abiotic stress (water use)	Book chapter (research)	West Africa
14.	Fatondji et al. 2012	Abiotic stress (water use)	Book chapter (research)	West Africa
15.	Maithani et al. 2023	Climate resilience	Review article	Japan, Korea, India,China
16.	Grovermann et al. 2018	Climate resilience (economic feasibility)	Research article	India

Method and type of millet	Highlights/results
Study uses real production data from 1970 to 2018 to examine climate resilience in sorghum and millet production, using an autoregressive distributed lag cointegration approach.	The analysis confirms that sorghum and millets are climate-resilient, with residuals free from conditional heteroscedasticity and serial autocorrelation. The study supports promoting these and other climate-resilient crops.
Descriptive study on pearl, finger, foxtail, little, proto, kodo, barnyard millets.	Researchers say that millets will be the best option for growing in pandemic situations and have taken into account information about their climatically smart and abiotic stress response.
This study employed methods such as additive main effects, multiplicative interaction (AMMI), and genotype × environment interaction (GGE) biplot on sorghum, pearl, finger and foxtail millets.	64 sorghum genotypesincluding landraces, relatives from the wild, modified varieties, and offspring from the fourth filial generation (F_4), were assessed in this study. F_4 descendants produced more resilient and high-yielding genotypes.
From 1981 to 2010, mean dates of sowing, flowering, and maturity in maize, rice, and soybean were calculated using temperature, precipitation, and sunshine data from China Meteorological Administration (CMA) stations.	The sensitivity and reaction of various crop phenologies to climatic conditions varies significantly.Comparison and thorough study of various crops would be useful in analyzing how cropsrespond to and adapt to climate change. The study found that temperature negatively correlated with crop growth phases, indicating that temperature rises primarily shorten the duration of these crops.
Decision Support System for Agrotechnology Transfer (DSSAT) is a software tool that integrates 16 crop models for various purposes, facilitating the evaluation and application of these models throughout the season.	Rainfall-dependent crop production is risky, with water stress affecting millet crops more than fertilizer treatments. DSSAT simulations show that crop yields increased under fertilizer use, even during dry spells. Farmers' practices remain unaffected by water stress due to nutrient limitations.
The CERES-Millet model of DSSAT was evaluated using data from a previous experiment.	Water use and yield of millet under the zai pit system; understanding the processes using simulation.
Meta-analysis on barnyard millet	Study highlights the nutritional value, stress tolerance, and antibacterial capabilities of Echinochloa spp.Restrictions on production, breeding goals, germplasm collections, and the initiatives needed to promote adoption globally are also discussed.
This 2016 farm household survey conducted by the National Academy of Agricultural Research Management and the University of Agricultural Sciences, Bangalore, collected data on finger millet.	Study highlights the challenges in promoting finger millet cultivation, emphasizing the need for economic feasibility, productivity improvement, and labor and fertilizer reduction to make it a viable choice for South Indian farmers.

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S.No.	Reference	Segment	Article type	Study area
17.	Sultan et al. 2013	Climate resilience	Research article	West Africa
18.	Aggarwal et al., 2022	Abiotic stress	Review	India
19.	Still et al. 2003	Abiotic stress (temperature)	Research article	No particular region
20.	Dayakar Rao et al. 2021	Climate resilience	Policy paper	India
21.	Dwivedi. 2022	Climate risk and adaptation of minor millets.	GIZ -report	India
22.	Directorate of Sorghum Research, 2014	Sustainable Development Goals (climate change)	Report	India
23.	Traore et al. 2017	Climate resilience (food security)	Research	West Africa
24.	Wang et al. 2018	Climate resilience (crop yield)	Review	China, India, Indonesia, Bangladesh, Vietnam
25.	McAlvay et al. 2022	Climate resilience	Review	Ethiopia, Eritrea, Georgia

Method and type of millet	Highlights/results
This study uses climate data from 35 meteorological stations in 9 West African countries, compiled by the AGRHYMET Regional Centre and National Meteorological Agencies, specifically on sorghum.	Climate change significantly impacts West African millet and sorghum yields, with higher temperatures and rainfall fluctuations causing yield losses and evapotranspiration, affecting crop-cycle shortening.
Qualitative analysis on foxtail millet	This review lists the current research trends on understanding climate resilience and other crucial traits in foxtail millet. It discusses the knowledge gap, and how the information could be applied.
The authors use remote sensing products, physiological modeling, global crop fraction distribution, and national harvest area data relating to major millet crops.	The primary role of temperature in determining C_3/C_4 distribution.
Meta-analysis on millets overall	The authors present detailed information on harvesting, health benefits, cost analysis, climate resilience, etc.
Qualitative analysis on millets overall	Mainstreaming climate adaptation in minor millets value chain.
Qualitative analysis on millets overall	Report discusses the shelf life, health benefits, identification of cultivars/genotypes for specific end products of millets and the economics of millet farmers.
Authors analyze three years of experimental data on maize and millet from a region in southern Mali.	Study discusses future climate changes and their impact on cereal crop production. Temperatures in southern Mali's are likely to rise under the worst and low emission scenarios, negatively impacting crop production and food self-sufficiency. However, large and medium-sized farms can sustain food production despite climate change.
Mean data analysis on rice, millets, maize, wheat	Climate change likely to reduce the production of cereal crops except millets.
The authors use ethnohistorical, agronomic, and ecological literature on maslins to study climate change adaptation focused on wheat, barley, millets, oats, wheat, rice.	Varietal mixtures and multispecies polycultures are promising options for climate-resilient cropping systems.

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S.No.	Reference	Segment	Article type	Study area
26.	Tadele 2016	Abiotic stress (drought adaptation)	Book chapter	India and Africa
27.	Singh et al. 2021	Abiotic stress (nutrition)	Review	Study area not mentioned
28.	Satyavathi et al. 2021	Climate resilience	Review	Asia and Africa
29.	Huet et al. 2022	Abiotic stress (temperature)	Research	Southern Mali
30.	Davis et al. 2019	Climate resilience (water)	Research	India, Australia, USA
31.	Yang et al. 2022	Abiotic stress (drought)	Case study	China
32.	Ullah 2017	Climate resilience	Review	Pakistan
33.	Ananda et al. 2020	Climate resilience (drought adaptation)	Review	Africa
34.	Abreha et al. 2021	Biotic stress	Review	South Africa, China
35.	Shivhare and Lata 2017	Abiotic and biotic stress tolerance	Review	India
36.	Gupta et al. 2017	Abiotic and biotic tolerance	Review	India

Method and type of millet	Highlights/results
Intercropping method for cultivating traditional millets such as pearl, little, finger, foxtail and wild millets.	Millets are resilient to extreme climatic and soil conditions. They are climate-smart alternative crops that adapt quite well to challenging environments.
Quantitative data analysis on millets overall.	Small millets have climate-smart traits, and can tolerate harsh conditions. They are climate-compliant crops due to their unique genetic characteristics.
Statistical analysis on pearl millet	Pearl millet are next-generation crops, having the potential of nutritional richness and climate-resilience.
Risk/hazard assessment of crops, especially focused on maize, sorghum, millets.	Millets have low yield variability and low sensitivity to extreme weather hazards.
The authors conducted national optimizations to evaluate the potential benefits of diversifying cereal production by promoting coarse cereals such as finger and pearl millet sorghum.	Millet and sorghum crops are sustainable food systems. They are climate-smart and reduce the demand for irrigation water.
Mean data analysis (not any particular millet)	Millets are adaptable to extreme drought conditions.
Meta data analysis on pearl millet	Pearl millet is a water-saving, drought-tolerant and climate change- compliant crop ideal for environments prone to drought and heat stress.
Crop rescue method and statistical data analysis on sorghum crops.	Sorghum can withstand severe drought and can be grown in regions where other crops cannot be grown.
Quantitative analysis focused on sorghum	This review identifies potential sources of resistance for sorghum breeding.
Prediction/future outcomes analysis on pearl millet	Pearl millet is superior in protein content and quality, protein-energy ratio, metabolized energy levels compared to sorghum.
Future perspective study on finger millet	Finger millet is a solution to food insecurity and hidden hunger under stressful environments. This study suggests genetic manipulation as an effective method in millet improvement.

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S.No.	Reference	Segment	Article type	Study area
37.	Sharma et al. 2014	Climate resilience (drought resistance)	Research	India, UK, Niger
38.	Varshney et al. 2017	Climate resilience	Research	India, China
39.	Shrestha et al. 2023	Climate resilience (drought)	Review	Sub-Saharan Africa
40.	Sun et al. 2020	Climate resilience (stress and drought conditions)	Research	China
41.	Dudhate et al. 2018	Climate resilience (drought tolerance)	Research	Japan, China
42.	Hittalmani et al. 2017	Climate resilience (drought), nutraceutical properties	Research	India
43.	Yuan et al. 2022	Climate resilience (drought response) and transcriptome in broomcorn millet	Review	China

Method and type of millet	Highlights/results
Statistical analysis focused on pearl millet	Drought tolerance of pearl millet is related to reduced salt uptake and enhanced growth under salt stress.
The authors use resequencing data and focused on pearl millet	Pearl millet adapts well to arid, hot, semi-arid regions.
Transcriptomics data reveals pearl millet's drought resistance mechanisms.	Pearl millet's unique combination of genetic and physiological mechanisms enable it to be drought- tolerant.
The authors analyze Pacbio sequencing data for analyzing Illumina data on pearl millet under heat and drought stress.	Pacbio sequence data of differentially expressed genes of pearl millet have been identified for drought and stress conditions.
Focused on pearl millet, the authors conducted experiments in controlled greenhouse conditions, testing around 20 seeds under drought stress for growth tests and RNA-Seq, comparing them to control plants.	The underlying molecular mechanisms of drought tolerance lay the foundation for pearl millet's genetic improvement.
The authors created a drought-tolerant and blast disease-resistant finger millet variety ML-365 through recombination breeding by crossing IE1012 and Indaf-5 in the laboratory.	Finger millet genome analysis reveals that more drought tolerance related genes are present that can be used for treating drought-tolerant varieties.
Study analyzes 300 broomcorn millet varieties in 21 Chinese locations for drought response mechanisms.	Broomcorn millet is a drought-tolerant crop preferred for water-saving agriculture because of its short life cycle and high water-use efficiency.

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Claim 5: Millets need fewer synthetic pesticides as they have few economic pests, have in built genetic resistance to pests and the option of traditional nature-positive pest management approaches

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Summary

Research on sorghum, pearl millet, finger millet and other millets has shown that they have fewer pests that limit yield compared to other staple crops. The resistance sources available in millets are vast and offer environmentally safe management of pests with minimal use of pesticides. Multiple traditional technologies serve as viable options for pest and disease management without the need to apply synthetic pesticides.

Scientific evidence

Claim 5A: Millet cultivation minimizes the use of synthetic pesticides through in-built genetic resistance and traditional pest control knowledge

Savary et al. (2019) conducted a study on the global burden of pathogens and pests on five major food crops — wheat, rice, maize, potato and soybean—which contribute 18.3%, 18.9%, 5.4%, 2.2% and 3.3%, respectively, of the global human calorie intake (2013 estimates) (FAO 2018). The study identified 137 such individual pathogens and pests on these five crops. More than 100 insect species that attack rice, of which 20 species cause economic damage, are listed in the Rice Knowledge Bank (IRRI, n.d.).

Worldwide, at least 150 insect species have been recorded as feeding on millets (Nwanze and Harris 1992). Of these, 116 species have been recorded in India (Kishore 1996; Gahukar and Reddy 2019; Sajwan et al. 2022) on sorghum, pearl millet, finger millet, teff, foxtail millet, kodo millet, proso millet, little millet, barnyard millet, fonio millet and browntop millet.

In a global review of the key insect pests of sorghum, Okosun et al. (2021) highlighted their biology, ecology, management and crop losses caused by them. The insect pests that cause major economic losses are sugarcane aphids, greenbug, sorghum midge, stink bugs, lesser grain borer and the Indian meal moth (stored grain pests). Sorted by region or country, the maize stem borer was found to be a key pest in Africa, sorghum warhead bug in Asia, white grubs in the USA, Africa and Asia, and shoot fly and sorghum borer in Africa and Asia.

Thakur et al. (2007) documented screening techniques for sorghum diseases. Over 50 diseases were reported, of which only a few are economically important globally, while several others are regionally and locally important in specific agroecosystems. The important diseases of sorghum identified were grain mold, anthracnose, leaf blight, downy mildew, charcoal rot, rust, ergot, and smuts and virus diseases like maize stripe and maize mosaic in semi-arid tropical environments.

In a review of economically important pests of eight millets including pearl millet, Gahukar and Reddy (2019) reported more than 100 insect pests in pearl millet-based cropping systems. However, the following were found to be of economic importance: shoot fly (*Atherigona approximata*), stem borer (*Chilo partelus*), white grubs (*Holotrichia consanguinea*) in India; Coniesta ignefusalis in western Africa and earhead worms (*Helicoverpa armigera*), gray weevil (*Myllocerus species*) and leaf roller (*Marasmia trapezalis*). Ten major insect pests of pearl millet are important globally, of which 6 are found in the Sahel, 2 in India, and 1 each in the USA and Pakistan.

Genetic gains in pearl millet in India and breeding strategies for diseases were the subject of a review by Yadav et al. (2020) who demonstrated that the major diseases considered for resistance breeding in pearl millet are downy mildew [*Sclerospora graminicola* (Sacc.) J. Schröt], blast or leaf spot (*Pyricularia grisea* Sacc.), rust [*Puccinia substriata* var. *indica* Ramachar & Cummins], smut [*Moesziomyces penicillariae* (Bref.) Vanky] and ergot (*Claviceps fusiformis* Lov.).

A review by Sajwan et al. (2022) reported the following insect pests to be associated with finger millet in India: White grubs (*Holotrichia consanguinea, Anomala dimidiata*), grasshoppers (*Kraussaria angulifera, Oedaleus senegalensis, Hieroglyphus sp*. and *Cataloipus* sp.), blister beetle (*Psalydolytta fusva*), flea beetle (*Chaetocnema basalis*), millet stem borer (*Acigona ignefusalis*), pink stem borer (*Sesamia inferens*), stink bug (*Bagrada cruciferarum*), green stink bug (*Nezara viridula*), shield bug (*Agonoscelis pubescens*) and root aphid (*Tetraneura nigriabdominalis*). Though the symptoms of damage by the pink borer, finger millet stem borer and finger millet root aphid are known and may cause losses in certain regions, the yield/economic losses due to them and other associated pests have not been reported.

Finger millet is affected by diseases such as blast, foot rot, smut, streak, and mottling virus; however, blast caused by *Magnaporthe grisea* has been reported as a serious disease of the crop in Africa (Mbinda et al. 2021) and Asia (Das et al. 2021; Kumari et. al. 2022).

In a study on farmers' knowledge and perception of finger millet blast disease, Mbinda et al. (2021) surveyed its occurrence and interviewed farmers in Bungoma and Kisii counties of Kenya. Blast disease was prevalent in all the surveyed areas and adversely affected productivity, leading to poor yields. Disease occurrence varied from 92% to 98%, and was significantly higher in the major finger millet growing areas compared to the areas where it is not widely grown.

In a multilocation evaluation of blast disease in India, Das et. al. (2021) documented the disease caused by the fungus *Pyricularia grisea* (Cooke.) Sacc. [teleomorph: *Magnaporthe grisea* (Hebert) Barr] as the most important production constraint in finger millet. The disease occurred every year during the rainy season and the extent of damage depended on the severity and the time of onset of disease. The pathogen infected all stages of the crop and caused leaf blast, neck blast and finger blast. Finger millet blast has also been reported as a serious disease in several other Asian countries, including Sri Lanka (Kumari et al. 2022).

A field trial was carried out in Nandyal, India (Kamakshi et al. 2021) with foxtail, barnyard, proso, little, kodo and finger millets. Seasonal incidence of thrips was recorded in all the six millets. Shoot fly incidence was restricted to proso millet and little millet, which were, however, free from *H. armigera*, which was recorded in the other four millets. Foxtail millet was listed as a host to shoot fly in a review by Gahukar and Reddy (2019). Blast disease (caused by *Pyricularia setariae* Nishikado) has been cited as a major constraint to foxtail millet production by Rajesha et al. (2021).

There is very limited information and research on pests and diseases of proso millet as per a review by Gahukar and Reddy (2019). Insect pests have not been reported in proso millet while bacterial stripe, kernel smut and head smut have been reported occasionally (Marsalis et al. 2012). Little millet is susceptible to grain smut caused by *Macalpinomyces sharmae* (Ashwini Kumar et al. 2017).

A field experiment by Rawat et al. (2019) showed field damage due to stem borer and shoot fly varied in barnyard millet.

Sangappa et al. (2018) reported shoot fly, head smut and rust as pests and diseases of kodo millet.

A study in Ethiopia identified *Atherigona lineata, Delia flavibasis* and *Oscinella nartshukiana* Beschovski species of shoot fly as infecting teff (Chekole and Damte 2018).

A recent review by Degete (2021) recorded 27 pathogens associated with teff. Five diseases were considered important: teff leaf rust (*Uromyces eragrostidis* Tracy), head smudge (*Helminthosporium miyakei* Nishikado), zonate eye spot (*Helminthosporium giganteum*), teff smut (species not identified) and damping off (*Drechslera miyakei*).

In a comprehensive study conducted in Kenya, Koima et al. (2023) evaluated sorghum genotypes' reaction to *Colletotrichum sublineola*, which is responsible for anthracnose in sorghum plants, and found varying degrees of susceptibility under greenhouse and field conditions. The severity of anthracnose symptoms differed among genotypes, with some exhibiting resistance. Grain yield, 100-seed weight and harvest index also varied significantly. Regression analysis indicated that anthracnose did not significantly impact grain weight, yield or 100-seed weight.

A study by Xu et al. (2020) in China evaluated resistance to anthracnose in 167 sorghum accessions from various sources. Anthracnose infection responses were evaluated 40 days after inoculation of the pathogenic isolate of *C. sublineolum* (SY-1); disease severity was assessed based on the percentage of infected leaf area using a 1-9 rating scale that included five reaction classes: Highly resistant (HR), resistant (R), moderately resistant (MR), susceptible (S), and highly susceptible (HS). A significant proportion of accessions (68.26%) had a resistant response (HR, R, and MR), whereas 31.74% were susceptible (S and HS). Chinese accessions 19 HR, 37 R and 49 MR exhibited 64.03% resistance. These resistant accessions hold promise for future breeding and cultivation efforts aimed at enhancing disease resistance.

A study by Core (2006) to screen for new sources of anthracnose resistance in approximately 43,000 sorghum accessions was successful in identifying and characterizing resistant accessions.

Chandrashekar and Satyanarayana (2006) reviewed information on the mechanisms of resistance to insect pests and fungal pathogens in sorghum and millets. Sorghum cultivars resistant to fungal attack contained both a greater variety and higher amounts of free phenolic acids, especially in the case of tannin-containing sorghums. The presence of a pigmented testa as well as seed phenols and glume color caused by phenolic pigments also contributes to grain mold resistance.

In a review by Sivakumar et al. (2006), ammonium sulfate fractions derived from extracts of various millet grains, including sorghum, were tested for their inhibitory effects against alpha-amylases from different insect pests (rice weevil, red flour beetle, pulse beetle, rice moth, tobacco caterpillar, gram pod borer, castor semilooper and diamond back moth). The extent of inhibition varied among the different insect pests, with sorghum's effect ranging from 8.0% to 69.9%. The potential of sorghum's proteinase inhibitors can influence the activity of alpha-amylases in various insect pests, contributing to pest control strategies.

A study by Puri et al. (2023) investigated greenbug feeding-induced resistance to two aphid species, sugarcane aphid (SCA) Melanaphis sacchari and greenbug (GB) Schizaphis graminum in sorghum using genotype RTx430 as a focal point. Aphid colonies were reared on the susceptible BCK60 sorghum genotype under consistent environmental conditions. The study found that SCA exhibited higher reproductive success compared to GB on sorghum plants following aphid counts. Sequential herbivory experiments revealed that pre-infestation of sorghum plants by GB led to enhanced resistance against subsequent SCA colonization, resulting in fewer SCA on these plants. However, pre-infestation with SCA did not have a significant impact on subsequent GB colonization. Gene expression analyses found that GB-infested sorghum plants exhibited elevated expression levels of pathogenesis- related (PR) genes and jasmonic acid (JA)-related defense genes, indicating a strong activation of SA and JA pathways. Furthermore, genes related to the flavonoid biosynthesis pathway were upregulated in response to GB infestation. In contrast, SCA-infested plants showed lower induction of these defense-related genes. The findings suggest that sorghum plants mount a more robust defense response against GB compared to SCA, potentially influencing their respective reproductive success.

A screening for shoot fly resistance with interlard fish-meal technique in 100 mutant sorghum lines along with two checks — IS-2312 (resistant) and DJ6514 (susceptible) — conducted in India (Navinkumar et al. 2020) revealed that the mutants IS 925-21, IS 925 -124, IS 925-125, PV-21 and PV-51 showed resistant reactions in respect to oviposition, dead heart, glossiness and seedling vigor, suggesting that these lines were tolerant to shoot fly infestation.

Sources of resistance to downy mildew Singh (1990) evaluated sources of resistance to downy mildew (DM) and rust in 3,163 germplasm accessions of pearl millet collected globally from

Table 5A. Summary of research outcomes and insights from key studies on the claim that millets need fewer synthetic pesticides as they have few economic pests.

Sl. No.	Reference	Segment	Article type	Study area	Method and type of millet
1.	Savary et al. 2019	Pest control	Meta-analysis	Various locations	Various millets
2.	Nwanze and Harris 1992	Pest control	Field research	Global	Millets (focus on India)
3.	Okosun et al. 2021	Pest control	Field research	Global	Sorghum
4.	Thakur et al. 2007	Pest control	Lab research	Global	Sorghum
5.	Gahukar and Reddy 2019	Pest control	Field research	India and USA	Millets (focus on India)
6.	Yadav et al. 2020	Pest control	Field research	India and Australia	Pearl millet
7.	Sajwan et al. 2022	Pest control	Field research	India	Millets
8.	Mbinda et al. 2021	Pest control	Field research	Kenya	Finger millet
9.	Das et al. 2021	Pest control	Field research	India	Finger millet
10.	Kumari et al. 2022	Pest control	Field research	Sri Lanka	Finger millet
11.	Kamakshi et al. 2021	Pest control	Field research	India	Various millets
12.	Rawat et al. 2019	Pest control	Field research	India	Barnyard millet
13.	Sangappa et al. 2018	Pest control	Field research	India	Kodo millet
14.	Chekole and Damte 2018	Pesticide use	Field research	Ethiopia	Teff

Insights/results
Identified 137 individual pathogens and pests affecting millets, contributing to pest control efforts.
Reported 116 insect species associated with millets in India, contributing to pest control strategies.
Identified 9 key insect pests of sorghum globally, informing pest control practices.
Described important diseases of sorghum, contributing to disease control strategies.
Provided insights into economically important pests of various millets.
Highlighted major diseases considered for resistant breeding in pearl millet, contributing to disease control.
Detailed various insect pests associated with millets.
Investigated blast disease occurrence in finger millet in Kenya.
Researched blast disease in finger millet in India, contributing to pest control knowledge.
Studied finger millet blast in Sri Lanka, contributing to pest control efforts.
Recorded the incidence of insect pests in millets.
Assessed field damage due to stem borer and shoot fly in barnyard millet.
Detailed pests and diseases of kodo millet, contributing to pest control knowledge.
Identified species of shoot fly affecting teff, contributing to pest control efforts.

(Continued)

Sl. No.	Reference	Segment	Article type	Study area	Method and type of millet
15.	Koima et al. 2023	Pest resistance	Field research	Kenya	Pathogenicity, characterization, and resistance of Colletotrichum sublineola in sorghum
16.	Xu et al. 2020	Pest resistance	Field research	China	Evaluated resistance to anthracnose in sorghum accessions
17.	Core 2006	Pest resistance	Field research	USA	Evaluated sorghum germplasm for anthracnose resistance
18.	Chandrashekar and Satyanarayana 2006	Pest resistance	Review	India	Resistance mechanisms in sorghum and millets
19.	Sivakumar et al. 2006	Pest resistance	Lab research	Not specified	Test millet grain extracts against insect pests
20.	Puri et al. 2023	Pest resistance	Lab research	USA	Investigated greenbug feeding-induced resistance to sugarcane aphids in sorghum
21.	Navinkumar et al. 2020	Pest resistance	Field research	India	Screened sorghum mutant lines for shoot fly resistance
22.	Singh 1990	Pest resistance	Field research	Not specified	Screened for downy mildew and rust resistance in pearl millet
23.	Yadav et al. 2020	Pest resistance	Review	India	Genetic gains in pearl millet
24.	Singh et al. 1997	Pest resistance	Field research	Not specified	Identified disease-resistant pearl millet cultivars
25.	Goud et al. 2016	Pest resistance	Lab research	India	Evaluation of designated hybrid seed parents of pearl millet for blast resistance

Insights/results
Identified seven Colletotrichum isolates causing anthracnose in sorghum and evaluated their pathogenicity. Found variations in colony color and conidia production.
Identified sorghum accessions resistant and susceptible to anthracnose. Some accessions exhibited resistance.
Identified and characterized anthracnose-resistant accessions.
Overview of resistance mechanisms in sorghum and millets.
Sorghum exhibited inhibitory effects against alpha-amylases of various insect pests. Sorghum's effect ranged from 8.0% to 69.9% against different pests.
Greenbug-infested sorghum plants exhibited elevated expression levels of pathogenesis-related genes and jasmonic acid-related defense genes.
Mutant sorghum lines IS 925-21, IS 925-124, IS 925-125, PV-21 and PV-51 showed resistance to shoot fly infestation.
Identified resistant pearl millet accessions.
Reviewed past breeding strategies and future approaches to accelerate genetic gains in pearl millet productivity.
Identified disease-resistant pearl millet cultivars.
Identified resistant pearl millet genotypes against blast disease.

(Continued)

Sl. No.	Reference	Segment	Article type	Study area	Method and type of millet
26.	Sharma et al. 2021	Pest resistance	Review	India	Harnessing wild relatives of pearl millet for germplasm enhancement
27.	Akhtar et al. 2012	Resistance to greenbug	Research	Charsadda and Khyber Pakhtunkhwa, Pakistan	Resistance assessment with susceptible Pearl millet cultivar to greenbug
28.	Babu et al. 2012	Disease resistance	Research	Hyderabad, India	Field screening, artificial inoculation, evaluation of Finger Millet
29.	Dida et al. 2021	Disease resistence	Research	Kenya	Controlled infections, genotypic data (DArT sequencing in finger millet
30.	Mbinda and Masaki 2021	Breeding strategies and challenges	Literature review	Japan	Breeding strategies, molecular tools, advanced varieties in finger millet
31.	Ramakrishnan et al. 2016	Disease resistence	Research	Tamil Nadu, India	Association mapping (Finger millet QTLs for leaf blast resistance), in silico comparative genomics
32.	Manyasa et al. 2019	Genetic diversity	Research	Kenya, Malawi, South Africa	Evaluation of resistance to blast disease
33.	Kumar et al. 2017	Disease resistence	Research	Jabalpur, India	Evaluation of little millet cultivars for grain smut resistence
34.	Harshal et al. 2021	Disease resistence	Research	Gujarat, India	Development of little millet variety GV-4

Insights/results
Discussed the importance of using wild Pennisetum species in pearl millet breeding and pre-breeding efforts.
Identified resistant, moderately resistant, and susceptible entries. C-591 was identified as completely resistant with potential for breeding programs.
Identified resistant entries originating from various countries. Correlation between neck and finger blast.
Significant heritability, wild accessions showed greater resistance. Identified markers for trait introgression.
Identified promising strategies and challenges in breeding for blast resistance in finger millet. Introduction of advanced varieties.
GWAS on finger millet identified multiple QTLs associated with leaf blast resistance, revealing genomic regions crucial for understanding and breeding for resistance in this crop.
Resistance levels of various accessions. Correlation between disease severity and traits.
Identified resistant and moderately resistant cultivars.
Identified improved little millet variety with resistance and other desirable traits.

(Continued)

Sl. No.	Reference	Segment	Article type	Study area	Method and type of millet
35.	Rawat et al. 2019	Screening of the germplasm	Research	Uttarakhand, India	Evaluation of barnyard millet entries for pest damage
36.	Kim et al. 2008	Antifeedant properties	Research	Japan	Study of chemicals in barnyard millet against insects
37.	Danladi et al. 2003	Genetic improvement	Research	Abuja, Nigeria	Use of molecular markers for fonio germplasm analysis
38.	Woldeyohannes et al. 2022	Disease resistence	Literature review	Ethiopia, Italy	Efforts in teff breeding for pest and disease resistance
39.	Rathore et al. 2021	Traditional pest management practices	Research	Uttarakhand, India	Documentation of 32 indigenous pest management practices

Insights/results
Identified cultivars resistant to shoot fly and stem borer.
Identified compounds with antifeeding activity against brown planthopper.
Used DNA markers for germplasm characterization and breeding.
Use of mutagenesis, molecular markers, and genome editing for teff improvement.
27 of the practices were found to be rational by a panel of 30 scientists.

regions where the crop is grown. Accessions originating from West Africa exhibited the highest frequency of DM-resistant sources, while those from East Africa demonstrated greater resistance to rust. With the diverse collection, 48 selections from 37 early- to medium-maturing accessions, with bloom durations ranging from 45 to 60 days, displayed exceptional combined resistance to both DM and rust across three separate experiments. Five selections (IP1481-L-2 from India, P2895-3 from Niger, IP6240-2 from Cameroon, IP8877-3 from Burkina Faso and 700481-5-3 from Nigeria) consistently exhibited minimal disease severity, with no more than 5% incidence of DM and rust in all tests. Six selections (D322/1/-2-2 from Niger, P1449-3 from Senegal, IP6147-4 from Cameroon, P8695-1 and P8899-3 from Sudan and P3281 from Togo) displayed remarkable resistance, maintaining an average DM severity of 5% or less across various locations over the course of 2-3 years of multilocation testing in India and West Africa. Notably, four late-maturing accessions with bloom durations exceeding 60 days (P310, P472 from Mali, P1564 from Senegal and 700516 from Nigeria) showcased complete resistance to DM and exhibited favorable agronomic performance across diverse regions, including Zambia, Zimbabwe, Malawi and Tanzania.

Yadav et al. (2021) analyzed past breeding strategies and future approaches to accelerate genetic gains in pearl millet productivity to meet future demand and also examined the development and application of high-throughput genomic tools.

Singh et al. (1997) identified and developed pearl millet cultivars resistant to downy mildew (caused by *Sclerospora graminicola*) and rust (caused by *Puccinia* spp.) through screening, breeding and evaluation techniques. These involved 4,771 accessions, 50 accessions of intermediate weedy forms and 534 accessions of wild relatives from 40 countries. The identified sources of resistance were used to develop more than 20 breeding products (new pearl millet cultivars) through controlled breeding efforts.

Goud et al. (2016) screened 160 designated B-lines of pearl millet along with a resistant restorer parent and a susceptible seed parent for resistance to five pathotype-isolates of *Magnaporthe grisea*, the causal agent of blast disease, under controlled greenhouse conditions. Significant variations were observed in blast severity among the pathotypes and the pearl millet genotypes (B-lines), indicating differing levels of virulence among the pathotypes and varying degrees of resistance among the host lines. Several B-lines displayed resistance to multiple pathotypes, with some showing resistance to all five pathotypes tested. This diversity in resistance sources among the B-lines suggests potential opportunities to develop blast-resistant pearl millet hybrids and hybrid parent lines and the importance of using them in breeding programs for more effective disease management.

Sharma et al. (2021) reviewed the use of wild *Pennisetum* species for the improvement of cultivated pearl millet. These wild relatives are a diverse and valuable source of genetic variation essential for enhancing breeding and the development of pearl millet cultivars and are a rich repository of novel alleles and genes associated with traits essential for addressing biotic and abiotic stresses, forage yield and quality. By introgression genes from wild relatives, pearl millet breeders can enhance the adaptability and resilience of cultivated varieties, thereby contributing to sustainable, and climate-resilient agriculture.

Pre-breeding also facilitates the incorporation of exotic germplasm to improve adaptability. The availability of genomic tools and markers empowers precise trait mapping and introgression. Furthermore, pre-breeding efforts extend to introducing apomixis, a form of asexual seed reproduction to maintain hybrid vigor without yearly hybrid seed production. Overall, pre-breeding in pearl millet has been instrumental in enhancing genetic variation, leveraging wild germplasm and harnessing genomic tools for resilient and productive varieties.

Akhtar et al. (2012) studied resistance to greenbugs (collected from Charsadda, Khyber Pakhtunkhwa) in 135 pearl millet entries from Islamabad, Pakistan. A damage rating (DR) scale was employed to classify plant resistance levels. Among the tested entries, 21 were classified as resistant (DR 0-3), 69 as moderately resistant (DR 4-6) and 45 as susceptible (DR 7-9). Only C-591 was identified as completely resistant. The study highlights the potential for incorporating resistant or moderately resistant entries into breeding programs to enhance crop yield and minimize aphid- related damage.

A study to identify blast resistance in 622 accessions of finger millet in India (Babu et al. 2012) showed that 402 accessions displayed resistance to neck blast, 436 to finger blast and 372 exhibited resistance to both diseases. These resilient accessions were from a range of sources originating from 19 countries, underlining their broad geographical diversity among the resistant varieties. While most of the Asian-origin accessions succumbed to neck and finger blast susceptibility, those of African origin demonstrated resistance. A noteworthy finding was the robust positive correlation ($r = 0.85$, $P<0.0001$) between neck and finger blast ratings. The outcome highlighted the potential of using accessions with consistent resistance in future breeding programs.

Das et al. (2021) evaluated finger and neck blast resistance in 115 finger millet genotypes, comprising 108 germplasm of African and Asian origin, alongside a selection of improved cultivars across three locations representing areas where it is cultivated in India. A combination of natural field conditions and deliberate artificial inoculation was used to assess the genotypes' response to the diseases. Of the 115 genotypes, a subset of 29 exhibited notable resistance to either finger or neck blast, while a smaller subset of 6 genotypes displayed commendable combined resistance to both diseases. A subsequent stability analysis of the 29 genotypes revealed that 5 of them (IE Nos. 2883, 2871, 6240, 2710 and GE3767) demonstrated consistent resistance to both finger and neck blast while also exhibiting desirable agronomic traits such as moderate plant height (100-110 cm), medium maturity (106-115 days), and a semi-compact earhead shape characterized by the inward curvature of the tip of the finger-like structures. This result underscores the success of identifying genotypes with resistance to these blast diseases while also maintaining favorable agronomic attributes.

A study by Dida et al. (2021) assessed the reactions of both cultivated and wild relatives of finger millet to a specific strain of blast disease originating from western Kenya. Initial germplasm collections underwent a meticulous purification process involving two consecutive generations of single seed descent. The refined germplasm samples were then subjected to screening alongside improved varieties and selections preferred by farmers, known as farmer-preferred varieties (FPVs). The screening process was carried out in a controlled environment, specifically a screen house, over the course of three distinct seasons. The selection of FPVs was guided by participatory varietal selection, which incorporated the insights and preferences of local farmers. In order to induce controlled infections, the plants underwent hand-sprayed inoculation twice during each growth cycle. Subsequently, data on disease incidence was recorded during grain-filling stage. Genotypic information was obtained through the use of Diversity Arrays Technology (DArT) sequencing. Data was analyzed using Genstat 18.2 and TASSEL 5.2.58. The study revealed a substantial heritability of 81%, underscoring the predominantly genetic nature of the observed variation. Notably, wild accessions demonstrated greater resistance to the disease compared to their cultivated counterparts. The preliminary Genome-Wide Association Study (GWAS) yielded significant outcomes. This effort identified 19 markers that exhibit associations with blast disease which hold promise as they are set to be developed into assays to ensure genotype quality control and facilitate the incorporation of desirable traits through trait introgression. Wild accessions and traditional landraces of finger millet are valuable reservoirs harboring novel genes with potential for integration into ongoing crop improvement initiatives.

In a study conducted in Japan, Mbinda and Masaki (2021) provided a comprehensive understanding of promising concepts for finger millet breeding, and empirical examples of the use of advanced molecular tools and challenges associated with breeding for blast resistance. In regions primarily characterized by subsistence farming in developing countries, the breeding of blast-resistant finger millet varieties stands out as a pragmatic, cost-effective and dependable approach. The emergence of advanced finger millet varieties (IE4795, IE1055, IE2821, IE2872, IE4121, IE4491, IE4570, IE5066, IE5091 and IE5537) with broad-spectrum resistance to the blast pathogen alongside desirable agronomic attributes such as early flowering, medium stalk length and elevated yields, all achieved through conventional breeding techniques predominantly in eastern Africa and Asia, demonstrates how breeding efforts can elevate overall crop productivity and resilience. Contemporary finger millet breeding strategies are characterized by the convergence of multiple key objectives such as enhancing grain yield, bolstering resistance against an array of biotic and abiotic stressors, and amplifying the nutritional profile of the crop. The multifaceted approach to breeding not only addresses the immediate challenges posed by different stress factors but also aims to create a holistic solution that encompasses the diverse requirements of modern agricultural systems and consumer needs.

Ramakrishnan et al. (2016) conducted an extensive leaf blast assay on 128 finger millet genotypes to assess their susceptibility to leaf blast disease and its impact on agronomic traits. Despite variations, no genotype exhibited high resistance to leaf blast, with incidence ranging from 1.0% (IE4795) to 99.6% (HR374). Notably, six genotypes demonstrated low Percent Disease Incidence (PDI) (<5.0%), with IE4795 being resistant and four genotypes being moderately resistant. Eight key agronomic traits such as plant height, tiller number, and finger length were evaluated, showcasing significant variations. Phenotypic relationships between traits and leaf blast incidence were established, with factors like plant height and root length found to be significantly associated with PDI. Cumulative ranking classified genotypes into four groups based on resistance and agronomic performance. Association mapping identified Quantitative Trait Loci (QTLs) associated with traits through both General Linear Model (GLM) and Mixed Linear Model (MLM) methods. Overall, the study offers insights into finger millet genotypes' response to leaf blast and disease impact on agronomic characteristics, paving the way for better understanding and management of this important cereal crop.

A study by Manyasa et al. (2019) on exploiting genetic diversity for blast resistance assessed the resistance of 81 finger millet germplasm accessions to blast disease caused by *Magnaporthe grisea* using both natural and artificial inoculation trials in East Africa. The accessions were selected from a larger pool of germplasm based on their potential for high productivity and blast resistance. Disease pressure was found to be higher under artificial inoculation compared to non-inoculated plots. The severity of blast disease was recorded for three progressive stages: leaf, neck and panicle blast. Lesions caused by the disease were first observed on the leaves and later progressed to the neck and panicle, impacting grain formation and yield. Certain accessions showed resistance to all three stages of blast, while others were resistant to specific stages. Accessions G18, G43 and G67 were identified as resistant to all three stages of blast. Some accessions exhibited resistance only to leaf or neck blast.

The study also revealed correlations between disease severity and other traits. Disease severity had a significant negative correlation with grain yield, meaning that higher disease severity led to reduced grain yield. It was also negatively correlated with days to flowering, indicating that early flowering accessions were more vulnerable to disease damage. There was a positive correlation between leaf, neck and panicle blast severity, implying that these three blast types tend to progress together in susceptible plants.

Kumar et al. (2017) assessed the resistance of different little millet cultivars against grain smut through three sets of experiments. Firstly, twenty pre-released and released little millet cultivars (DhLtMV 36-3, TNPSU 174, BL 8, Kadiri 1, DLM 89,

TNPSU 167, BL 150, OLM 203, DLM 103, TNPSU 171, JK 8, TNPSU 170, BL 6, DhLtMV 10-2, TNAU 160, BL 41-3, KOPLM 53, GPUL 1, GPUL 2 and JK 36) with varying maturity periods were selected for the study. During the dough stage, the incidence of grain smut was recorded by counting both healthy and smutted plants in each row, and severity of grain smut was assessed by counting the number of infected grains per panicle. To gauge the susceptibility of each cultivar, a susceptibility index (SI) was calculated based on these observations. In the second stage of the experiment in the Donor Screening Nursery (DSN), 13 little millet cultivars (RLM 135, RLM 175, RLM 192, RLM 203, RLM 204, RLM 208, RLM 224, JK 8, OLM 203, TNAU 163, TNAU 176, TNAU 178 and RLM 4-1) were assessed. Grain smut incidence and severity were recorded during the dough stage. Subsequently, SI was calculated for these cultivars.

In the third phase, 100 landraces collected from 7 districts in Madhya Pradesh state of India were evaluated alongside susceptible check variety JK 8. Grain smut incidence was recorded by counting both healthy and smutted plants in each row at the dough stage. Furthermore, grain smut severity was assessed in 20 randomly selected panicles per variety. The results showed that DhLtMV 36-3, Kadiri 1, OLM 203, KOPLM 53, GPUL 1 and GPUL 2 exhibited high resistance to grain smut and were completely free from it while BL 8, TNPSU 171, TNPSU 170, BL 6, DhLtMV 10-2, TNAU 160 and BL 41-3 showed resistance. TNPSU 174 and JK 8 were found to be susceptible, and DLM 89 and JK 36 were highly susceptible. In the DSN, 13 little millet germplasm entries were screened for their reaction to grain smut. Among them, OLM 203, TNAU 163, TNAU 176 and TNAU 178 were highly resistant, with no grain smut incidence. RLM 208 exhibited resistance, while RLM 175, RLM 203, RLM 204 and RLM 224 were susceptible. In the case of landraces, 14 were highly resistant to grain smut, with no incidence observed; 28 were resistant, showing minimal susceptibility; and 42 were moderately resistant. Only 12 landraces were susceptible and 5 were highly susceptible.

Little millet genotype WV-126 was developed through a systematic breeding approach and released as high-yielding variety Gujarat Vari4 (GV-4) (Harshal et al. 2021). A single plant with desired traits, including medium maturity, high yield, resistance to blast (leaf, neck and panicle), and moderate resistance to grain smut and sheath blight, was selected from germplasm accessions and propagated into progeny rows. Over seven years of evaluation, WV-126 demonstrated superior performance and underwent pest and disease screening and grain quality analysis. A pedigree flow chart tracked its genetic lineage, leading to its release as GV-4, suitable for diverse agroecological regions. This resistance was observed consistently across multiple trials and locations, highlighting the genotype's ability to withstand these diseases effectively.

In an experimental screening of barnyard millet germplasm against shoot fly and stem borer damage, six entries (VL 249, DHBM 99-6, TNEF-204, DHBM 99-7, RBM-36A and DHBM-33) along with two checks (VL 172 and PRJ 1) were evaluated

(Rawat et al. 2019) at two locations in Tehri Garhwal, India (Plant Breeding Block at 2100-2200 m above mean sea level and Gaja Research Station at 1600-1700 m above mean sea level). The infestation level (deadheart percentage) caused by shoot fly and stem borer was recorded in each plot. The result revealed that shoot fly damage ranged from 5.28% to 19.33% and from 7.22% to 25.00% while that from stem borer ranged from 2.63% to 16.36% and from 4.07% to 22.96% at the Plant Breeding Block and Gaja Research Station, respectively. Notably, Gaja Research Station generally recorded higher pest damage. DHBM 99-6 displayed the lowest shoot fly damage (5.28%) and DHBM 33 had the highest damage (18.23%) at the Plant Breeding Block while DHBM 99-6 had the least stem borer damage (2.63%) and DHBM-33 had the highest (16.36%). At Gaja Research Station, DHBM 99-6 again showed the lowest shoot fly damage (7.22%), while DHBM 33 had the highest (23.33%) while DHBM 99-6 had the lowest damage (4.07%) and DHBM 33 had the highest (21.48%) from stem borer. Based on these results, DHBM 99-6 and TNEF-204 demonstrated resistance to both shoot fly and stem borer. Identifying and utilizing these resistant cultivars could be an effective strategy for managing pests in barnyard millet cultivation.

Kim et al. (2008) conducted a series of procedures to isolate and identify potential antifeedant properties of the Indian barnyard millet against the Brown planthopper. They conducted a series of procedures, beginning with the collection of millet stems and leaves, followed by methanol extraction. This extract was separated into neutral, basic and acidic components using column chromatography. The acidic fraction, after further separation, yielded eight compounds: l-malic acid, trans-aconitic acid, (+)-isocitric acid, 5-O-caffeoylquinic acid, 4-O-caffeoylquinic acid, isocarlinoside, 2-O-rhamnosylisoorientin, and 7-O-(2-O- glucuronosyl) glucuronosyltricin. Analytical techniques like GC-MS, SIMS, HPLC and NMR were employed to identify these compounds. Bioassays demonstrated that a combination of these compounds displayed significant antifeeding activity against the Brown planthopper, indicating synergy among the compounds. Notably, the presence of trans-aconitic acid in Indian barnyard millet, but not in rice plants, suggests its potential role in pest resistance. This study offers insights into the chemical basis of pest resistance in millet crops and the complexity of plant-insect interactions.

Addressing problems of inherent low yield, weed competition, shattering of grains, lodging, bird damage, insect pests and diseases require access to a diverse range of accessions with varying agronomic traits, the collection and conservation of local and exotic germplasm and their effective use in breeding programs after they have been properly analyzed (Danladi et al. 2003). DNA markers, such as Restriction Fragment Length Polymorphism (RFLP), Random Amplified Polymorphic DNA (RAPD), Amplified Fragment Length Polymorphism (AFLP) and Simple Sequence Repeats (SSR) are valuable tools to enhance the precision of gene pool analysis. Among these markers, RAPD markers have been extensively used in genetic mapping, molecular taxonomy and molecular diagnostics. Both RAPD and AFLP markers have proven effective for characterizing diverse rice germplasm. These markers have the potential to be equally effective for DNA fingerprinting and characterizing fonio millet accessions collected from diverse fonio millet-growing regions in Africa. The next step would involve initiating a research project to screen a variety of decamer primers for their ability to generate polymorphisms in the genomic DNA of fonio millet. Primers that successfully produce polymorphic bands on gels can then be selected for use in analyzing the entire fonio millet germplasm. This molecular approach can provide valuable insights into the genetic diversity and relationships among fonio millet accessions, ultimately aiding the development of improved varieties that are better adapted to local conditions and more resilient to the challenges faced by farmers, including pests and diseases.

Woldeyohannes et al. (2022) explored mutagenesis, molecular markers, QTL analysis, and potentially genome editing to improve teff's resistance to pests and diseases and enhance traits such as yield, drought tolerance, and lodging tolerance. The study noted some level of resistance to head smudge (*Helminthosporium miyakei*) and aphids (*Rhopalosiphum padi*), which are significant problems in teff farming. In contrast, teff rust (*Uromyces eragrostidis*) does not have complete resistance developed yet; however, it tends to occur after the heading stage and generally causes minimal grain yield losses compared to other challenges. Efforts are on to use mutagenic agents to generate novel genetic variation and enhance resistance traits as well as genome editing to harness the genetic diversity in teff germplasm collections to develop improved varieties that can thrive in different agroecological conditions and resist biotic stresses.

Claim 5B: Traditional knowledge on dealing with pests is available, obviating the need to use synthetic pesticides

Rathore et al. (2021) documented 32 indigenous pest management practices in hill agriculture in Uttarakhand state of India, where 76.73% of the net sown area is rainfed and average chemical fertilizer consumption is about 3.92 kg/ha. Among the practices assessed were setting fire and spreading properly decomposed farmyard manure in the field, using cow dung cakes, burning pine leaves, using translating over direct seeding in rice, and the use of common salt. A panel of 30 scientists judged their rationality on a five-point scale (very rational, rational, undecided, irrational and very irrational), with weightage of 5, 4, 3, 2, and 1, respectively. Of the 32 practices judged, 27 was found to be rational. The technology/practices that were assigned a weighted mean score above 3.0 were considered rational.

Priorities for future research

Millets' pest complexes vary with different ecosystems. Pests and diseases that limit yield need to be investigated thoroughly in millets.

Sorghum: Research priorities in sorghum include the need for detailed genetic analysis to identify specific resistance genes or markers associated with anthracnose resistance. There is also a need to investigate the impact of varying environmental conditions on the expression of this resistance, as well as the agronomic benefits in terms of yield, grain quality and other traits. The biochemical and molecular mechanisms underlying resistance to anthracnose and marker development for resistance are critical areas of study. Additionally, studying the dynamics of anthracnose development over multiple seasons can provide insights into the influence of environmental factors. Understanding the molecular mechanisms of resistance to sugarcane aphids and shoot fly, as well as their interactions with other aphid species should be explored. Transcriptomic and genomic analyses are also needed to identify key genes and pathways associated with these resistances.

Pearl millet: Research gaps in pearl millet include a deeper exploration of the genetic mechanisms underlying resistance to downy mildew and rust, considering the influence of environmental factors on resistance expression. Innovative breeding strategies like genomic selection should be employed to accelerate genetic gains and develop multifaceted cultivars. Investigating pathotype variations in blast disease, understanding host-pathogen interactions, and enhancing resistance in designated hybrid seed parents are important for disease management.

Finger millet: For finger millet blast resistance, research gaps involve understanding the genetic mechanisms underlying resistance to different blast stages and considering the influence of agronomic traits and geographical origin. Comprehensive screening methods that account for various blast types and interactions should be developed, and advanced genomics tools should be integrated into breeding efforts to identify genetic markers associated with resistance.

Little millet: Research gaps in this crop relate to assessing genetic diversity for enhanced grain smut resistance, investigating genetic mechanisms of resistance and developing molecular markers for breeding. Future research should focus on adaptation, performance in different agroecological zones and nutritional attributes.

Barnyard millet: Among the areas that need exploring are the genetic mechanisms of resistance, their agronomic traits and yield under different conditions and for antifeedants against Brown planthopper, exploring deterrence mechanisms and ecological implications.

Fonio millet: Further research is needed to understand and address the potential pest and disease issues and genetic marker research to explore marker effectiveness and genetic diversity among accessions.

Teff: There are research gaps in exploring mutagenesis techniques, integrating breeding techniques for overall improvement and assessing the genetic basis of resistance to pests and diseases.

Proso millet, Kodo millet, Browntop millet, Guinea millet and Job's tears: As there are no studies on pest resistance in these crops, this research gap needs to be addressed.

There is an urgent need to validate and inform scientific evidence of traditional pest management practices that have been successfully adopted by communities and are in harmony with nature-positive pest and disease management approaches.

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Claim 6: Millets have good potential to increase yields

Summary

Millets are predominantly grown in the semi-arid and tropical parts of the world. Dry semi-arid tropical areas typically have 2 to 4.5 humid months a year while arid areas have only 1 or 2 (Virmani et al. 1980). Millets are suitable crops for such areas as they are both thermophilic (thriving at relatively higher temperatures) and xerophilic (can reproduce with limited water input) crops (Saxena et al. 2018).

Scientific evidence

Claim 6A: Millets have the potential to give optimal/modest yields even in marginal lands and under adverse conditions of climate change

A study conducted on pearl millet (Singh 2017) at six locations in India and two in West Africa demonstrated that higher CO_2 concentration in the atmosphere could have a beneficial effect on crop growth. The detrimental effects of rising temperature—depending on the degree of temperature rise—may be nullified with crop transpiration reducing under elevated CO_2 conditions. Pearl millet could be the most climate change-resilient crop that can perform better under adverse conditions.

Finger millet is a nutritious and climate change-resilient crop; however, it is affected by drought stress which can decrease germination and growth during the early seedling stage, plant height, length, biomass, weight, and grain number. Drought stress contributes significantly to economic yield losses in finger millet.

However, Mude et al. (2020) assessed the morpho-physiological and biochemical changes that occur in finger millet under drought and found that the genotype RAU 8 was drought-tolerant in three phenological stages while the genotype GPU 67 was sensitive at seedling stage but its tolerance level improved in the vegetative and early flowering stages.

In a study in semi-arid central Senegal aimed at evaluating the agronomic performance of millet-cowpea intercropping and its variation with climate variability, Senghor et al. (2023) showed that millet intercropping with low-density cowpea improved millet productivity under conditions of low and medium nitrogen input. The effect of fertilization on millet above-ground biomass did not significantly interact with the cropping system (sole vs intercrop). However, for grain yield, fertilization did interact significantly with the cropping system in the irrigated trial: The benefits of intercropping on millet grain yield were greater with 69 kg/ha N than with 0 kg/ha N. These results show that the level of water stress and fertilization modulate the performance of millet-cowpea intercropping in the semi-arid context of Senegal. Overall, fertilization had a stronger effect on millet grain yield than intercropping. This suggests that these two strategies (intercropping and mineral fertilization) can possibly be used complementarily to achieve sustainable intensification of millet cropping systems.

Proper utilization of available natural resources can be achieved through better and suitable intercropping practices, which have multifaceted benefits such as greater resource use, reduction in the population of harmful organisms, higher resource conservation efficiency, soil health, and agricultural sustainability. Small millets are important and ecologically hardy crops of the drylands that can provide food and nutritional security. Based on their review of available literature, Sharmili et al. (2021) found that intercropping small millets with pulses is one of the best suitable options to harness ecologically sound agriculture.

Sorghum is a prospective crop in view of the challenges posed by climatic vulnerability and the need for food and nutritional security as it can withstand high salinity and low water supply, making it well-suited to marginal areas where both conditions are prevalent. DeFries et al. (2023) assessed the historical sensitivity of sorghum and wheat yields to temperature and compared their water requirements in districts where both cereals are cultivated. Crop water requirements for wheat were 1.4 times greater than for sorghum due to its longer growing season that extends into summer, but wheat had higher yields, resulting in an approximately 15% smaller water footprint (m^3 per ton) than sorghum. However, without changes in management, sensitivity to future climate projections suggests a 5% decline in wheat yields and a 12% increase in the wheat water footprint by 2040, compared with a 4% increase in the water footprint for sorghum.

In a study on the benefits of millet intercropping with black gram on broadbed and furrows (BBF), Paslawar et al. (2023) conducted an experiment involving intercropping of foxtail millet, finger millet, and barnyard millet with black gram as well as sole cropping of black gram and the three millets. The experimental field was slightly alkaline, with 0.52% organic carbon, low available nitrogen (220 kg/ha), very low available phosphorus (17.2 kg/ha) and high available potassium (337.6 kg/ha). While sole cropping of black gram recorded the maximum values of growth parameters, in the case of the minor millets, these parameters were greater in the intercropping treatment with black gram than sole cropping. The study identified black gram and finger millet as the best intercropping system followed by sole black gram (860 kg/ha). The takeaways from this experiment were that sole cropping in these poor soils yielded as much as 750 kg/ha in the case of foxtail millet and 798 kg/ha for finger millet and 835 kg/ha for barnyard millet, which shows the innate nature of their performance on marginal lands. The study also indicated that adaptation of simple methods not only increases yields but also improves soil health and structure.

Studies also indicate that careful screening and selection of proper entries for cultivation under conditions of stress would help achieve better millet yields in such situations. In a study on the effects of drought stress on pearl millet genotypes during the vegetative stage and their mechanisms for survivability under stress, Shukla and Panda (2023) experimented with 6 different nitrogen treatment regimes, and identified 5 entries from a pool of 15 with more tolerant and sensitive characteristics. They found that drought stress induces production of hydrogen peroxide, which in turn leads to accumulation of proline that increases stress tolerance under low nitrogen and polyethylene glycol treatments. Varietal behaviors are different under different treatments. However, this study again shows the innate tolerance and escape mechanisms that crops have under multiple stress regimes.

On the contrary, Wang et al. (2023) showed that foxtail millet grown under nitrogen deficiency exhibits lower grain folate content. They evaluated 29 diverse foxtail millet cultivars under two N regimes (0 and 150 kg/ha) for 2 years to explore the folate potential when grown under low N. Their structural equation models showed that nitrogen fertilization had a positive indirect effect on grain folate content through influencing plant nitrogen and potassium accumulation. Collectively, the results indicate that much more attention should be paid to N management when foxtail millet is cultivated in infertile soil to improve folate contents.

Claim 6B: Improved package of practices can increase millet yields

While millets do have potential for resilience under adverse conditions, good agronomic practices like providing irrigation at crucial stages are still necessary to avoid yield losses. Debieu et al. (2018) studied pearl millet response to early drought stress and identified the quantitative trait loci (QTL) controlling biomass production under drought conditions. In an experiment involving 188 inbred lines from West Africa that were phenotyped under early drought stress as well as well-irrigated conditions, the authors observed a variable response to both conditions with drought stress having a strong impact on yield components. Many plants did not produce panicles, indicating that drought stress in the early stages has an impact on grain yield in the later stages.

The importance of improved package of practices was reported by Goswami (2023) on the basis of a demonstration conducted by the Sehgal Foundation in participation with pearl millet farmers in Runera in Haryana state of India. Selection of the right fertilizer and proper use of fertilization was demonstrated on a half-acre plot alongside a half-acre plot using traditional farmers' practices. While the demonstration plot showed practices that included use of micronutrients such as zinc, sulfate, boron, ferrous sulfate, potassium and magnesium, the farmers followed the traditional cultivation practice of unabated use of urea and diammonium phosphate. The study showed that adoption of cultivation by farmers increased along with area under pearl millet even though the demonstration area was brought down year after year (Figure 6A).

In 2022, without any demonstration, millet cultivation was adopted by 36 farmers, which is about 20% of the entire farm area in Runera (Figure 6A). When considering the variance in yield, the half-acre demonstration plots achieved a peak production of 480 kg, 560 kg and 720 kg in 2019, 2020 and 2021, while the equivalent half-acre control plots yielded a maximum of 380 kg, 460 kg and 430 kg during the same years, respectively. This resulted in average yield increases of 23%, 25% and 31% in 2019, 2020 and 2021, respectively.

There is also evidence available to indicate that new improved practices (including unconventional practices like the use of superabsorbent polymer) could lead to yield enhancement opportunities just by adopting simple farm practices such as crop residue mulching (CRM). Bana et al. (2023) demonstrated the use of superabsorbent polymers (SAP) and crop residue recycling in pearl millet to enhance yield stability, water-use efficiency and soil microbial activity. Co-application of CRM and SAP was found to increase pearl millet grain and stover yield by up to 45% and 36%, respectively. However, pearl millet responded significantly only up to 2.5 kg/ha of SAP application (irrespective of CRM). Further, soil microbial biomass carbon improved significantly with CRM (20%) and SAP (10.9–12.1%) application individually and up to 30%

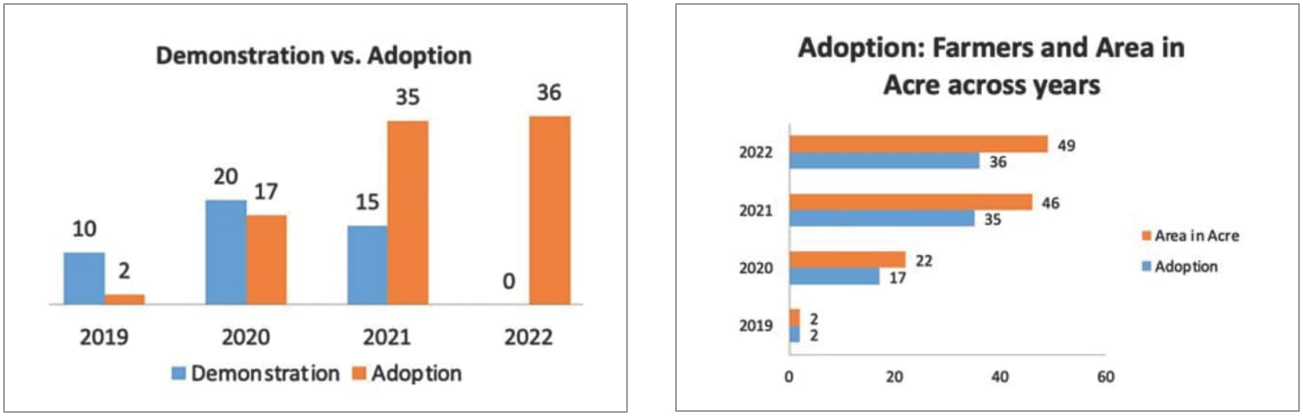

Figure 6A. Millet demonstrations influence the area of adoption and number of farmers.

with their simultaneous application. Several soil enzyme activities also improved significantly due to co-use of CRM and SAP. Positive effects of CRM and SAP individually and in co-application were witnessed on soil microbial populations (bacterial, fungal, actinobacteria) and water-use efficiency across environments.

Aune and Ousman (2011) experimented with seed priming and micro-dosing of fertilizer on yields of sorghum and pearl millet. Seed priming alone increased sorghum yield by 32.6% and millet yield by 29.8%. The combination of seed priming and micro-doses of fertilizer in on-farm trials increased yield by 69.5% in sorghum and 71% in pearl millet. In addition, these methods were assessed for economic feasibility using partial budgeting techniques and value/cost ratios. It was found that application of a micro-dose of 0.3 g/ pocket was most feasible for millet while in sorghum the rate of 0.9 g fertilizer/ pocket gave the best economic benefit. These results indicate that agronomic efficiency of mineral fertilizer can be improved in both crops by adopting simple seed priming methods, which are not economically intensive in nature.

On the other hand, Ruiz-Giralt et al. (2023) showed the potential of traditional cultivation practices of finger millet, pearl millet and sorghum as a response to the recent increase in aridity levels worldwide. The study indicated that these practices can play a pivotal role in crop resilience and sustainability of dryland agriculture. The methodology included collection of data on variables such as intensity of cultivation (casual, extensive and intensive), watering regimes (rainfed, reduce and irrigation) and duration of the growing cycle of each crop. The data collected was analyzed using redundancy analysis (RDA). The results indicated that there is some importance to the adaptation of methods by traditional small-scale farmers based on their surrounding environment.

Layek et al. (2023) performed an experiment in an organic production system in the northeastern Himalayan foothills of India for three consecutive years by evaluating high- yielding varieties of different millets (finger, foxtail, little, barnyard, proso, and browntop millet) along with local landraces of finger millet (Sikkim-1 and Sikkim-2; Nagaland-1 and Nagaland-2) to identify stable, high-yielding, and nutritionally superior genotypes suited for the region. Among the various millets, finger millet followed by little millet and foxtail millet proved their superiority in terms of productivity (ranging between 1.16 and 1.43 Mg/ha, mean metric ton) compared to the other millets. Root traits such as total root length, root volume, average diameter of roots and root surface area were significantly higher in the finger millet landraces Nagaland-1, Nagaland-2 and Sikkim-1 compared to the rest of the millet genotypes. The landraces of these millet crops can ensure food and nutritional security in fragile ecosystems; therefore research focusing on cultivating these entries is beneficial for identification of crop breeding.

Ahmad et al. (2016) also indicated that basic on-farm enhancement of a package of practices can give better yields than untreated protocols. They evaluated the effect of 1% sorghum water extract, 3% moringa leaf extract and compared them with untreated seeds. Two foliar applications, the first at one month after sowing and the second at 45 days after sowing, were carried out. In comparison to untreated seeds, which produced the lowest green forage yield (43 t/ha), the treatment of spraying moringa leaf and priming with sorghum water extract in combination produced the highest yield of 52 t/ha of green forage yield, while the individual treatments gave 49 t/ha and 48 t/ha for leaf extract spray and priming, respectively.

Ausiku et al. (2020) used wetting front detectors (WFDs) and Chameleon soil water sensors to adapt water and nitrogen applications with the goal of increasing pearl millet yields as well as nitrogen- and water-use efficiency. The results showed that treatments that received both high water and nitrogen outperformed other treatments by 11-68% in terms of biomass production and 16-54% in terms of grain yield. Combined adaptive water and nitrogen management reduced the nitrogen application rate by 38% without decreasing biomass and grain yield. Thus, without a meaningful yield penalty relative to high production input management, integrated adaptive water and nitrogen management is a more suitable path to increase yield than to use predetermined high irrigation and nitrogen rates.

Claim 6C: Millet yields can be increased with crop improvement measures resulting from use of genetic resources and genomic tools to achieve accelerated genetic gains

In an evaluation of genetic diversity in finger millet accessions for 13 agronomic traits, Singh, Sehrawat et al. (2023) attempted to identify entries that tolerate water scarcity and produce gainful crops. They found that days to 50% flowering and days to maturity had a positive correlation with each other but negative correlation with yield-contributing traits such as grain yield per plant, harvest index and thousand-grain weight (Figure 6B). Cluster analysis revealed genotypes with high grain yield per plant and early maturity that could form a good genetic base and make selection of parents for breeding programs easier. Furthermore, expansion of trait-specific heterotic gene pools, promising trait-specific superior genotypes of finger millet will assist as donors for crop improvement, nutritional security and crop diversification.

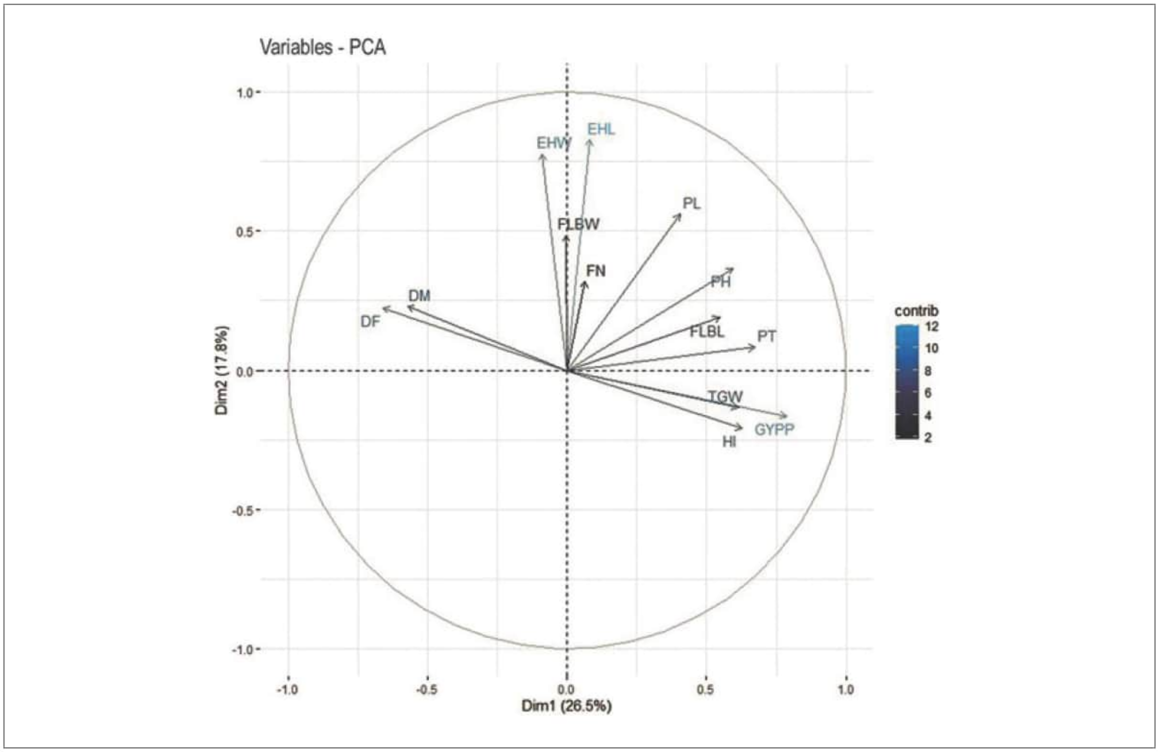

Figure 6B. Trait diversity and relation between agronomic and grain-yield-related traits, to perform selections without trade-off. (Source: Singh, Sherawat et al. 2023)

In a similar evaluation performed on 224 finger millet germplasm accessions by Nagaraja et al. (2023), days to 50% flowering and days to maturity were found to be highly correlated with each other (0.97). However, there was either negative association or no significant association with yield or yield-derived traits (plant height, number of productive tillers, number of fingersear, main ear length, grain yield per plant). The negative association of days to 50% flowering with grain yield is a beneficial association because early-maturing types are most preferred by farmers. Studies like these will help to identify and utilize elite accessions as the base for parental organization for hybridization programs.

In a similar experiment, characterization was performed for 148 finger millet accessions by Sharma et al. (2023) to screen for high genetic variation. Such research can form the basis for comprehensive and systematic germplasm collections of finger millet for further genetic conservation and utilization.

Singh, Lawrence et al. (2023) also concluded that use of varied germplasm in breeding is critical for increasing productivity in foxtail millet, which is best suited to hot and dry climates. The results of a characterization of 50 germplasm accessions showed that direct selection based on traits like panicle weight, test weight, and straw weight had a high and positive effect on grain yield per plant in both rainy and summer seasons.The existence of variability in foxtail millet germplasm enables plant breeders to effectively select appropriate donor lines for genetic improvement programs.

Sampath et al. (2023) evaluated for genetic diversity in barnyard millet when grown under sodic soil conditions and identified the number of productive tillers per plant as one of the component traits for yield improvement. This could turn out to be an added advantage for simultaneous improvement of yield while attempting crosses between diverse parents.

Lakhani et al. (2023) performed a similar screening protocol on little millet to identify genetic relatedness in 16 genotypes. The study classified the genotypes into two major clusters and further sub-clusters, and concluded that genetic relatedness can be used to improve programs with conventional and molecular breeding.

Similarly, Ravikesavan et al. (2023) screened 145 accessions of barnyard millet for 15 quantitative traits to study genetic divergence. The study concluded that intercrossing between accessions from diverse clusters in all combinations would show high heterosis and generate the segregating generations for development of high-yielding cultivars.

The studies of various millets cited above reported that there is untapped diversity in each millet that can be used in breeding programs. In India's Green Revolution, the pedigrees of highly adapted rice, wheat and maize cultivars were all common and hence the yield saturation plateau was reached. However, in the case of millets, there is a huge opportunity to explore less exploited genetic accessions that can act as sources of diversity for desired traits. Govindaraj et al. (2015) suggest that loss of diversity could happen due to genetic erosion. Modern crop varieties have been especially developed focusing on yielding potential under optimal production conditions. It is the landraces or wild cultivars that come to the rescue of marginal farmers. Further the use of untapped genetic material can be extended to the use of existing genomic sequence for sorghum (Paterson et al. 2009), pearl millet (Varshney et al. 2017), finger millet (Hittalmani et al. 2017) and foxtail millet (Zhang et al. 2012), to achieve faster genetic gain.

According to a review by Yadav et al. (2021), adoption of high-yielding, disease-resistant and stress-tolerant cultivars along with advanced crop management techniques led to yields increasing by 26% in sorghum, 59% in wheat, 69% in rice, 113% in maize, and an impressive 162% in pearl millet (Figure 6C). These gains translate to annual yield increases of 0.9% in sorghum, 2.0% in wheat, 2.3% in rice, 3.8% in maize and a remarkable 5.4% in pearl millet. These growth

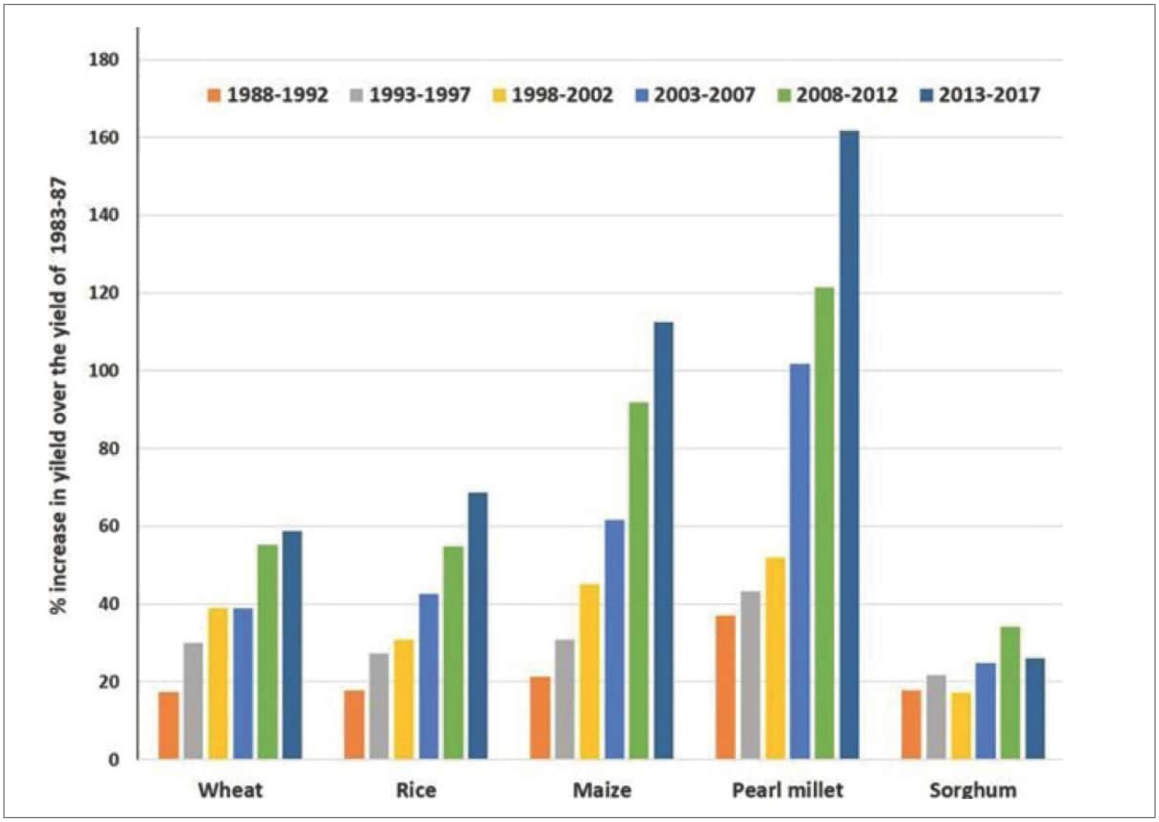

Figure 6C. Percentage improvement in the average yields of sorghum, wheat, rice, maize, and pearl millet from 1988 to 2017 compared to average yields during the period 1983-1987. (source:www.agricoop.nic.in) rates significantly surpass the global average (FAO 2020). Such productivity enhancements result from a combination of improved genetics and management practices. The substantial increase in pearl millet productivity is particularly noteworthy for two reasons: Firstly, over 90% of pearl millet is cultivated in rainfed and marginal lands, and secondly, pearl millet has received comparatively less infrastructural and human resource support compared to other food crops. This underscores the success of India's breeding programs and highlights the pivotal role of hybrid technology in elevating crop productivity in arid regions.

In pearl millet, wild relatives of the crop offer the potential to provide new genes crucial for broadening genetic diversity.It is therefore necessary to implement a stage-gate procedure to effectively oversee prebreeding initiatives that utilize wild collections as a reservoir for enhancing germplasm diversity and advancement.Ananda et al. (2020) on sorghum and Sharma et al. (2021) on pearl millet did an extensive review on the use of wild relatives and the many useful genes that they harbor for biotic and abiotic stress tolerance.

Pearl millet has shown impressive genetic gains in India over the past seven decades (Yadav et al. 2019). Achieving success in national and international pearl millet breeding programs hinges on gaining a more profound comprehension of new germplasm, the genome and the genes specific to unique traits. This necessitates combining traditional and contemporary tools, as well as utilizing rapid generation techniques (Yadav et al. 2021).

Pearl millet is now poised to take a quantum leap in genetic gains. Genome sequence information can speed up gene innovation and trait mapping and help in the understanding of several complicated gene pathways and their interactions (Varshney et al. 2017). More than 1,000 accessions of pearl millet have been sequenced with ~1.79 Gb draft whole genome sequence of reference genotype Tift 23D2B1-P1-P5, which contains an estimated 38,579 genes.

Genome-wide SNP data was generated for 288 test-cross progenies of PMiGAP lines for 20 traits, identifying 1,054 strongly significant marker trait associations (MTAs) for 15 traits which might be relevant for pearl millet breeding (Varshney et al. 2017) (Figure 6D). The resequencing data was then utilized to carry out genomic selection to predict grain yield for test crosses. The current genome discovery will enhance comprehension of the genetic foundation responsible for the remarkable drought and heat resistance seen in pearl millet.

The expansion of gene families linked to drought and heat resilience in pearl millet will generate knowledge to expand its performance in adverse climates. A thorough comprehension of the performance of pearl millet crops in hot, dry, and semi-arid regions may pave the way for the enhancement of not only pearl millet but also other cereal crops such as rice, maize, and wheat. These crops presently yield only modest harvests in arid or semi-arid regions (Varshney et al. 2017). The availability of high-quality whole-genome sequencing and resequencing information

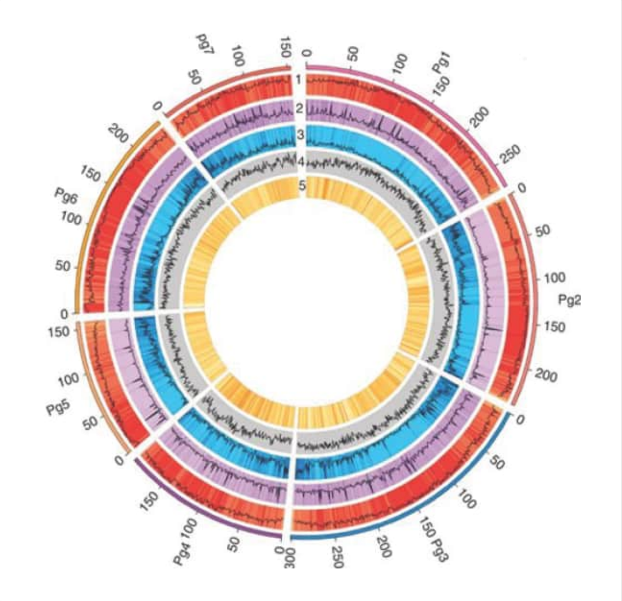

Figure 6D. Pearl millet genome features in 1Mb intervals across seven pseudomolecules. Units on the circumference are the megabase values of pseudomolecules. (Source: Varshney et al. 2017)

of several lines may aid genomic dissection of stress tolerance and provide a good opportunity to further exploit the nutritional and climate- resilient attributes of pearl millet (Satyavathi et al. 2021).

Priorities for future research

While millets have the potential to give optimal or modest yields even in marginal lands and under conditions of climate change, further research into genetic enhancement of climate-resilient traits in millets can help to improve their yield under changing climatic conditions. For instance, genetic modification of pearl millet can lead to yield gains under climate change.

Optimization and improvement of cultivation practices is another area with scope for further research. Careful use of resources like water, fertilizer, micronutrients and pesticides, instead of unchecked use of urea and DAP, has been shown to improve yields. The behavior of crops in different seasons and under different soil conditions has a lot of potential to explore. There is a need to revisit the knowledge transfer of traditional practices that are low or no cost to farmers. For instance, night-time tillage and sowing can be an effective and simple agronomic practice to improve seed imbibition, germination, and emergence in regions that experience frequent dry and hot environmental conditions. This practice has been shown to reduce the time it takes for seed germination and seedling emergence and improve the final yield. The delayed soil desiccation process in night-time tilled plots may promote unexpected weed germination, which can affect crop productivity. Seed priming is another technique that can improve seed germination and field performance in moisture- stress conditions.

While assessment of genetic diversity has been performed in crops like sorghum, pearl millet, finger millet, foxtail millet, barnyard millet and little millet, further research into plant genetic resources will enable plant breeders to develop or improve crop varieties with desirable qualities. Genetic engineering can also be used to improve the nutritional quality of millets and their resistance to biotic and abiotic stresses.

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Claim 7: Millets (mainly sorghum) can be used to produce biofuel, contributing to lower carbon emissions and slowing down the depletion of fossil fuels

Sorghum and millets like pearl millet and finger millet have great potential for use in biofuel production and power generation.

Summary

The use of agro-residues to produce reusable energy is regarded as a sustainable closed-loop approach to tackle issues associated with waste management and energy recovery. Given their diverse adaptive features and low nutrient requirement, millets are ideal crops for biofuel recovery and power generation. Specifically, sorghum, finger millet and foxtail millet have shown promising results in biofuel production and power generation. However, some challenges need to be addressed to increase process efficiency and optimum biofuel yields from millets. A summary of research studies, reviews and opinion articles on the potential role of millets in biofuel production, and their potential contribution to slowing down the depletion of fossil fuels is provided in Table 7A.

Scientific evidence

Claim 7A: Turning agro-residue from millets into useful energy is a sustainable, closed-loop solution to waste management and energy recovery

Worldwide interest in alternative fuels is growing as a result of the depletion of petroleum supplies and the rise in public concerns about global warming. Biomass energy is acknowledged as a renewable energy source with the greatest potential. The contribution of biomass energy to the global energy system is substantial and increasing. Energy derived from it may significantly lower carbon emissions (Reid et al. 2020). India and the United States Partnership to Advance Clean Energy (PACE) worked together in 2011 to produce biofuel with minimal carbon emissions (Packiam et al. 2019).

Burning agricultural waste, such as millet crop waste, is the main cause of air pollution, which has adverse effects on climate change, the environment and human health. There are three main pathways to thermochemically convert biomass into energy: Combustion, gasification and pyrolysis. Of these, pyrolysis is less expensive and produces high-energy-density biofuel (Van de Velden et al. 2010). It has significant benefits since it mainly produces liquid and solid fuel that is convenient to store and transport. It is viewed as an eco-friendly technique to convert waste into energy with minimal toxic byproducts, thereby addressing the twin issues of disposal of agro-residues and bioenergy production (Tagade and Sawarkar 2023). A viable and ecologically benign solution to raise the energy density of lignocellulosic residues can be provided by technical advancement and process optimization.

Physico-chemical characterization, kinetics, thermodynamic parameters, reactors used for the pyrolysis of millet agro-residues as well as the characterization of biochar made from millet agro-residues have all been the subject of documented research. According to a study by Ajikashile et al. (2023), the variability in millet agro-residues affects biochar properties as well as the generation of bio-oil. Sorghum is the primary material used in most pyrolysis investigations. During pyrolysis, biomass is thermally decomposed to yield products like pyro-gas (gaseous), bio-oil (liquid) and biochar (solid) (Foong et al. 2022). Studies (Borgohain et al. 2020; Tekade et al. 2020; Sharma et al. 2023) have demonstrated that pyrolysis is the only thermochemical conversion process that is versatile in terms of products in all three forms, solid, liquid and gas.

A recent study on the valorization of biomass for energy applications (Kuhe et al. 2021) using millet husk as a waste material and gum arabic as a binder to develop briquettes for domestic cooking in northern Nigeria demonstrated the potential economic viability of millet husk briquettes as a fuel source, with benefits such as reduced fuel wood consumption, monetary savings and mitigation of deforestation. The findings showed that particle size, compacting pressure and binder concentration affect the density, compressive strength, impact resistance index, porosity, ignition time and burning rate of the briquettes produced, thereby influencing their quality. The briquettes produce enough energy for cooking as compared to the wood fuel predominantly used in the country. Also, they are considered carbon-neutral because when growing, the millet biomass removes as much CO_2 as is emitted into the atmosphere from its combustion. Moreover, the briquettes produced are renewable, environmentally friendly, economically viable and are generally acceptable by dwellers in the region.

Claim 7B: Sorghum (especially sweet sorghum), with its array of adaptive features and low input requirements, is a leading candidate for biofuel feedstock and power generation

Millets are climate-resilient crops that prosper in regions prone to drought and excessive heat, which is one of their distinctive qualities (Das and Rakshit 2016). Millets can grow under a broad range of temperatures, moisture regimes and input conditions and are renowned for their resistance to pests and diseases, short growing season, reduced reliance on synthetic fertilizer and resistance to environmental stress. They suit a variety of cropping systems since they have a wide range of crop cycles, some of which are rather short (Saxena et al. 2018).

Sorghum, a crucial food and fodder crop in arid and semi-arid regions, occupies 45 million hectares globally, with Africa and India accounting for 80% of the area. Its higher ethanol productivity, shorter growing period and lower water requirement as compared to rice and wheat make it a profitable crop under rainfed conditions (Hossain et al. 2022).

Sweet sorghum, also known as sweet stalk sorghum, refers specifically to genotypes that have been selected for high lignocellulosic biomass that can be converted into biofuel. Energy sorghum is specifically bred for high biomass (Bandara et al. 2020). Sweet sorghum is a warm-season crop that could be grown by smallholder farmers in rainfed locations. According to Rao et al. (2019), the crop can grow on clay, clay loam or sandy loam soils and can survive salty and alkaline conditions in soils to a significant level. Sweet sorghum is grown in much the same way as grain sorghum. The concentration of sugar in sweet sorghum stalks, juice from which can be converted into ethanol for blending, is the only difference between sweet and grain sorghums.

Previous experience with sorghum and the ease of cultivation have made sweet sorghum popular among farmers. Any potential food vs fuel conflict resulting from the use of agricultural land for sweet sorghum production is mitigated by the fact that it has multiple uses as food, fodder and fuel. Sweet sorghum grain can be used for food and the bagasse after juice is extracted from the stalk serves as good animal fodder. Additionally, sweet sorghum-based bioethanol is more eco-friendly than molasses-based ethanol (Basavaraj et al. 2013). Although it is economical to produce ethanol from molasses, there is a problem of sustainability. Also, direct conversion of sugarcane juice into ethanol is not economical; moreover, it raises concerns of food security due to the diversion of land for sugarcane cultivation.

According to the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), the technology for ethanol production from sweet sorghum is gaining popularity in India and other countries. Dahunsi et al. (2019) investigated the effect of pretreatment methods on biogas generation from *Sorghum bicolor* stalk. They analyzed the physicochemical, elemental, and structural changes in the biomass before and after pretreatment using sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2). The results showed significant reduction of hemicellulose and partial solubilization of cellulose with H_2SO_4 pretreatment, while H_2O_2 pretreatment caused solubilization of lignin and partial dissolution of hemicellulose. The use of H_2O_2 resulted in higher biogas production and reduced production time compared to other pretreatment methods, making it a promising approach for biogas generation.

Sorghum-based biogas plants have energy and environmental advantages if they use co-generation technologies and utilize the digestate as biofertilizer. Havrysh et al. (2022) reported that sorghum energy production cost was less expensive than fossil fuels and comparable to other biofuels. Moreover, the grain output of sorghum can be utilized for food or animal feed. Comparatively, sorghum produces fewer pollutants and has a better biological value than ethanol made from sugarcane. In field experiments that determined indicators such as sorghum silage yield, production costs, embodied energy and well-to-tank (WTT) carbon dioxide emissions, sorghum silage's energy and environmental metrics were compared to those of other biomass, including maize silage, cereal straw and maize stalk. Analysis done on the energy-specific costs as well as heat and power produced by one hectare of sorghum demonstrated that sorghum is an appropriate biofuel for cogeneration and local power plants.

Lao et al. (2015) demonstrated that application of nitrogen fertilizer increases the energy efficiency of sorghum production.

Evaluating the economic effectiveness of sorghum-based energy supply systems is, therefore, important. There are many different physical and phenotypic traits displayed by sorghum cultivars (Mathur et al. 2017). They have been categorized into four types: grain, fodder, energy andsweet sorghum, based on production features and consumption (Shoemaker and Bransby 2010). Grain sorghum varieties range in height from 3 to 6 feet, have enormous ear heads and are generally used as food or animal feed. For feed, silage and grazing, the coarse, fast-growing forage sorghum types are used (Shoemaker and Bransby 2010). While sweet sorghum refers exclusively to genotypes that accumulate soluble sugars in the stalk, energy sorghum is developed primarily for the high lignocellulosic biomass that can be converted to biofuel (Melillo et al. 2014). Due to its high sugar content and ease of extractability, sweet sorghum is one of the leading feedstock crops for new-age biofuels.

Claim 7C: Achieving optimum outcomes and biofuel yields from sorghum is a challenge but solutions do exist

Sweet sorghum ethanol production technology is gaining popularity in India and other countries (Mathur et al. 2017; Basavaraj et al. 2013). However, there are challenges relating to seasonality, the limited harvest window, high labor requirement and delayed sugar reduction. The solutions to these include wider geographical cultivation, staggered sowing, cultivar selection, decentralized crushing and provision of irrigation. Sorghum's ability to withstand various stresses and grow well in hot and dry environments makes it an ideal option for climate-change-ready agriculture (Ravinder and Zou 2014). To meet the demand for large-scale biofuel production, research and development efforts should focus on developing genotypes suitable for different agroclimatic conditions and optimizing processing technologies (Janssen and Rutz 2011; Rao et al. 2019). However, challenges remain in terms of technology for large-scale harvest, transportation and storage of biomass, as well as commercial ethanol production from lignocellulosic material, or energy sorghum. Policy support from governments and regional considerations are crucial to draw the advantages of biofuel production from this multipurpose crop (Rao et al. 2019).

Claim 7D: Among millets, pearl millet also is suitable for biofuel production; its energy requirement is lower than that of sorghum

The cellulose and hemicellulose found in pearl millet biomass are crucial components in the production of cellulosic biofuel, which makes pearl millet a suitable bioenergy crop due to its production cost, availability, conversion efficiency and compatibility with existing fuels (Packiam et al. 2018). A life cycle analysis of the economics of biofuel production in India using sorghum and pearl millet as feedstock revealed that due of its higher water requirement, sorghum feedstock requires more energy than pearl millet feedstock (Reddy and Reddy 2021).

Pearl millet is well-adapted to poor soils, requires fewer inputs for establishment, and gives high biomass yield per unit area. The desirable chemical composition of the biomass holds energy yield potential. These characteristics make it a potential feedstock for fuel production in hot and dry areas where other cereal crops do not grow (Khairwal et al. 2007).

Claim 7E: Finger millet has great potential for biofuel production, but faces challenges in terms of efficiency

Finger millet has great potential as both a high-nutrition food source and a biomass feedstock for bioethanol production. To further enhance its utilization, the development of highly productive genotypes through molecular marker-assisted breeding and application of genetic engineering techniques offer promising avenues (Yemets et al. 2020). Optimizing biomass productivity through non-transgenic methods and exploring enzymatic hydrolysis and fermentation techniques can contribute to the economic viability and efficiency of bioethanol production from finger millet (Vasić et al. 2021). The utilization of biomass as a feedstock is associated with a more sophisticated technological method of producing bioethanol. Utilizing straw and agricultural waste, such as husk, may help to prevent a conflict between the use of grain for food and non-food purposes. (Ben-Iwo et al. 2016). However, not much information is available on technologies to turn finger millet biomass into alcohol.

Priorities for future research

Among the areas that warrant more study are a comparison of energy efficiency and carbon budgeting in biofuel production from different millet varieties. This would call for a systematic life cycle analyses approach as this is critical, especially for waste-to-resource economy models. More research is also needed to gain insights into current operational, technological and environmental challenges in biofuel production from millets.

Table 7A. **A summary of research studies, reviews and opinion articles on biofuel production, contribution to lower carbon emission and slowing down the depletion of fossil fuels.**

S.No	Authors	Article type	Origin	Method and millet type
1	Schmer et al. 2014	Research	USA	Statistical Analyses from 2000 to 2007 on corn and switchgrass
2	Houghton et al. 2006	Research	USA	
3	Sharma et al. 2009	Policy paper	India	Investigative analysis focused on sorghum stover
4	Mathur et al. 2017	Review	India	Meta analysis focussed on Sweet sorghum
5	Patel et al. 2020	Research	India	Cumulative data collection on economy, energy, and GHG emissions from farmers' focussed on Bamboo, Sorghum and Pearl millet
6	Packiam et al. 2018	Research	India	Statistical data analysis focussed on pearl millet

Key Highlights	Results obtained
Corn and switchgrass bioenergy production reduces GHG emissions by 29-396 GHG/megajoule of ethanol per year. Conversion of corn stover at a standalone cellulosic plant resulted in an ethanol contribution ranging from 820 to 998 L/ha/year.	The study suggests a multifeedstock, landscape approach for cellulosic ethanol production, minimizing economic and environmental risks. Co-located biorefineries reduce capital costs and share infrastructure costs, benefiting other cellulosic feedstocks. This approach can increase new energy yield values.
The Biomass to Biofuels Workshop, held in 2005, aimed to identify barriers and challenges to cellulosic ethanol production and develop solutions using modern biology tools. The workshop focused on ethanol but is relevant also to biodiesel and other bioproducts.	The report on this workshop provides a roadmap for accelerating cellulosic ethanol research, aiming to make biofuels practical and cost-competitive by 2012 and potentially replace 30% of gasoline use by 2030.
Sweet sorghum ethanol production technology is gaining popularity in India and other countries. However, challenges include seasonality, limited harvest window, high labor, and delayed sugar reduction. Solutions include wider geographical planting, staggered sowing, cultivar selection, decentralized crushing and irrigation.	Sorghum's higher ethanol productivity, shorter growing period, and lower water requirement make it a profitable crop under rainfed conditions.
Sweet sorghum, with its array of adaptive features and low input requirements, is a leading candidate for biofuel feedstock. However, sorghum exhibits huge genetic diversity and resources adapted to region-specific climatic conditions or changing climatic conditions. The amount of fermentable sugar and grain yields vary considerably in different sweet sorghum cultivars.	Sweet sorghum is a promising feedstock for new-age biofuels due to its high sugar content, ease of extractability, short life cycle, environmental adaptability, low cultivation cost and C_4 photosynthesis.
The authors assessed the trade-offs between feedstock costs and GHG emissions, focusing on high energy content biomass, and conducted economic, sensitivity and carbon emission analyses.	The authors found that sorghum and pearl millet yielded biomass net incomes of USD 52.02 and USD 20.37 per metric ton, respectively and recorded positive GHG emissions.
The authors utilized current fuel statistics, data on supply and demand, and future ethanol production in India, discussed the chemical composition of selected biomass, and did a cost-benefit analysis of pearl millet biomass feedstock.	Pearl millet is rich in cellulose (41.6%) and hemicellulose (22.32%); it can be used for commercial ethanol production.

(Continued)

S.No	Authors	Article type	Origin	Method and millet type
7	Umakanth 2016	Book chapter	India	Sorghum
8	Dar et al. 2018	Review	India	Meta data analysis focussed on sweet sorghum
9	Laouge and Merdun 2020	Research	Turkey	Pearl mellet biomass samples were characterized according to ASTM D3173-03.
10	Reddy et al. 2007	Research	Asia & Africa	Sorghum, rice stover, maize
11	Havrysh et al. 2022	Research	Ukraine	Conducted some field experiments focused on sorghum.
12	van der Weijde et al. 2013	Review	USA	Comparative study focused on maize, sugarcane and switchgrass
13	Reddy and Reddy 2021	Review	India	Study included farmers' perceptions on sorghum and pearl millet based on feedstock energy intensity.
14	Yemets et al., 2020	Review	Ukraine	The study used metadata to understand finger millet for bioethanol production from *E. coracana* feedstock.

Key Highlights	Results obtained
India announced a National Policy on Biofuels in 2009, aiming to blend at least 20% biofuels with diesel and petrol by 2017. It aims to develop renewable energy sources like high-energy sorghum, ensuring continuous feedstock supply.	Demand for ethanol blending is expected to outstrip supply, necessitating alternative feedstock like sweet sorghum. India needs over 6.3 billion liters of ethanol to meet its 20% EBP target by 2017. By 2020, bioethanol demand is estimated at 3.46 billion liters at 10% blending.
This paper explored bioethanol production from sweet sorghum technologies, highlighting potential benefits, recent advancements, pretreatment, novel processes, biogas production, and environmental and socioeconomic aspects.	The review acknowledges outstanding issues in ethanol production and yield but suggests sweet sorghum-derived bioethanol could gradually replace fossil fuels to meet energy demand.
The study analyzed biomass samples from pearl millet harvested in Niger in October 2018 using thermogravimetric, FT-IR, kinetic and thermodynamic parameters.	Pearl millet biomass, with low moisture content and high heating value, is suitable for thermochemical conversion due to its lower moisture and fixed carbon content.
Ethanol is the primary biofuel used globally, accounting for 90% of production. Major feedstocks include sugarcane molasses in Asia and Africa. Sweet sorghum is a promising alternative to sugarcane and corn feedstocks.	Stovers contain lignin, hemicellulose and cellulose, making them difficult to convert into ethanol. Brown midrib maize and sorghum mutants have lower lignin content, making research investments in high-biomass-yielding hybrids necessary for biofuel production and subsistence farming.
This study explores biomass-based power generation systems using sorghum, a drought-resistant crop with high biomass yield and marginal land cultivation.	Biogas cogeneration plants offer higher efficiency and carbon dioxide savings compared to combustion-based technology, while sorghum-based power plants can reduce emissions by 600-4,000 kg CO_2/ha.
Biofuel production from plant carbohydrates relies on solar energy stored in soluble sugars, starch, and structural polysaccharides through photosynthesis. Currently, bioethanol is primarily produced from soluble sugars and starch as they are easier to process than cell wall polysaccharides.	This review highlights C_4 grasses as key players in future lignocellulose supply due to their productivity, diverse ecological conditions, and dual-purpose and biomass-dedicated crops.
Rainfed sorghum and pearl millet feedstocks are analyzed for bioethanol production using Net Energy Ratio, Net Energy Balance, Net Carbon Balance, and Carbon reduction (%), evaluating environmental impacts.	The study reveals that dilute alkali pretreatment is the most energy-intensive process due to alkali consumption, while dilute acid pretreatment has higher conversion efficiency due to glucan and xylan conversion.
The authors discuss the potential of finger millet seeds for ethanol production, including conversion of straw and agricultural waste into bioethanol. They also discuss the development and testing of a tentative technology for sweet sorghum and finger millet combined processing.	White-rot fungus (*T. versicolor*) has been shown as a viable alternative to yeast in converting finger millet straw, utilizing both pentoses and hexoses. Saccharification with recombinant enzymes could increase efficiency in industrial bioethanol production, using *E. coracana* (finger millet) as cellulosic feedstock.

(Continued)

S.No	Authors	Article type	Origin	Method and millet type
15	ICRISAT	Newsletter	India	Sorghum and pearl millet
16	Tagade and Sawarkar 2023	Review	India	Mentioned all varieties
17	Rao et al. 2019	Book chapter	India	Meta data analysis focussed on Sorghum
18	Rooney et al. 2007	Review	USA	Sorghum
19	Reynolds et al. 2015	Review	USA	Reviewed recent research on crop-environment interactions for rice, maize, sorghum/millet, sweet potato/yam, and cassava in Africa and South Asia since 2000.
20	Samson et al. 2008	Book chapter	Canada	Quantitative data analysis focused on switchgrass and corn.
21	Ray and Behera 2011	Book chapter	India	Metadata analysis focussed on Sorghum
22	Abdullah et al. 2022	Review	Pakistan	Investigative analysis focused on walnut shell and pearl millet.

Key Highlights	Results obtained
70 participants from India's government, industry, and academia convened at ICRISAT headquarters to devise an action plan to tackle bioethanol production issues.	The workshop discussed the roadmap to meet India's blending target (10%) using lignocellulosic ethanol, focusing on creating a sustainable biomass supply chain for proposed ethanol plants by public sector oil marketing companies.
The study critically analyzes pyrolysis investigations on millet agro-residues, focusing on physico-chemical characterization and relationship between reaction conditions and millets-derived biochar's potential applications.	Unlike most pyrolysis research based on sorghum, the study demonstrated that the variety of millet agro-residues affects not only bio-oil and biochar generation but also biochar properties.
This chapter examines sorghum feedstock properties, biofuel production models, sustainability indicators, and commercialization.	The economic feasibility study of second-generation ethanol synthesis from sorghum biomass found that profitability is determined by processing costs and enzyme prices, with reduced enzyme prices being critical.
Sorghum, a dedicated crop for bioenergy production, is expected to be utilized for its potential to generate a large, sustainable biomass supply for profitable biofuels generation.	Sorghum, a drought-tolerant species with a history of lignocellulose, sugar, and starch production, is expected to develop hybrids for dedicated bioenergy production in the near future.
The authors discuss the environmental impacts of crop production systems, including soil degradation, erosion, loss of biodiversity, genetic loss, and climate change, which become more severe constraints to crop yields.	Sorghum and millet residues are widely used for fodder, fuel, and construction, but they deprive farmers of valuable resources like fodder, fuel, and income.
The chapter explores the use of energy crops for thermal energy, comparing bioheat, biogas, and liquid biofuel production, finding switchgrass pellets and corn silage biogas as the most efficient.	Switchgrass pellets offset 86-91% of emissions compared to coal, heating oil, natural gas, or LNG, with each hectare of land reducing CO_2 emissions by 7.6-13.1 tons annually.
The authors discussed Sweet Sorgum Agronomics, Sweet Sorgum as a Bio-Fuel Crop, and Sweet Sorgum Bio-Fuel's Economic Impact.	In India, sweet sorghum juice can produce ethanol at a cost comparable to sugarcane molasses and less than maize and cassava. It can yield 380-390 L alcohol/ton of grain.
This study examines the synthesis of value-added solid char using pearl millet and walnut shell biomass blends under torrefied and non-torrefied conditions, focusing on the impact of process parameters on torrefied solid products.	The study explores the use of torrefaction as a potential coal replacement method for biomasses, revealing significant temperature- dependent properties and potential for solid biofuel production.

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Claim 8: Millets have multiple uses

Millets offer a plethora of ecosystem services including weed management and control, which boosts soil health and nutrient acquisition, and are a means of subsistence agriculture (for feed and fodder).

Summary

Apart from being a source of nutrition for humans and animals, millets also provide a range of ecosystem services for the environment. As food and fodder, they are available throughout the year; they are not season-specific like other cereals and legumes. As a crop, millets have a great potential to curb weed dominance through different cropping approaches. Millets also promote the growth of rich microbial communities in the rhizosphere, which promotes soil health and enhances nutrient acquisition.

Scientific evidence

Claim 8A: The use of millet grain for animal feed and fodder supports subsistence farming

The contribution of cereals and pulses to food security is season-specific while millets support food, fodder, health and nutrition needs throughout the year. In Africa, millets are used as fodder for domestic animals (Hassan et al. 2021). They are a complete package of nutrients. The fodder is rich in minerals, which improves the quality of milk and meat (Kumar et al. 2012). Pearl millet fodder is very popular among the Zaafrana community of Tunisia and is gaining popularity among commercial farmers worldwide (Bouajila et al. 2020; Chapuis-Lardy et al. 2015; Jukanti et al. 2016). The use of millet fodder dates back to ancient Iraq. Evidence found in the dung of animals indicates that the Mesopotamian community used fodder from millets in significant ways (Laugier et al. 2022). Apart from pearl millet, foxtail millet is used as fodder/feed in many Asian and African countries due to its quality and quantity (Lata et al. 2013). Similarly, barnyard millet, which is widely cultivated in China, Korea and India, finds use as feed and fodder because it is rich in nutrients, easily digestible and provides food security throughout the year (Nagaraja et al. 2023).

The nutritional quality of millet fodder can be improved by adding diverse fertilizers. Moussa et al. (2021) reported that applying integrated nutrients (organic and inorganic) during millet cultivation substantially increases the quantity of green and dry fodder. Intercropping of pearl millet with groundnut or cowpea with a treatment of farmyard manure (FYM)+100% recycling-derived fertilizer (RDF) helps increase the quality and quantity of pearl millet, including the number of tillers per plant (4.52), plant height (149 cm), dry fodder yield (2.38 t/ha) and green fodder (14.47 t/ha) (Bijarnia et al. 2020).

Claim 8B: Intercropping with millets helps in weed management and control, promoting sustainable agricultural practices

Proper attention is required during the pioneer stage (4-6 weeks) of millet growth as it can be affected by weed dominance. After the primary stage, millets can withstand weed dominance and accelerate growth and production. Intercropping with millets helps farmers manage weeds with less effort as the canopy restricts weed growth (Mishra 2015; Mahapatra et al. 2023). Thambi et al. (2021) found that application of herbicides such as Pretilachlor 6 G @ 495 + Pendimethalin Bensulfuron methyl 0.6 G gram active ingredient per hectare (g.a.i./ha) for 3 days followed by 20 days of hand weeding reduces weed dry weight (2.94, 2.69 and 4.87 g/m^2, weed density (4.05, 3.03, and 4.03 number/m^2) and weed index (2.66%) in barnyard millet.

In a comparative study between legumes and millets (Japanese millet and forage sorghum), Matloob and Chauhan (2021) found that millets were effective in reducing the growth (20-92%) of *Echinochloa colona* weeds in terms of leaf count, intolerance and plant height and simultaneously produced the highest biomass.

Weeds affect finger millet yield as they can adapt to the environment to compete with the crop. Hand weeding, intercropping and herbicides such as chlorimuron-ethyl, isoproturon and 2,4-D effectively restrict weed growth. However, the issue needs to be addressed at the pioneer stage since plant growth is moderate during that time (Rao 2021).

In a field experiment in the kharif season of 2010-2011 in Bengaluru, three tillage practices—conventional tillage (3 ploughings + 3 inter cultivations), minimum tillage (1 ploughing + 1 inter cultivation), and reduced tillage (2 ploughings + 2 inter cultivations)—were compared in finger millet cultivation (Nanjappa and Ramachandrappa 2016). Of the three practices, the conventional tillage practice, which involved checking the growth of weeds in intercropping of pigeonpea and finger millet, produced higher grain weight (12 g/plant), tiller number (6.16/plant) and grain yield compared to the other tillage practices. Intensive tillage practices can reduce the growth of weeds.

Apart from sorghum and finger millet, proso millet and teff also reduce weed growth without affecting the plant's physical characteristics (Das et al. 2019; Gebrehiwot et al. 2020). Teff is a popular staple millet in Ethiopia; however, infection and control of weeds is a major challenge. Ten varieties of teff were analyzed on the basis of their weed management capacity in two locations. Of these, DZ-Cr-387 and Kora varieties were found to be effective in reducing the dry weight and density of weeds with less loss of grain weight and yield. Hand weeding reduces the density of weeds significantly (Gebrehiwot et al. 2020).

Of these, DZ-Cr-387 and Kora varieties were found effective in reducing the dry weight and density of weeds with less loss of grain weight and yield. Hand weeding reduces the density of weeds in a significant way (Gebrehiwot et al. 2020).

Claim 8C: Millets enhance soil health and promote nutrient acquisition when used in intercropping systems

Fertilizer promotes soil fertility and yield by reducing the microbial population, while bioinoculants help increase carbon and nitrogen-fixing bacteria (Mattoo et al. 2021). Intercropping systems help accelerate radiation-use efficiency and photosynthetically active radiation, dry matter and their photosynthetic character. Due to this effect, yields increased by 6.8-37.3% in monoculture (Gong et al. 2020). Enzyme activities and rhizosphere soil nutrient content increase with changes in soil temperature, bulk density and soil water content. Bacterial growth is more dominant than fungal phylum, which is less in the case of monoculture. On the other hand, fungi's nitrate and nitrogen contents have vital roles in soil microbial health (Gong et al. 2019). Isolated fungi and bacteria from the rhizosphere regions in an intercropping system have the potential to increase zinc and phosphate in the crop, which impact root and shoot length. These endophytes help increase nitrogen, phosphorus and potassium (NPK) mobilization which helps increase zinc and NPK content in the grain (Choudhary et al. 2020; Dang et al. 2020). Arbuscular mycorrhizal and rhizobacteria can help millet and legume intercropping systems improve soil health and grain production (Mathimaran et al. 2021).

A pot experiment was conducted (Wu et al. 2019) with three different cropping systems: continuous sorghum, continuous sorghum with the application of *Bacillus amyloliquefaciens* and sorghum and maize rotation. It was found that the richness of the fungal community was greater than that of the bacterial community in the rhizosphere with continuous sorghum cropping compared to sorghum and maize rotation. Continuous cropping harms soil health by increasing the pathogenic fungal population and reducing sorghum growth. The sorghum-maize rotation reduces pathogenic fungi such as *Tremellomycetes* and increases positive rhizobacterial growth. Continuous cropping decreases bacterial growth and increases fungal growth. These results suggest that plant-promoting rhizobacteria could be enhanced by intercropping sorghum and maize. Intercropping millets with other cereals and pulses has many other advantages.

In a comparative study between multicropping (foxtail-potato-soybean) and sole cropping involving foxtail millet (Xu et al. 2023), downy mildew disease was found to be less active in the multicropping treatment due to the active participation and greater enzymatic activity of abundant beneficial bacteria such as *Aeromicrobium* and *Pseudomonas* and the lesser presence of *Fusarium* (pathogenic fungi). The fungus *Ustilago crameri* causes smut in foxtail millet, limiting its growth and yield. Seeds of three varieties of foxtail millet—Changnong35, Jigu20 and Jingu21—were mixed with chlamydospore powder of U. *crameri* and cultivated in the field. It was reported that Jigu20 provides a platform for beneficial rhizosphere bacteria such as

Streptomyces and Bradyrhizobium, which helps to decrease the growth of U. *crameri* by increasing enzymatic activities more than in Jigu21 and Changnong35 (Han et al. 2017).

Apart from the benefits of soil and plant nutrient acquisition, microbiome communities associated with some millets have been shown to offer climate-adaptive features. Kodo millet has rich microbiome communities in the rhizosphere zone which help it withstand rough climatic conditions. It is dominant with actinobacteria. The microbial gene sequence is connected with physiological pathways that help fix nutrient and carbon cycles. Xenobiotic degradation reflects the secondary metabolism that supports the growth and sustainability of plants under rough conditions (Prabha et al. 2019).

Priorities for future research

While research has shown that cultivation of millets offers a plethora of ecosystem services and has multiple end-uses for humans, animals and the environment, more research is needed in the areas of extended ecosystem services provided by millets, especially its effects on soil health and plant-microbiome communities. More lab- and field-based experiments will provide insights into the role of millets in shaping beneficial microbiome communities. Weed management is another priority area for research as it remains one of the biggest challenges for farmers globally. Mechanistic studies on weed control and soil health in millets should also be considered as they can shed light on how millets offer such benefits, thereby aiding in integrating millets into current agricultural systems. More research is also needed to understand how millets work with other cereals, pulses and legumes to improve crop nutrition and soil health through microbiome services. This is critical against the backdrop of global loss of biodiversity and deterioration in soil quality.

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Claim 9: Millets are good for tribal people

The Shree Anna Abhiyan (SAA) has emerged as a force reshaping the agricultural and socioeconomic landscape of tribal people in Odisha state of India. This compilation of case studies serves as a compelling testament to the far-reaching impact of SAA, shedding light on the lives of individuals and communities touched by its endeavors. Rooted in the principles of sustainable agriculture, economic empowerment and social inclusivity, these stories illustrate SAA's commitment to promoting millet cultivation in marginalized tribal communities. These stories unveil how millets, which are resilient crops known for their nutritional value and climate adaptability, have not only revitalized farming practices but also paved the way to enhanced livelihoods. Moreover, they underscore the pivotal role of women in agriculture, highlighting their leadership in promoting millets as a sustainable and nutritious food source.

Case study 1: How SAA became a game changer for Badal Sahoo

Background

Twenty-nine-year-old Badal Sahoo joined the Saunta Gaunta (SG) Foundation in 2019 as a Community Resource Person (CRP) under SAA. A financial crisis in his family had previously forced him to discontinue his education after schooling. After working at an iron company for a few years, he returned to his village, Barakhandia, to start a poultry farm. He still hoped to go to college.

However, unable to raise the money for higher education through poultry farming, he joined SG Foundation and was assigned three Gram Panchayats (village assemblies)—Khuntapada (6 villages), Chauthia (5 villages), and Gunduria (3 villages)—to mobilize farmers and share knowledge and best practices related to millet cultivation.

Intervention

In 2020, in line with the SG Foundation's guiding principles that all CRPs must themselves undertake millet cultivation on at least 1 acre of land, Badal and his mother started growing millets on their one-acre plot following the System of Millets Intensification (SMI) agronomic practices. They invested approximately ₹17,000 and produced 1,000 kg of finger millet (mandia in local parlance) in the first year. They sold 940 kg at ₹ 32.95/kg in the market, earning ₹ 30,973 plus an incentive of ₹2,000. Growing finger millet has been a learning experience for Badal. He has learnt several agronomic practices, which he now teaches other farmers. He encourages other farmers to grow finger millet in their fallow lands and use bio-inputs.

Impact

Most farmers in Barakhandia village are sharecroppers. Very few undertake rice cultivation. They lacked the skills and confidence to undertake millet production. Barring a few self-help group members, nobody showed interest in growing millet. However, Badal's example and efforts helped mobilize 25 farmers who started millet cultivation on 25 acres of land. As millet cultivation grew, so did the demand for bio-inputs. Badal and his mother started making bio-inputs like Handi Khata and Jeevamruta for the entire village to use. Badal's efforts to mobilize the community to cultivate finger millet increased his household income and ultimately helped him complete his education.

Figure 9A. Badal Sahoo's mother weeding their one-acre finger millet plot.

Case study 2: Balaram Paik's liberation from indebtedness began with SAA

Background

"Our whole community has been in the clutches of moneylenders. We knew we were being cheated but were really helpless," bemoans Balaram Paik, as he relates how SAA transformed his life in 2018.

Balaram used to grow finger millet, maize, vegetables and paddy on his 6.5 acres of land. Over the years, as maize cultivation became common and the use of chemical fertilizer increased significantly, a vicious cycle began developing. As productivity fell, the use of fertilizers increased, further degrading soil quality. With declining yields, he was fully trapped in debt and forced to keep growing maize. "The *sahukara* (landlord) gave us seeds and fertilizer to cultivate but would take away all the produce for a fixed price, further increasing our debt. While the government's Minimum Support Price (MSP) was ₹ 1,800/100 kg, the *sahukara* only gave us ₹ 1,000/100 kg," recalls Balaram.

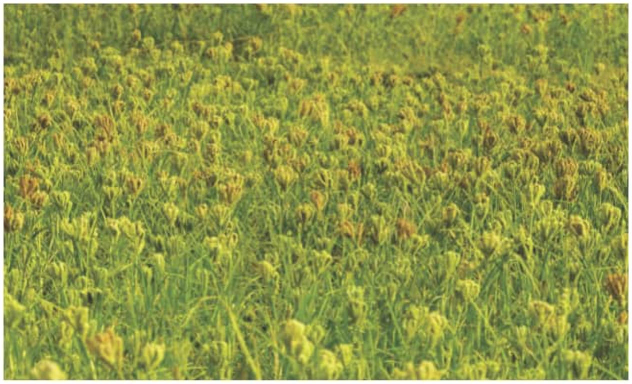

Figure 9B. Balaram Paik's healthy finger millet field.

Intervention

In the last three years, Balaram and others have been cultivating finger millet. The MSP of ₹ 3,295/100 kg has helped them earn a decent livelihood and avoid borrowing from moneylenders. "Though millets have been grown since the time of our forefathers, new methods of cultivation have led to significantly higher yields," he admits, while expressing his gratitude to the CRP which taught him new methods of millet cultivation and how to make bio-inputs.

Impact

In the first year, Balaram's finger millet yield was 50 kg before doubling the next year. He has devoted 2 acres to finger millet this year and plans to gradually shift completely from maize to finger millet.

Figure 9C. Balaram Paik explaining the benefits of growing finger millet.

Case study 3: Farmers' profit from millet farming reaches new high

Background

Life has begun to look up for Gokul Madhaba Mahakud, a farmer from Bhagabanpur village in Ganjam district, Odisha, ever since he became a member of the Panchanan Farmer Producer Organisation (FPO). He now earns a better price for his produce and leads a better quality of life. The financial gains from the sale of finger millet produced on his 3-acre farm have seen a big jump. He was able to sell 400 kg of finger millet, making ₹ 13,508 at a market set up in his village for the first time.

Intervention

The Panchanan FPO set up in 2019 has played a crucial role in improving the lives of farmers like Gokul by providing input support, training, and marketing solutions to farmers. The FPO has 2,000 members. During the harvest period, farmers are trained in post-harvest management and Fair Average Quality (FAQ) specifications of finger millet. The FPO organizes village-level planning meetings to estimate production and surplus, and enrols farmers for procurement through the Millet-Procurement Automation System (M-PAS). The Assistant Agriculture Officer verifies the documents, and a final procurement list is generated.

In the Kharif Marketing Season (KMS) of 2021-22, the FPO sold 359,930 kg of finger millet to the Tribal Development Co-operative Corporation of Odisha Ltd. (TDCCOL) at the MSP, providing a significant boost to the local economy. They procured the same from 1,313 farmers at the MSP. In 2022-23, the FPO sold 687,247 kg purchased from 2,485 farmers at the MSP. The FPO currently covers millet growers in 160 villages of 26 Gram Panchayats in Sorada block of Ganjam district, providing them with support and marketing solutions to improve their livelihoods.

Impact

The FPO has been a game changer for farmers like Gokul, who have seen a significant increase in their income and less uncertainty associated with selling their produce. The initiatives taken by the FPO have not only improved the lives of farmers but have also contributed to the overall development of the local economy. This collaborative approach is expected to have a ripple effect, positively impacting thousands of farmers like Gokul across Ganjam. As the FPO continues to grow and evolve, it is not only elevating the financial well-being of farming communities but also fostering a sense of empowerment and self-reliance among its members.

Apart from their ongoing procurement activity, the FPO has initiated the marketing of black rice. It buys black rice from farmers and sells it to different buyers, thereby providing more profit to the farmers. It also has plans to implement a seed village program for crops other than finger millet in their area of operation.

Figure 9D. Farmers of the FPO weigh their finger millet produce at the FPO office.

Figure 9E. Produce packaged at the FPO office for sale.

Case study 4: Millets on Wheels

Background

'Millets on Wheels' was the brainchild of the Centre for Regional Education, Forest & Tourism Development Agency (CREFTDA) and was started in June 2020 as a food truck. The truck is managed by Jashipur Farmer Producer Company Ltd. in Jashipur block to provide hot cooked millet foods like chakuli, bara, idli and jilapi as well as biscuits and savouries, with the support of Mission Shakti SHGs (self-help groups). The truck goes to both rural and urban areas to inculcate a healthier eating culture among the people of Jashipur block.

Intervention

Jashipur Farmers Producer Company received a grant-in-aid of ₹ 400,000 (₹ 200,000 for the vehicle and ₹ 200,000 as working capital) from the Government of Odisha to start this initiative. They recruited a manager, a driver and a chef. The profit is deposited in the company account and profit sharing will start once the working capital is recovered. The vehicle sells hot cooked dishes, the most popular among them being *mandia malpua* and *mandia samosa*.

Impact

Three months after it began business, Millets on Wheels' operations had to come to a standstill because of COVID-19. In those 3 months, the total revenue earned was ₹ 132,000, with a profit margin of approximately 25-30%. It participated in the Krushi Odisha fair in Bhubaneswar, organized by the Department of Agriculture and Farmers Empowerment, Government of Odisha and received positive feedback. The company has decided to launch mandia chow mein very soon. As part of its future plan, company personnel have been visiting government and private establishments to procure orders for snacks.

Figure 9F. The "Millets on Wheels" food truck.

Figure 9G. The food sold in the food truck.

Conclusion

The Shree Anna Abhiyan has not only revitalized agriculture but has also become a lifeline for tribal communities, illuminating a path to sustainable livelihood and economic empowerment. The case studies presented here serve as compelling evidence of how millet cultivation has breathed new life into tribal regions, offering hope and boosting resilience. As these stories continue to develop, they highlight the profound impact of millets in improving the lives of tribal communities, ultimately setting a precedent for inclusive and sustainable development in Odisha and beyond.

Claim 10: Millets are good for women

Women's economic empowerment is integral to sustainable development. The case studies from various districts in Odisha, India, conducted under the Shree Anna Abhiyan, underscore the transformative effects of initiatives that empower women in agriculture, particularly in the realm of millet cultivation and promotion. Millets, with their resilience in the face of climate challenges and rich nutritional profile, emerge as a pivotal solution for both food security and economic upliftment. From bio-input units initiated by Maa Hingula Women's Self-Help Group (SHG) in Jashipur to the distribution of threshing machines among women's SHGs in Koraput, women have taken the lead in championing sustainable agricultural practices. Role models like Raimati Ghiuria, dedicated to conserving traditional crops and supporting fellow farmers through Bamandei Farmers Producer Company Ltd, exemplify the potential for transformative change. Meanwhile, the Mao Saraswati Women's SHG in Mayurbhanj has ventured into entrepreneurship, grinding not only millets but also rice and turmeric, with aspirations for further expansion. The success of Koraput Cookies, emphasizing teamwork and product quality, reinforces the potential of millet-based enterprises. Rinki Panda, a millet recipe trainer, has not only increased her income but also serves as an inspirational advocate for millets' health benefits. Pratima Pradhan's transition from conventional farming to exclusive millet cultivation sets a powerful precedent, motivating other women to follow suit. These diverse initiatives, carried out under SAA and led by women SHGs and individual entrepreneurs, represent a collective effort to advance millets as a sustainable and nutritious food source, simultaneously improving livelihoods and advancing gender equity.

Case study 1: Bio-inputs' production aids women's economic empowerment

Background

Finger millet, which has traditionally occupied a significant place in the diets and cropping systems in the tribal areas of Odisha, can grow with a very low water footprint (around 80% less compared to rice, wheat and sugarcane). It is rich in fibrous organic matter and slow to break down in soil. This aids in maintaining soil structure and retaining water. Farmers need to adopt farming practices that have the least impact on the environment while continuing to produce a good quantity of crops to sustain their livelihood and meet the country's food demand.

Intervention

Ever since the launch of SAA, farmers have mostly been using bio-inputs like Handi Khata, Jibamruta and Nimastra as part of their agricultural practices. Noticing the growing market demand for these products, Maa Hingula Women's SHG started a bio-input unit in 2020 with the support of and technical guidance from Jashipur Farmers Producers Company Limited (JFPCL), which provided financial assistance to the tune of ₹ 25,000 as well as the required equipment. All the SHG members received two days of training from Watershed Support Services and Activities Network (WASSAN) on making the bio-inputs. These three bio-inputs are now produced using local resources like cow dung, cow urine, Arakha (*Calotropis*) leaves, Karanja (Indian beech) leaves, neem leaves, jaggery, white ant sand and gram flour.

Impact

The first batch of these products was rolled out in July 2020 and JFPCL started its marketing in the block in August 2020. The SHG was able to sell 2,904 liters of Jibamruta, 30 liters of Handi Khata and 20 liters of Nimastra, making a profit of ₹ 7,148. Based on discussions with agriculture officials, JFPCL estimated a demand for 3,000 liters Jibamruta, 1,000 liters of Handi Khata and 500 liters of Nimastra in the block, and an increase in demand in the future. With JFPCL taking the responsibility of marketing, the SHG is ready to scale up production and its members are quite hopeful of a secure income stream in the future. Moreover, these inputs are also being used in rice and vegetable cultivation.

Figure 10A. Bio-inputs being prepared at a women's SHG.

Figure 10B. Bottled Handi Khata.

Case study 2: Mechanization brings relief from drudgery

Background

In southern Odisha's Koraput district, tribal women farmers predominantly rely on traditional methods to thresh finger millet, a laborious process that escalates processing expenses. They spend approximately 5-6 hours daily, manually drying and extracting finger millet seeds, which takes three to five days and costs them around ₹ 3,000.

Intervention

To address this challenge, under SAA, 10 finger millet threshers-cum-pearlers were distributed to 10 women's SHGs in Boipariguda block of Koraput district in 2021. This has enabled the SHGs to process high-quality finger millet efficiently. Of these groups, Sabari Women SHG in Doraguda village has been successful in earning a substantial income from their processing units. The units also come in handy for other women farmers who bring their harvested finger millet to be processed at a cost of ₹1/kg. The SHG has plans to rent out the threshers to millet farmers. The threshers typically handle 300 to 400 kg/day. They also plan to charge ₹100/100 kg of finger millet processed. Mechanized threshing does in one day what manual threshing can do in 5-6 days.

Impact

The adoption of finger millet threshers by women SHGs has increased awareness of their benefits among farmers. It has not only improved processing efficiency, but also increased incomes of both finger millet farmers and Women SHG members. Many farmers are now interested in processing their raw finger millet into a finer, marketable product that can fetch a good price. This collaborative effort between SAA, civil society and government departments has played a crucial role in empowering women farmers and promoting sustainable agricultural practices in the region.

Figure 10C. Women using a thresher at a women's SHG.

Case study 3: Custodian and torchbearer for farmers of Koraput

Background

Raimati Ghiuria, a resident of Nuaguda village in Koraput district, lives with her husband and three children and is a role model for many women in her village. A brief interaction with the M S Swaminathan Research Foundation sparked an interest and active engagement with agrobiodiversity and agriculture, and a commitment to preserve traditional rice and finger millet varieties. She is a community resource person and an active trainer at the farm school and has trained many farmers in adopting improved Package of Practices for millets and other traditional crops.

Intervention

As a custodian farmer, Raimati has conserved more than 72 traditional varieties of indigenous rice and more than 30 varieties of millets. She was an active participant in participatory varietal trials under SAA and took part in the largest farmer field landrace evaluation trial in collaboration with the Indian Institute of Millets Research (IIMR). The varieties conserved by her have been profiled; some of them have been found to perform better than high-yielding varieties in farmer's fields. These efforts over a period of 5 years led to the release of landraces by the Government of Odisha, following technical evaluation by scientists.

As chairperson of the Bamandei Farmers Producer Company Ltd, Raimati engaged an FPO as a procurement agency. In the last 4 years, the company has procured 2,485,800 kg from farmers in the block, contributing to their livelihoods. Under her leadership, the company runs processing and post-harvest units. She has also been supporting FPOs in anchoring the millet tiffin center in Kundra block. In addition, Bamandei FPC Ltd is also actively preparing and selling bio-inputs to its members.

Raimati has been instrumental in anchoring the farm school in Kundra block since 2012. To date, she has trained more than 2,500 farmers in millet intensification, line transplanting, intercropping and organic pest management.

Impact

Raimati is both a seed conservator and leader in value addition and community mobilization. Apart from being a member of a team that received the Genome Saviour Community Award conferred by PPV&FR Authority in 2012, she was the recipient of the Jamsetji Tata National Virtual Academy Fellowship Award in 2015, the Best Farmer Award by Tata Steel in 2015, 2017 and 2018, the Best Farmer Award conferred by ICAR–IISWC, Sunabeda in 2016, Inspiring Women of the Year award by the Central University of Odisha. She has been felicitated at the state level and is part of the state landrace varietal release committee. A woman with vision, Raimati plans to scale up FPO activities related to value addition and processing in millets, enhancing the supply of labor-saving implements to women farmers, maintenance breeding, seed production and supply of landraces to the government. In addition to millets, she is keen to scale up the marketing of indigenous rice variety Kala Jeera through the FPO.

Figure 10D. Raimati Ghiuria, a well known custodian farmer, stands amidst her flourishing millet field in Kundra village of Koraput district.

Case study 4: Empowering women through millet processing

Background

The community in Badasialnai village in Mayurbhanj district was used to consuming millets in the form of *mandia jau*. But, without a grinding machine, they had no access to millet flour and were consequently unaware of the many ways it could be consumed.

Intervention

The Shree Anna Abhiyan signed a memorandum of understanding with the Mission Shakti Department to supply a pulverizer to SHGs. Applications were invited from groups through the Integrated Child Development Services (ICDS). The facilitating agency undertook a feasibility study to finalize the SHG and to help them initiate their enterprise. A pulverizer was thus allocated to Mao Saraswati Women's SHG of Badasialnai. The pulverizer can grind 5-8 kg of grain an hour. This was done with a view to facilitating decentralized mechanized processing of small millets.

The Mao Saraswati women's SHG began operations in April 2021. After receiving the pulverizer, it invested ₹5,000 from savings to obtain an electricity connection. The pulverizer grinds millets, rice and turmeric, among others. The SHG was given the freedom to fix the rent for the pulverizer. While the SHG members can rent it for ₹1/kg for all kinds of grain, others have to pay ₹5/kg for rice and millets and ₹20/kg for turmeric.

The lack of space to store raw material and finished products has been a key challenge the SHG is facing.

Impact

The SHG plans to start activities related to value addition in millets and to set up a millet kiosk at the Jashipur market. It is in talks with shops in the market to launch the Saraswati brand of millet flour as well as with the Child Development Project Officer (CDPO) and Jashipur Farmers Producers Company to provide marketing support.

Case study 5: The success story of Koraput Cookies

Background

Koraput Cookies originally started out as a fellowship project of a SBI Youth for India (YFI) fellow in Semiliguda block, Koraput. With the support of DHAN Foundation, rural women of Koraput were brought together to form the Koraput Millet Producer Group, with the objective of producing and selling value added millet products and generating employment for women. The group started out by baking millet-based cookies and launched Koraput Cookies.

Intervention

The SHG was inspired by the business model of Shri Mahila Griha Udyog Lijjat Papad. Their guiding principles are transparency, quality and teamwork. The business started small but with a vision to scale up quickly. After receiving training, it was also important for the SHG to build their capacity to independently continue production. With the support of DHAN Foundation's regional coordinator Bijaya Kumar Nayak and the SBI YFI Fellow project, these women have been able to reach customers in Delhi, Assam, Rajasthan, Uttarakhand and Odisha. Orders for the cookies can now be placed on their website (https://koraput-cookies.business.site/) as well as retail outlets. The business faced multiple challenges, including a resource crunch, market competition, non-availability of infrastructure, and the lack of clear processes to run the enterprise. The second wave of COVID-19 hit the enterprise hard. However, the dedicated women continue to put in efforts to run the business and make it sustainable.

Impact

Koraput Cookies, made of organic finger millet, whole wheat flour, jaggery and nuts are popular for their excellent taste and health benefits. The SHG plans to expand the enterprise by increasing production capacity and providing employment to more women.

Figure 10E. Koraput finger millet cookies.

Case study 6: Rooting for millets through recipes

Background

Rinki Panda is a millet recipe trainer and Community Resource Person in Keonjhar district of Odisha. She learnt about millets from CRP training sessions and began meeting farmers to persuade them to cultivate millets because of their health benefits. On YouTube, she chanced upon millet-based foods and decided to try making finger millet *laddoos* for her family. The positive feedback from her family and community members lit the spark of entrepreneurship in her. Soon she began distributing the *laddoos* among farmers to convince them to grow finger millet.

Intervention

In 2020, Rinki started value addition activities with the objective of gaining entry into a competitive market rather than to earn profits. She prepared innovative recipes, and soon became a millet recipe trainer. Today, she conducts 25 to 30 training sessions annually, for which she gets paid ₹400/day. Additionally, she supplies millet-based food items like *dahi vada, ragi jadoo, mandia chuna, idli,* custard, and *mandia* coffee to public/government staff and SHGs. She also prepares *mandia* chicken *biryani* and chicken *pakoda* on special occasions.

Impact

Rinki now earns an average of ₹20,000/month. She plans to start a food court in Keonjhar district in 2-3 years' time and has already planned the menu for it — *dosa, vada* and *idli* for breakfast; finger millet *biryani* for lunch and dinner and finger millet *pakoda* as an evening snack.

Figure 10F. Millet recipes by Rinki Panda.

Case study 7: Mandia maa Subasa Mohanta

Background

A resident of Singarpur village in Mayurbhanj district, Subasa Mohanta started finger millet cultivation on her one acre of wasteland, aided by the Centre for Regional Education, Forest & Tourism Development Agency (CREFTDA). She was able to get a yield of 8 quintals of finger millet. Awareness generation activities on the nutritive value of finger millet initiated by SAA resulted in growing demand for the crop in local markets. This helped Subasa sell 500 kg at ₹40/kg. The rest of the harvest was retained for domestic consumption and distributed among her friends and relatives.

Intervention

In 2021, she diversified into growing sorghum and kodo millet on 8 acres (leased at ₹2,000/year) and began cultivating two varieties of finger millet — Bhairabi and Srichaitanya. Subasa expects to harvest approximately 6,000 kg of both millets, 4,000 kg of which she will sell via M-PAS to earn ₹ 135,080 (₹33.77/kg) and the rest in the local markets to earn approximately ₹ 80,000 (₹40/kg). She also makes her own bio-inputs using poultry manure. Eager to know more about agronomic practices, she regularly seeks information and assistance from the Block Agriculture Officer and Assistant Agriculture Officers.

Over the years, Subasa has received training on agronomic practices, crop cutting, bio-input preparation, seed treatment/preparation, value addition and recipe preparation, developing expertise which she shares with other farmers. Owing to her dedication and hard work, she is known as Mandia maa across the district.

Impact

Subasa has received various awards and recognition for her dedication and determination to promote millet in Odisha. At a national workshop on nutricereals (millets) on the eve of World Food Day in 2019, she was felicitated as a leading millet farmer in the State.

Figure 10G. Mandia maa Subasa Mohanta.

Case study 8: Millet for health is Pratima Pradhan's mantra

Background

A chance visit to the local marketplace on a futile search for millets to deal with her anemia led Pratima Pradhan of Lamungia village of Raikia block to seriously consider growing the same on her own one-acre farm. Lamungia is well-known for growing vegetables and turmeric. Like other members in the community, she too only grew these crops along with rice.

In 2019, the SAA community resource person and block coordinator conducted an awareness session on the economic, environmental and health benefits of growing millets. However, there were no takers for millet cultivation, as there was a ready market and assured price for rice and turmeric that they were growing as opposed to millets.

That was when the block coordinator's advice to grow millets came back to her, and she decided to grow millets on the land she owned.

Intervention

Pratima became the first woman in her village to undertake millet cultivation. She received technical support from the CRP and block coordinator and learnt about SMI agronomic practices to cultivate finger millet. She also grew sorghum (*janha*) on a small patch using line sowing. Her first harvest was 3,500 kg of finger millet and 80 kg of sorghum. She received an incentive from the government and sold 300 kg of finger millet in the market at ₹31.50/kg and also earned ₹1,500 selling 50 kg of sorghum to the Raikia Farmers Producers Company Limited at ₹30/kg. She expanded the area under millet cultivation in the second year to 2 acres, and by the third year, she only grew millets, from which her profit exceeded ₹25,000.

Impact

Pratima is now happier and healthier, thanks to SAA. Inspired by her success, her neighbor Sibaram Digal followed in Pratima's footsteps. Besides growing finger millet, Pratima has spread awareness among women to start millet cultivation, roping in 12 women to grow it on 17 acres of land. Eager to learn new skills, the last two years have seen her attending several training programs organized at Raikia. Putting her learnings to use, she organized a recipe demonstration with the help of other women in her community.

"Together with other women, I always try to make millets available in each and every household so that people will consume it for their health," says Pratima Pradhan.

Conclusion

These case studies showcase the transformative power of women's involvement in agriculture and the promotion of millets in Odisha. From the establishment of bio-input units to the distribution of threshing machines, from innovative millet-based enterprises to dedicated millet trainers and cultivators, these women have demonstrated resilience, entrepreneurship and a commitment to healthier and more sustainable farming practices.

Their efforts have not only increased millet production and consumption but have also inspired others in their communities. These success stories underscore the importance of providing training, resources and support to empower women in agriculture. As these initiatives continue to grow and expand, they offer a promising path toward sustainable agriculture, improved nutrition and economic empowerment of women in Odisha and beyond.

Figure 10H. Pratima doing intercultural operations in her finger millet field.

Claim 11: Millets are good for farmers

Millets play a crucial role in agriculture, offering numerous advantages to farmers. They are adaptable to diverse climate conditions, require fewer inputs, and have the potential to increase yields. Additionally, millets are a sustainable alternative for farmers on marginal lands and help to reduce production costs. They also have multiple benefits, including carbon credit opportunities.

Rainfed crops are found in some concentration in Rajasthan and Odisha states and in parts of southern and northeastern India (Figure 11A). Farmers in these areas will benefit from millet cultivation. India is a prominent global millet producer with an impressive output of 17.9 million tonnes in the 2020-21 season, contributing 15% to the world's total millet production (ICAR 2023). Millet cultivation in India spans 21 states and covers approximately 12.5 million hectares.

Millets are significant food crops due to their adaptability. They thrive in diverse temperature ranges, varying moisture levels and conditions with minimal inputs (Wang et al. 2018; Sood et al. 2023; Regmi et al. 2023). They exhibit adaptability to various ecological conditions, low water requirement and high water-use efficiency. Millets are hardy crops that can thrive in dry and arid conditions, making them well-suited for regions with erratic rainfall. In contrast, rice and maize are typically grown in areas with ample water supply, while wheat is grown in areas with limited water resources and appropriate temperatures.Sorghum and millets are preferred in areas with scarce water resources and infertile and acidic soils (Saxena et al. 2018; Ramu et al. 2023). Millets have minimal

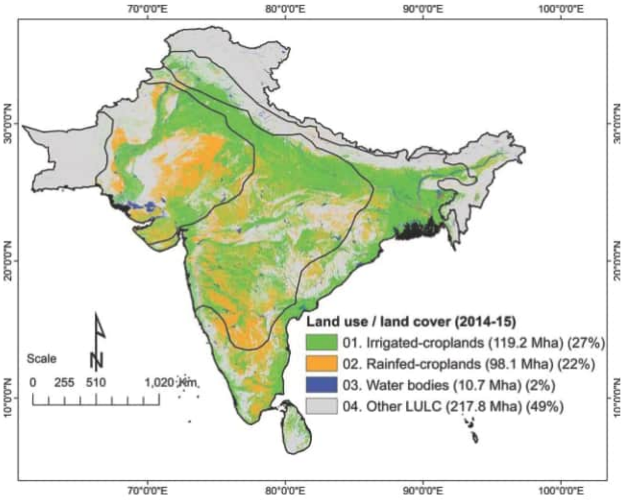

Figure 11A. The rainfed cropland map of South Asia (2014-15) based on Landsat 8 data on Google Earth Engine (GEE). (Gumma et al. 2022) carbon and energy footprints compared to other crops, which reduces environmental degradation and mitigates climate change (Dayakar Rao et al. 2021; Saxena et al. 2018; Jain et al. 2016). They are energy-efficient, consuming less energy for fertilization and irrigation (Dayakar Rao et al. 2021). Millets often have shorter growing seasons compared to other grains, which allows farmers to grow multiple crops in a year and increase agricultural productivity. They are more often grown as rainfed crops. Given their deep root systems, they improve soil health (structure and fertility) over time.

Millets are resistant to diseases and pests, reducing the need for synthetic fertilizer and pesticides (Kole et al. 2015). They require minimal inputs, less fertilizer and pesticides than mainstream cereals (Bandyopadhyay et al. 2017; Dayakar Rao et al. 2021). Intercropping and traditional farming practices help manage weeds and enhance growth (NRC 1996). Hand-weeding, intercropping and herbicides effectively restrict the growth of weeds in millet cultivation as its canopy covers the land. Millets also host rich microbiome communities in the rhizosphere, aiding their resilience in challenging climatic conditions (CIRAD 2023). Millet fodder is rich in minerals, which increases the quality of milk and meat through a chain process. Millet intercropping with legumes or groundnut helps to increase the quantity of fodder (NRC 1996).

Farmers can boost millet yields with improved practices such as micronutrient use and traditional practices without adding additional costs (Aune and Ousman 2011; Ruiz-Giralt et al. 2023). Also, the use of FYM/vermicompost rather than unabated use of urea and DAP (Goswami 2023) is a potential practice to increase yield. Untapped genetic material and genomic sequencing can accelerate breeding programs (Singh et al. 2023; Nagaraja et al. 2023). This could be extended to the use of the genomic sequence available for sorghum (Paterson et al. 2009), pearl millet (Varshney et al. 2017), finger millet (Hittalmani et al. 2017) and foxtail millet (Zhang et al. 2012) to identify QTLs or SNPs for traits of interest and achieve faster genetic gain. The short crop duration of some millets makes them suitable for crop rotation, which can benefit smallholder farmers (Dayakar Rao et al. 2021). Their resilience to extreme climates and effective photosynthesis process (C_4 character) positions them as climate-smart crops capable of playing a role in both adaptation and mitigation strategies for climate change (Davis et al. 2019; Still et al. 2003). Moreover, millets have not reached yield plateaus unlike other staple crops (FAO 2010; Fischer et al. 2014; Shiferaw et al. 2013).

Millets serve multiple purposes, including food, feed, fodder, biofuels, brewing and industrial uses, enhancing livelihood resilience and market opportunities (NRC 1996). They are rich in protein, fiber, vitamins and minerals (such as magnesium, niacin and calcium), promoting digestive health and bowel movement, supporting cardiovascular health and reducing the risk of diabetes. Millets are also rich in antioxidants, flavonoids, anthocyanins, saponins and lignans, which provide impressive health benefits. Millets are also used as livestock feed and can be converted into biofuels, such as ethanol (Gross 2020). Millets can enhance livelihood resilience and market opportunities for small farmers, including women, nationally and regionally. Millet agro-residues can be converted into usable energy through pyrolysis, offering a long-term, closed-loop remedy to the issues associated with waste management and energy recovery. Sorghum-based biogas plants offer energy and environmental advantages if they use co-generation technologies and utilize digestate as a biofertilizer (IEA 2022). Pearl millet is another suitable bioenergy crop due to its production costs, availability, conversion efficiency and compatibility with existing fuels. The use of biofuels made from renewable resources benefits the environment while enticing capital expenditure and fostering economic growth.

Millets minimize the use of chemicals, making farming safer for farmers (Rathore et al. 2021). They naturally resist pests and diseases, reducing reliance on chemical pesticide use, which is useful in regions with limited access to agrochemicals and also contributes to reduced energy need and carbon emissions (Ceasar and Maharajan 2022). Millets have in-built genetic resistance to several pests, which makes them less prone to insect pest damage compared to other cereals (Prasad and Babu 2016). The genetic resistance of millets to insect pests has been confirmed by studies, which found that insect feeding was affected by both genetic and environmental effects (Gahukar and Reddy 2019).

Millets can be integrated into crop rotation systems and help break pest cycles by interrupting their host plants and thereby reducing pesticide intervention. This approach aligns with sustainable and eco-friendly farming practices. Millets are well-suited for organic farming, emphasizing reduced chemical usage and natural pest management (FAO 2010). They support biodiversity in fields, reducing the need for chemical pesticides. Traditional knowledge and practices are used for managing pests without synthetic pesticides.

Millets offer carbon credit opportunities based on mitigation, providing revenue-generation options for governments and farmers (United Nations 2023). Carbon trading initiatives can help countries and organizations earn carbon credits by reducing their carbon footprint. Millets can assist developing countries like India in generating revenue from carbon trading. A single tweak in policy, such as broadening the ambit of minimum support price to include crops such as millets, is insufficient. Carbon credits could provide the much-needed transition financing to buttress farmers against risks and encourage them to move away from the unsustainable practices they are locked into. Millets' climate resilience and high carbon content in crop residues make them suitable for carbon trading. Governments, especially in developing countries like India, are increasingly focusing on millets and carbon trading as revenue-generation opportunities. The Indian government has committed to ensuring that communities benefit significantly from carbon credit projects, which means that a portion of the revenue generated from carbon credits will be directed toward local people.

Conclusion

In a world grappling with the challenges of climate change, food security, and sustainable agriculture, millets emerge as a valuable and resilient crop. The versatility of millets in different ecological conditions, their resilience to pests and diseases, and their low input, water and energy requirements position them as climate-smart crops capable of being part of both adaptation and mitigation strategies for climate change. Their short crop durations make them suitable for crop rotation with low investment, thus benefiting smallholder farmers. Furthermore, the nutritional value of millets promotes better health and can provide livelihood opportunities for farmers, particularly women. Millets also align with sustainable and eco-friendly farming practices, reducing the need for chemical pesticides and supporting biodiversity in fields. The carbon content in their crop residues opens up avenues for carbon trading, offering revenue-generation opportunities for governments and farmers, especially in developing countries. Encouraging their cultivation and utilization can have positive impacts on agriculture, the environment, and the well-being of farming communities. Policymakers, researchers and stakeholders should continue to explore and promote the potential of millets in building a more sustainable and resilient agricultural future.

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Claim 12: Millets can bring diversity to staple foods

In the search for nutrition security and sustainable agriculture, it is necessary to turn our attention to a valuable resource often overlooked: Neglected and underutilized crops (NUCs). The theme of millets as NUCs is gaining attention in recent years. Millets are considered "nutricereals" due to their high nutritional content and have served as a traditional staple for hundreds of millions of people in Sub-Saharan Africa and Asia for 7,000 years. However, their cultivation is declining in many countries, and their potential to address climate change and food security is not being realized in full. These resilient crops possess ample nutrient content and climate adaptability, rendering them pivotal components of a diversified agricultural landscape (Ali and Bhattacharjee 2023).

The World Business Council for Sustainable Development (WBCSD) advocates for an all-encompassing approach to diversifying staple crops. This multifaceted strategy blends consumption, transformation, trade and production mechanisms to ensure the long- term resilience and economic viability of staples while promoting better nutrition (WBCSD 2021). In parallel, the Smart Food Executive Council, formed by leading agricultural associations in Africa and Asia, strives to diversify staples, aligning with the Sustainable Development Goals (SDGs) to make a substantial impact.

Within this strategy, millets and sorghum emerge as nutritional powerhouses with the potential to enhance nutrition security and sustainability. These crops offer essential nutrients like iron, zinc, and calcium, which are often lacking in mainstream cereals (Kane-Potaka 2018). Their resilience shines as they withstand drought, heat and water scarcity, setting them apart from other cereal crops. Millets, with their shorter growth cycles, reliably yield even in challenging conditions. Packed with nutrients, low in fat, and rich in protein, fiber, B vitamins and micronutrients, millets and sorghum hold the key to climate change mitigation, improved nutrition, and advancements in industrial agriculture. However, the integration of millets alongside traditional staples like wheat and rice presents hurdles that are deeply rooted in dietary preferences, limited consumer awareness, taste misconceptions and relatively higher price points compared to other cereals.

Diversifying staples takes various forms, including crop diversification—a valuable strategy for risk reduction, enhanced productivity and ecological system sustainability (Barman et al. 2022). Practical diversification encompasses crop rotation, multiple cropping and intercropping (NSAC 2023).

The WBCSD's comprehensive approach intertwines consumption, transformation, trade and production mechanisms to ensure the resilience and economic viability of staples, all while promoting improved nutrition (WBCSD 2021). Biofortification, an essential practice involving the development of micronutrient-dense staple crops through traditional and modern techniques, elevates the nutritional content of staples (Bouis 1996).

Efforts to diversify staples span the globe, often focusing on one or two foods at a time. A global movement promoting millets, including sorghum, as staples is gaining momentum (FAO 2023). A holistic approach is essential, engaging all stakeholders from farm to fork, including governments, researchers, and development agencies, to invest in and support the development of value chains and markets (WBCSD 2021). A critical but often overlooked approach is driving demand, the foundational step for supply efforts to bear fruit (FAO 2023). Engaging major players in staple agribusiness is vital to foster support rather than competition against diversification (FAO 2023). Supporting food entrepreneurs, often the pioneers of change, contributes to innovation in new industries. (FAO 2023). India stands as a prime example, witnessing a surge in small and medium-sized enterprises (SMEs) and startups focused on millet products (NABARD 2023).

India stands as a prime example, witnessing a surge in small and medium-sized enterprises (SMEs) and startups focused on millet products (NABARD 2023).

Diverse staples hold significance on several fronts—ensuring nutritional adequacy, bolstering food security, fortifying resilience to environmental shifts, enriching culinary and cultural diversity and promoting sustainable agriculture. Consumption of a variety of staple foods guarantees access to a broad spectrum of essential nutrients, including carbohydrates, proteins, vitamins and minerals (Yari et al. 2022). Over-reliance on a single staple renders populations vulnerable to crop failures and price fluctuations, emphasizing the importance of diversification for enhanced food security (Grote et al. 2021). Different staple crops exhibit varying resilience to environmental conditions, enabling communities to adapt to changing climates and environmental challenges (Van Helden 2011; Pappo et al. 2023). Diverse staples contribute to culinary variety and cultural richness, finding expression in various traditional dishes and cooking methods (Yari et al. 2022). Moreover, promoting a diversity of staple crops fosters sustainable agriculture by reducing the risks associated with monoculture practices, which can deplete soil nutrients and increase susceptibility to pests and diseases (Yari et al. 2022; Waha et al. 2022).

Conclusion

The pursuit of nutrition security and sustainable agriculture calls for a re-evaluation of NUCs as valuable resources. These resilient crops offer essential nutrients and climate adaptability, making them crucial components of a diversified agricultural landscape. Efforts to diversify staples through NUCs should encompass a multifaceted approach that aligns with SDGs and promotes better nutrition. However, challenges such as dietary preferences, consumer awareness, taste perceptions and pricing disparities must be addressed to integrate these crops alongside traditional staples like wheat and rice successfully. Strategies such as crop diversification, biofortification and global advocacy are keys to harnessing the potential of NUCs. By promoting diverse staples, we enhance nutrition, food security, environmental resilience, cultural diversity and sustainable agriculture, laying the foundation for a more robust and sustainable future. Governments, researchers, development agencies and food entrepreneurs play vital roles in supporting the development of value chains, markets, and demand for diverse staples.

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Claim 13: How millets are good for the environment

Summary

Climate change is a pressing global concern and challenge. The past few decades indicate that significant changes in the global climate were the result of enhanced human activities that altered the composition of the global atmosphere (IPCC 2007). The concentration of greenhouse gases (GHGs) such as methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O) has increased by 150%, 40% and 20%, respectively since 1750 (IPCC 2014). The emission of CO_2 from the combustion of fossil fuels and non-CO_2 GHGs such as nitrous oxide, methane and chlorofluorocarbons (CFCs) add to global warming.

The agriculture sector is most vulnerable to climate change owing to its huge scale and sensitivity to weather parameters, with huge economic impacts (Mendelsohn 2009). Changes in temperature and rainfall significantly affect crop yield. Agricultural practices too adversely impact climate change.

Millets possess numerous climate-resilient features including adaptation to ecological and environmental conditions such as water and heat stress, and insect/pest tolerance to a certain extent. Owing to their unique suite of properties, they can grow under nutrient limited conditions with minimal inputs, offering a sustainable and economical option to meet growing global food demand (Figure 13A).

Scientific evidence

The cultivation of millets, C_4 crops, gained traction after the Green Revolution as they can convert more CO_2 into oxygen with a lower carbon footprint. Among millets, proso millet has been shown to have higher efficiency of C_4 photosynthesis (Goron and Raizada 2015), low transpiration ratio, and it can efficiently fix carbon even under climate adversities (drought, high temperatures and limited nitrogen and CO_2) (Habiyaremye et al. 2017). Interestingly, millets are less vulnerable to pests, minimizing the need for intensive pesticide use, thereby contributing to reduced energy and carbon emissions (Ceasar and Maharajan 2022). Similarly, broomcorn millet (also known as proso millet) demonstrated the potential to fix carbon despite its physiological behavior under elevated CO_2 conditions in a longitudinal 3-year experiment conducted by Shi et al. (2022).

Millets have the potential to contribute to food security in the context of climate change, as they are well adapted to dry and marginal environments. They require less water, pesticide (Ceasar and Maharajan 2022) and fertilizer compared to other major cereals (Wang et al. 2018), and can grow on soils with low fertility (Saxena et al. 2018). Since millets are rainfed crops and do not require standing water in the field, there is no need for big dams or for forests to go under reservoirs or elaborate canal systems to bring water to farms. Millets do not need fertility enhancement or pesticides to grow well and yield a good harvest (Wang et al. 2018). A study on the growth and production of sorghum and millets in marginal environments highlighted their potential for stress mitigation and increased productivity (Saxena et al. 2018).

Millets are considered environmentally safe as most of them are resistant to pests. Pest management is achieved with minimal use of pesticides, and the pests do not cause economic losses, unlike in major cereals like rice, wheat and maize. Multiple traditional technologies serve as viable options for pest and disease management, obviating the need to use synthetic pesticides. Studies on gene expression analysis revealed that sorghum exhibited a more robust defense response against greenbugs, activating pathogenesis-related genes, jasmonic acid pathways and flavonoid biosynthesis (Puri et al. 2023). Research in India has highlighted sorghum's inhibitory effects on insect pests and its physical characteristics that reduce susceptibility to mold damage (Chandrashekar and Satyanarayana 2006). Additionally, Navinkumar et al. (2020) identified mutant sorghum lines resistant to shoot fly, offering genetic resources for breeding pest-resistant sorghum varieties. In Pakistan, researchers explored wild relatives of pearl millet as a source of disease resistance and other valuable traits, identifying potential resistance to greenbugs (Akhtar et al. 2012) and clearly demonstrating minimum or no requirement of pesticides in millet cultivation.

A study assessing climate change impacts on pearl millet in arid and semi-arid environments using the CSM-CERES-Millet model found that the crop is climate-smart, with inherent genetic potential for stress tolerance and yield improvement (Numan et al. 2021). Finger millet has been recognized for its genetic potential as a climate-smart crop and its ability to tolerate drought and heat stresses (Numan et al. 2021). There is limited research on foxtail millet, but as a type of millet, it is expected to share similar characteristics and potential for productivity in marginal environments. Small millets can grow under adverse climatic and soil conditions, making them suitable for marginal environments and climate change mitigation (Saxena et al. 2018). Barnyard millet is a climate-resilient crop that can be grown in marginal environments and has the potential to contribute to increased productivity in such areas.

Fine cereals such as rice and wheat require more agricultural inputs and emit more GHGs compared to coarse millets (sorghum, pearl millet and finger millet) (Rao et al. 2019). Millets have a considerably lower carbon dioxide equivalent per hectare (3,218 kg) compared to cereals (3,968 kg for rice and 3,401 kg for wheat) (Tiwari et al. 2022). Global warming potential carbon dioxide equivalent per hectare of rice (2,890-17,000 kg) and wheat

(2,000-18,000 kg) are also reported to be higher compared to that in millets (3,218 kg) and sorghum (3,358 kg) (Jain et al. 2016; Wang et al. 2018; Dayakar Rao et al. 2021).

Millets have deep root systems compared to fine cereals; the root to shoot ratios of sorghum, millet, wheat and barley are 5:9, 2:8, 7:4 and 6:3, respectively (Gelaw et al. 2014). A meta-analysis comparing cereals (wheat, maize, rice) with millets reveals the notable competitive edge the latter have due to their deep root system, which reduces the need for external supplementation of nitrogen, phosphorus and other nutrients, leading to lower fertilizer usage and enhanced sustainability. In a nutshell, millets make an ideal case for feed-to-biomass conversion; more can be obtained from less leading to reduced GHG emissions, making them a suitable choice for future agrifood ecosystems (Wang et al. 2018).

Exploring the potential of carbon sequestration in pearl millet, sorghum, little millet, finger millet and foxtail millet at three different growth stages, Vidhya and Pragasan (2022) reported finger millet to have higher phytolith occluded carbon (phytOC) content than other millets. The phytOC available in finger millet contributes to long-term terrestrial carbon sequestration when released into the soil after the crop is harvested and the soil is mulched in preparation for the next cropping cycle. Practices such as managing soil nutrients and regularly adding silicon fertilizers to agricultural lands can improve phytolith production, increase phytOC accumulation to contribute to terrestrial carbon sequestration and assist in mitigating climate change.

Intercropping between wheat and millet has been shown to lower carbon emissions in small land management units (LMU) than large and medium LMU. Sustainable practices have been shown to play an important role in conserving resources and decreasing the ecological footprint (Kumar et al. 2022). Kumar et al. (2021) reported that in intercropping, the carbon sustainability index (10.3) and carbon efficiency (11.3) give good results in millet-based systems due to the lower carbon input compared to other cereals. This process is very effective in farm management of millets.

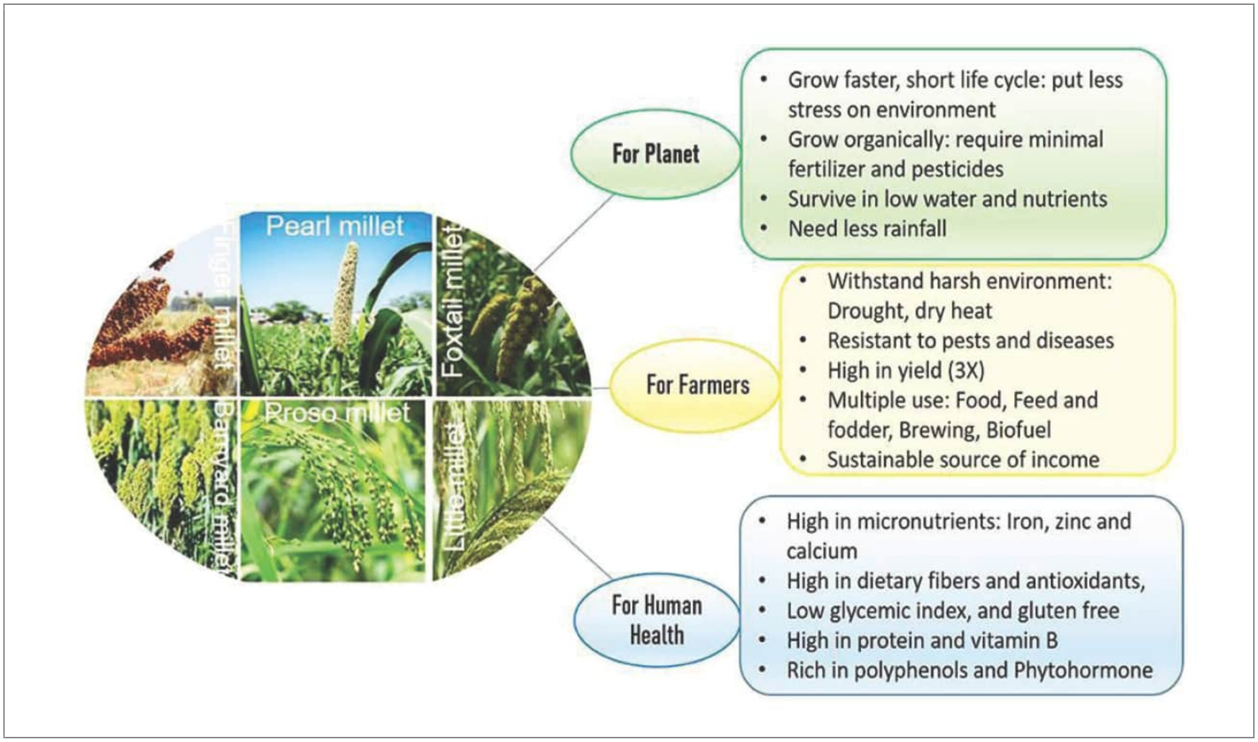
A comparative study of energy use patterns in millet cultivation in India and Nigeria revealed that the input of energy in Nigeria (3,283 MJ/ha) was almost two-fold lower than in India (7,000 MJ/ha). However, the energy output was similar in Nigeria (69,269 MJ/ha) and India (69,269 MJ/ha).

A pilot study in India showed that the lowest input of energy and highest yielding output was observed in small, medium and large farmers with pearl millet, with Indirect energy exceeding direct energy in the form of fertilizer (urea) (Kargwal et al. 2023).

Millets are the most drought-tolerant cereals and are known to provide more grain per unit of water than other cereals (Dwivedi et al. 2012), making them ideal crops to grow to save water resources and to adapt to decreasing rainfall and increasing temperatures. Foxtail millet requires 257 g of water to produce 1 g of dry biomass, whereas maize and wheat require 470 g and 510 g, respectively (Li and Brutnell 2011). Pearl millet can grow in areas with limited annual rainfall (300-500 mm) where crops such as maize and sorghum are very likely to fail in most years (Vadez et al. 2012).

Millets on an average require 300-400 mm of water whereas rice requires about four times that amount (1,250 mm). This is particularly important across Asia and Africa where a major part of agriculture is rainfed. In India, about 50% of cultivated land is rainfed (Department of Agriculture & Farmers Welfare, n.d.) and about 95% of African agriculture is rainfed (Abrams 2018).

Millets, including sorghum, pearl millet and finger millet hold immense promise in bolstering agricultural productivity in marginal environments, while also serving as a strategic tool in the battle against climate change (Figure 13A). It is mainly cultivated on marginal lands under rainfed conditions and can sustain and produce a significant amount of grain even in drought-prone areas that receive an average annual precipitation of <250 mm (Sanjana Reddy et al. 2021). Millets can be stored for long periods without spoiling. Their seeds can be stored for years, providing a reliable source of food even in times of scarcity. Sorghum and pearl millet are also regarded as climate-smart crops because of their extreme tolerance to heat (up to 42°C air temperature), drought and salinity (Chaturvedi et al. 2022).



For Planet

- Grow faster, short life cycle: put less stress on environment
- Grow organically: require minimal fertilizer and pesticides
- Survive in low water and nutrients
- Need less rainfall

For Farmers

- Withstand harsh environment: Drought, dry heat
- Resistant to pests and diseases
- High in yield (3X)
- Multiple use: Food, Feed and fodder, Brewing, Biofuel
- Sustainable source of income

For Human Health

- High in micronutrients: Iron, zinc and calcium
- High in dietary fibers and antioxidants,
- Low glycemic index, and gluten free
- High in protein and vitamin B
- Rich in polyphenols and Phytohormone

Figure 13A. How millets can benefit the planet, farmers and human health. (Babele et al. 2022)

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SECTION C

Market potential of millets

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Kane-Potaka, J., and Upadhyay, S. 2025. Market Potential of Millets. In: Padhee, A.K., Chaudhury, P.C., Khetarpal, R., Balam, D., and Kane-Potaka, J. (eds). Millet Foundation Guide: Scientific Evidence & Research Priorities. revised edn, Bhubaneswar, India: Department of Agriculture & Farmers' Empowerment, Government of Odisha.

Important note about data sources: All data for the following analysis on millet market size and growth was sourced from standard industry market research companies. Most of the estimates and projections seem very high, with some contradictions as well. It is recommended, therefore, to take into account the overall trend rather than the exact forecast. No primary data was collected for this analysis and the market research companies do not list the sources or methods for collating the data.

Markets for millet products are predicted to rise. Also, millets fit into many food product categories that are undergoing significant growth globally. This can be leveraged by positioning and promoting millet products in these categories.

However, market data collection for millets requires more rigor. It is highly recommended that a standard method is developed, and millet industry data is collected across countries and monitored. This will be valuable for industry, investors, researchers and governments to plan for and support the industry.

Claim 1: The gluten-free market is growing, and millets can leverage this

Medical issues concerning gluten

Incidence of gluten-related disorders is on the rise, with an estimated global prevalence of 5% (Bascuñán et al. 2018). Celiac disease impacts approximately 40-60 million individuals worldwide, and there are even larger numbers who remain undiagnosed (Lohi et al. 2007). This prevalence demands products that are gluten-free.

Gluten-free and related advantages of millets

As millets are completely gluten-free, they are becoming popular in this food category. Millets are also known for their better digestibility without producing any allergenic reaction in the body (Anitha et al. 2023).

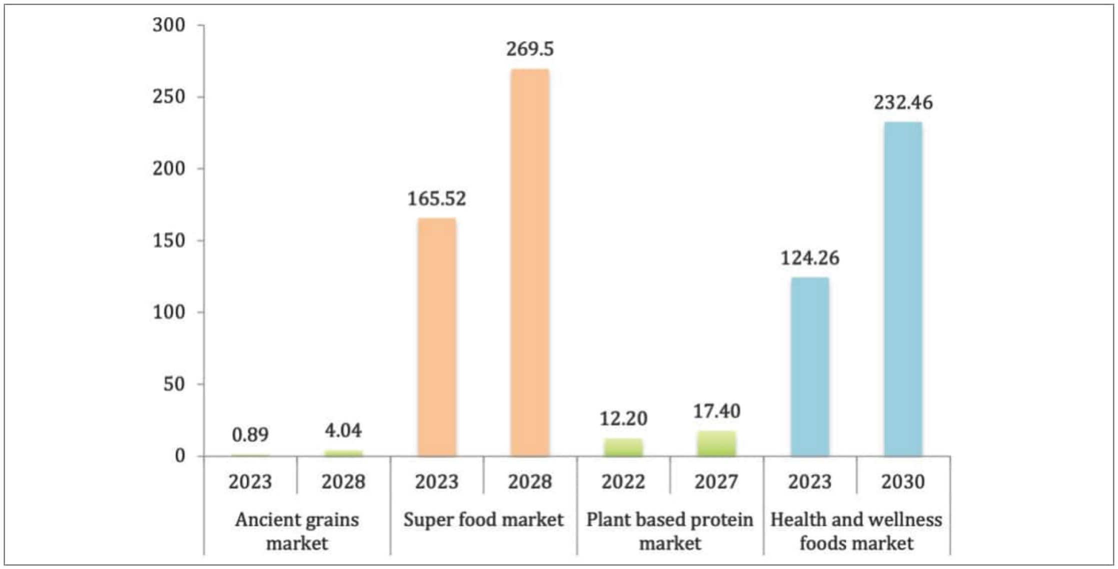
Gluten-free food market

The size of the global gluten-free food market was estimated at USD 5.72 billion in 2021, which is projected to reach USD 9.99 billion by 2028 with a compounded annual growth rate (CAGR) of 8.29% (Fortune Business Insights 2022).

Claim 2: The global market for ancient grains, superfoods, health and wellness foods, and plant-based protein is poised for significant growth; millets can tap these opportunities

The growing trend of health and wellness is anticipated to stimulate the global market for ancient grains, superfoods, plant-based protein and other health and wellness foods (Market Data Forecast 2023). The rising trajectory of these markets (Figure 2A) indicates growth opportunities for millets to meet the demand for healthier food alternatives.

- The global ancient grains market is estimated at USD 0.89 billion as of 2023 and is expected to grow to USD 4.04 billion by 2028 at a CAGR of 35.2% (Market Data Forecast 2023).
- The superfoods market size is expected to grow from USD 165.52 billion in 2023 to USD 269.50 billion by 2028 at a CAGR of 10.24% (Mordor Intelligence 2023).
- In terms of revenues, the global plant-based protein market was estimated to be worth USD 12.2 billion in 2022, and is poised to reach USD 17.4 billion by 2027, growing at a CAGR of 7.3% (Markets and Markets 2022).
- The market for global health and wellness foods, estimated at USD 124.26 billion in 2023, is projected to nearly double to USD 232.46 billion by 2030 (Research and Markets 2023a).



Sources: Market Data Forecast (2023), Mordor Intelligence (2023), Markets and Markets (2022), Research and Markets (2023a).

Figure 2A. The global market (USD billion) for ancient grains, superfoods, health and wellness foods, and plant-based protein based on reports from four different market research sources.

Claim 3: The global millets market is forecast to expand

Global forecasts

The millet market has been growing in recent years and is forecast to continue to grow. However, forecasts by different market research organizations vary widely; they range from USD 6.2-12.5 billion in 2022 or 2023 to USD 9.5-44.1 billion between 2028 and 2032 (Figure 3A). Forecasts of the CAGR expected during this time also have a very wide range, from 2.8% to 13.4%. The forecasts are as follows:

- The global millet market, according to DataM Intelligence (2023), was reported to be USD 6.2 billion in 2022 and projected to reach USD 9.5 billion by 2030. It is expected to grow at a CAGR of 5.5% during the period 2023-2030.
- As per a report by Market Research.Biz (2023), the millet market size is expected to grow from USD 8.4 billion in 2022 to around USD 10.9 billion by 2032, at a CAGR of 2.8%.
- A report by Research and Markets (2023b) expects the millet market to grow from USD 11.02 billion in 2023 to USD 13.80 billion by 2028, at a CAGR of 4.60%.
- Future Market Insights (2023) gave the millet market a valuation of USD 12.5 billion in 2023 and expects it to reach USD 44.1 billion by 2033, at a CAGR of 13.4%.

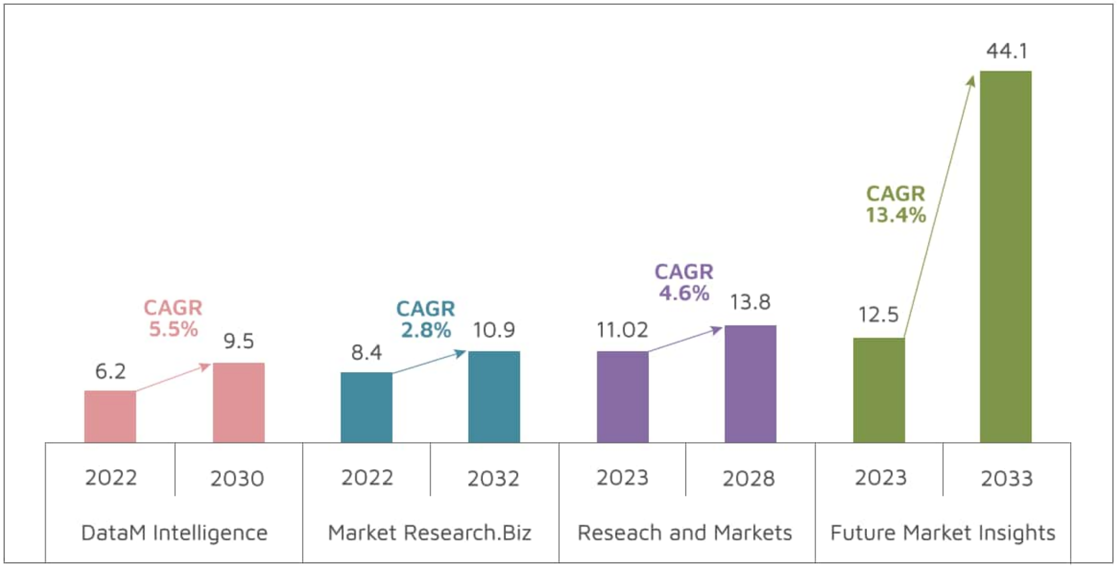


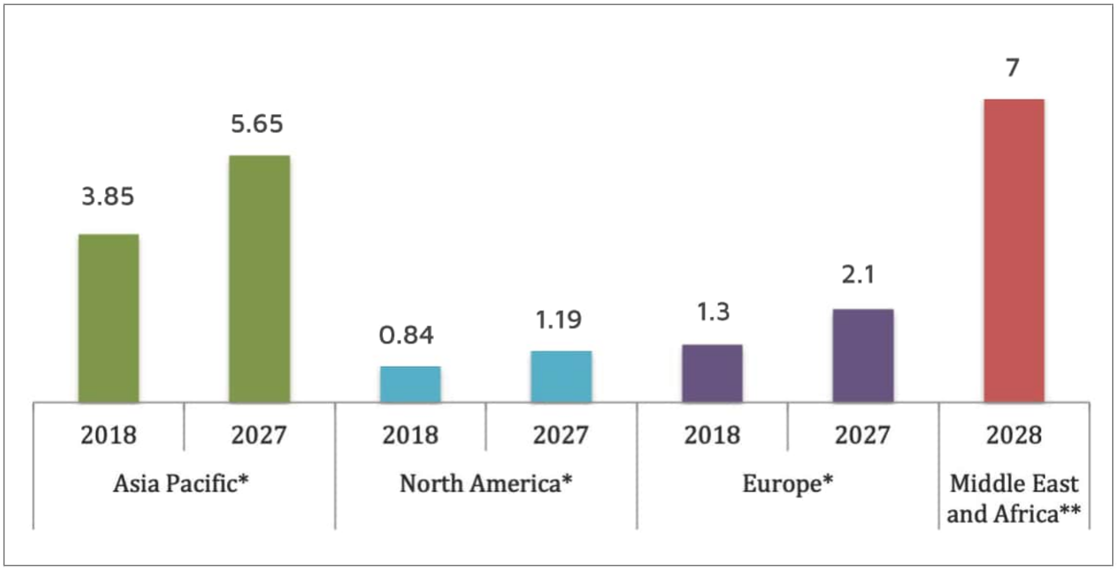
Figure 3A. Forecasts by different research organizations on global millet market growth (USD billion).

Millet market growth by region

Business Market Insights (2020a; 2020b; 2020c) forecast a significant expansion of the millet market in all regions of the globe. The Asia-Pacific region is emerging as a hotspot of millet activity with a 40.9% market share followed by the Middle East (32%) and Europe (14.1%). According to these reports

- The Asia-Pacific millet market, valued at USD 3.85 billion in 2018, is expected to grow at a CAGR of 4.4% during 2019-2027 to reach USD 5.65 billion;
- The North American millet market, valued at USD 0.84 billion in 2018, is expected to grow at 4% CAGR during 2019-2027 to reach USD 1.19 billion; and
- The European market (USD 1.32 billion in 2018) is expected to grow at a 5.4% CAGR to reach USD 2.13 billion by 2017.

According to Bonafide Research (2023), the Middle East and Africa millet market is expected to cross USD 7 billion by 2028. See comparison data in Figure 3B.



* Estimates by Business Market Insights (2020a; 2020b; 2020c).
** Estimate by Bonafide Research (2023).

Figure 3B. Forecasts on regional millet market growth (USD billion).

Claim 4: Demand for a range of millet products can propel the millet market to new levels

Global millet market by product category

With the increasing popularity of millets, there has been a diversification of millet products in the market. As per the UN Comtrade Database on world trade, as cited in NABARD (2023), a review of the global millet market by product category (Figure 4A) shows that breakfast foods have the largest market share (32.1%) followed by bakery products and beverages (16.9% each), fodder (14%), infant food (11.1%) and other (9%).

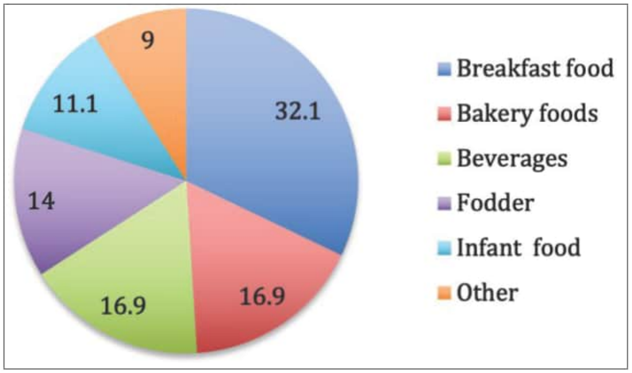


Figure 4A. Global millet market segments (%) based on application. (*Source:* UN Comtrade Database (2020), as cited in NABARD 2023).

Millet-based packaged food market: The millet-based packaged food market has grown substantially over the past 10 years. It is expected to grow at a CAGR of 5.5% from 2021 to 2026, reaching a market size of USD 2.5 billion by 2026 (NPCS 2023).

Millet-based snacks market: Snacks manufacturing companies are integrating millets into a variety of snacks that make it easier for consumers, especially new consumers, to eat millets. This has increased the market size of millets. The global millet snacks market was valued at USD 2.4 billion in 2021 and is projected to grow to USD 3.7 billion by 2031, growing at a CAGR of 4.9% (Allied Market Research 2022a).

The Asia-Pacific region was the highest revenue contributor in the millet-based snacks market, accounting for USD 1.04 billion in 2021, which is projected to rise to USD 1.53 billion by 2031 (Allied Market Research 2022b). In 2021, this region accounted for more than two-fifths of the overall millet snacks market, and is expected to maintain its dominance through the forecast period, growing at a CAGR of 4%.

However, the North American market is likely to grow the fastest (CAGR 6.8%) from 2022 to 2031 (Allied Market Research 2022c).

Millet-based extruded products: Various millet-based extruded snack foods like pasta, noodles, flakes, and chips are now available in the market and are showing excellent growth potential, contributing USD 1.99 billion to the market in 2021. This is estimated to grow to USD 3.13 billion by 2031 at a CAGR of 4.8% (Allied Market Research 2022a).

Millet flour markets

Millet flours are becoming increasingly popular as a gluten-free alternative to wheat flour. Millet flour is used in a variety of bakery and confectionery goods to make gluten-free cakes, cookies, biscuits, and other bakery items (Allied Market Research 2022d).

This trend is supported by a report by Data Bridge Market Research (2022), which projects the millet flour market to grow from USD 4.62 billion in 2021 to USD 7.25 billion by 2029 at a CAGR of 5.80%. This presents strong growth and market expansion opportunities for millets (Figure 4B).

Figure 4B. Growth projections (USD billion) of the gluten-free and millet flour markets based on reports by Fortune Business Insights* (2022) and Data Bridge Market Research** (2022).

Claim 5: Rising trend across generations will give a thrust to the millets market

Millennials (25-40 years age group) accounted for nearly half of the global millet snacks market in 2021, contributing USD 1.08 billion in 2021. This demographic class is expected to continue to be important for the millet market, with sales estimated to reach USD 1.58 billion by 2031 (Allied Market Research 2022a).

People in the 41-56 age group, called Generation X, are significant contributors to the millet market with sales to them estimated to reach USD 8.68 billion by 2031. Growth in this demographic class is being propelled by an increase in health and fitness concerns (Allied Market Research 2022e).

While the Millennial and Generation X markets are projected to grow at a CAGR of 4% and 5.2%, respectively during the period 2022-31, (Figure 5A), sales to the 57-75 years age group (Baby Boomers) are projected to grow faster, with a CAGR of 6.4% (Allied Market Research 2022c).

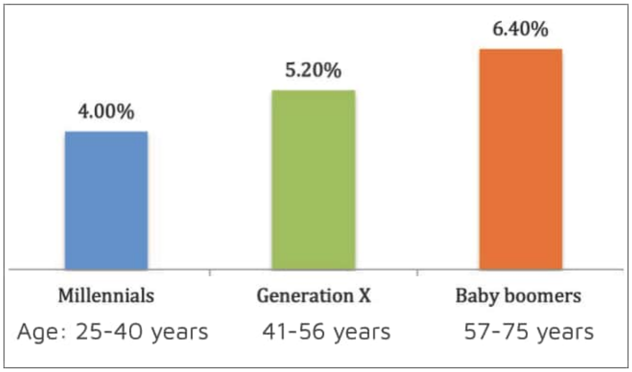


Figure 5A. Projected growth rates (CAGR) of the millet snacks market catering to different demographic groups for the period 2022-2031.
(Allied Market Research 2022a; 2022e; 2022c)

Claim 6: A number of viable online and offline distribution channels are emerging that can be harnessed to expand the millets market

Offline revenue channels accounted for three-fourths of the global millet snacks market in 2021. This dominance is expected to continue and grow at a CAGR of 4.6% through 2031 due to the wide availability of millet products (Allied Market Research 2022a).

However, the online retail segment of the market is expected to grow at a faster rate (CAGR 5.7%) during this period due to the increasing popularity of e-commerce platforms and the convenience of online shopping. The drivers of this rapid growth are availability of millet food products in online stores, doorstep delivery, convenient shopping facilities, and hassle-free payment gateways (Allied Market Research 2022c).

In the offline segment of the market, specialty stores are a significant contributor with sales estimated to reach USD 565.4 million by 2031, at a CAGR of 6.1% (Allied Market Research 2022e).

However, Research Dive Analysis (2021) has a different projection for specialty stores, noting that they will have a dominant share of the global market as well as fastest growth, reaching USD 15.05 million by 2028 from USD 8.16 million in 2020.

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