Household-Level Production and Consumption of Biofortified Iron Pearl Millet in India

Analysis and Implications for Nutrition-Sensitive Agriculture

Main Report

HarvestPlus

SVT COLLEGE OF HOME SCIENCE (Empowered Autonomous Status)

SNDT WOMEN'S UNIVERSITY Estb:1916

CONTRIBUTORS

Richard Alioma, Bho Mudyahoto, Ramesh Chitii Venkata, Jagmeet Madan, PhD, Shobha Udipi, PhD, Anuradha Ramesh, MD, Sunil Rao, Anil Udawat, Varsha Thakkar, Sharvari Desai, MD, Apurva Halbe, MD, Girija Damle, Shazia Mohammed, Siddesh Dholam, Pranali Pangerkar, Vaishnavi Damohe, Aashi Mehta, Chetna Desai, and Arvind Yenamadi

CONTENTS

Contributors i
List of Tables ii
List of Acronyms iii
List of Figures iii
Executive Summary 1
1. Introduction 2
1.1 Delivery of Iron Pearl Millet in India 3
1.2 Rationale 3
1.3 Overall Objective 4
1.3.1 Specific Objectives 4
2.0 Research Design and Methods 4
2.1 Study Context and Site Selection 5
2.2 Sampling Framework and Data Collection 5
2.2.1 Household Survey: Sampling and Implementation 5
2.2.3 Qualitative Component 5
2.2.4 Bio-physical Sampling 6
2.3 Ethical Protocols 6
2.4 Analytical Strategy 6
3. Results 7
3.1 Household Demographic Profile 7
3.2 Awareness of IPM and its products by value chain actors 8
3.3 Adoption of Pearl Millet and Iron Pearl Millet 8
3.4 Trends in Iron Pearl Millet Adoption Over Time 9
3.5 Input Use in Pearl Millet Production 9
3.5.1 Fertilizer Use Among Pearl Millet Farmers 10
3.6 Sources of Pearl Millet Seed 10
3.7 Land Allocation to Pearl Millet and Iron Pearl Millet 11
3.8 Production of Pearl Millet and Iron Pearl Millet in 2023 12

3.9 Utilization of Iron Pearl Millet Harvest 13
3.10 Allocation of Iron Pearl Millet Harvest........ 13
3.11 Market Channels for Pearl Millet Sales........ 14
3.12 Farm Level Revenue from Pearl Millet and Iron Pearl Millet........ 15
3.13 Farmer Access to Institutional Support Services 15
3.14 Farmer Perceptions of IPM Traits........ 16
3.15 Households Experiencing Food Insecurity........ 17
3.16 Consumption of Pearl Millet and Iron Pearl Millet........ 17
3.17 Sources of Iron Pearl Millet Consumed in the Household........ 18
3.18 Primary Forms in which Pearl Millet is Consumed 18
3.19 Consumption Frequency of Pearl Millet and Iron Pearl Millet........ 19
3.20 Per Capita Consumption of Iron and Zinc from Pearl Millet 20
3.21 Nutritional Contribution of Pearl Millet to Dietary Intake........ 20
3.22 Barriers and Drivers of Iron Pearl Millet Consumption 21
3.23 Micronutrient Analysis of Soil and Pearl Millet Grain 23
3.24 Mineral Content of Grain Across the Value Chain 23
3.25 Comparison of micronutrient content in IPM and Conventional Varieties 24
3.26 Association Between Soil and Grain Micronutrient Content........ 25
4. Conclusion........ 26
5. References........ 28

LIST OF TABLES

Table 1: Household Characteristics by State........ 7
Table 2: Proportion of VCA that are aware of Awareness IPM and its products 8
Table 3: Proportion of Farmers Growing Pearl Millet and Iron Pearl Millet (IPM), 2023........ 8
Table 4: Use Input Among Pearl Millet-Growing Households........ 10
Table 5: Fertilizer Use Among Pearl Millet-Growing Households (%) 10
Table 6: Sources of Pearl Millet Seed Used by Farmers in 2023 (%)........ 11
Table 7: Land Allocation to Pearl Millet and Iron Pearl Millet, 2023........ 12
Table 8: Pearl Millet and Iron Pearl Millet Production, 2023 12
Table 9: Proportion of Harvested Iron Pearl Millet Allocated to Various Uses 13
Table 10: Proportion of IPM farmers allocating harvested IPM to various uses (%) 14
Table 11: Proportion of Farmers Selling Pearl Millet by Buyer Type (%)........ 14
Table 12: Average Household Revenue from PM and IPM Sales (Indian Rupees ₹) 15
Table 13: Proportion of Pearl Millet Farmers with Access to Institutional Support 16

Table 14: Farmer Ratings of IPM Traits Relative to Preferred Variety (% of Respondents) 16
Table 15: Percentage of Households Experiencing Food Insecurity.. 17
Table 16: Proportion (%) of Households Reporting Consumption of PM and IPM, by Recall Period.................18
Table 17: Sources of Iron Pearl Millet Consumed at Home (% of Consuming Households)..............................18
Table 18: Percentage of respondents who consumed PM/IPM foods, by type 19
Table 19: Estimated Household-Level Daily Intake of Iron and Zinc from Pearl Millet Sources 19
Table 20: Average Number of Days Pearl Millet was Consumed in the Last 7 and 30 Days 20
Table 21 Percentage Contribution of Pearl Millet to Household Dietary Iron and Zinc Intake 21
Table 22: Key Barriers to IPM Consumption from Qualitative Analysis 22
Table 23: Mean Mineral Content in Soil and Pearl Millet Grain by State...23
Table 24: Mean Iron and Zinc Content in Pearl Millet Grain Samples by Value Chain Actor 24
Table 25: Mean Iron and Zinc Content by Pearl Millet Variety Type 24
Table 26: Regression Models for Association Between Soil Available Iron and Grain Iron Content 25

LIST OF FIGURES

Figure 1: Proportion of Pearl Millet Farmers Growing Iron Pearl Millet (IPM), 2013–2023..................................8
Figure 2: Location of Study Villages/Urban Blocks 31

LIST OF ACRONYMS

FPO .... Farmer-Producer Organization
FGD .... Focus Group Discussion
ICMR .... Indian Council of Medical Research
ICAR .... Indian Council of Agricultural Research
ICRISAT .... International Crops Research Institute for the Semi-Arid Tropics
IPM .... Iron Pearl Millet
KII .... Key Informant Interview
MSSC .... Maharashtra State Seed Company
OPV .... Open Pollinated Variety
PM .... Pearl Millet

Executive Summary

This study investigated the adoption, production, distribution, and consumption of iron pearl millet (IPM) in Rajasthan and Maharashtra, states of India. Data was collected between March and April 2024 from key stakeholders across the pearl millet value chain, including 3,342 farming households, 315 *Mandi* traders, 73 processors, and 277 retailers. We used mixed methods consisting of structured questionnaires for collecting quantitative data. Qualitative data were collected through focus group discussions and Key Informant interviews to explore adoption drivers and barriers, and consumption behaviors. Additionally, grain and soil samples were collected from respondent farmers' grain reserves and fields, respectively, and analyzed for iron and zinc content.

Key findings: Up to 64% of the households surveyed had cultivated pearl millet varieties in 2023, with significant ($p<0.001$) inter-state variation — 80% of households in Rajasthan grew pearl millet (all varieties), and only 50% did so in Maharashtra. "In Maharashtra, 18% of pearl millet farmers reported cultivating iron pearl millet (IPM) in 2023, compared to only 1% in Rajasthan during the same season. Across both states, households allocated an average of 6% of their pearl millet area to IPM, equivalent to 0.45 hectares per household. However, the share of pearl millet area planted to IPM differed significantly ($p < 0.001$) between the 2 states: farmers in Maharashtra devoted 12% of their pearl millet area to IPM, whereas those in Rajasthan allocated just 0.2% of their pearl millet area to IPM. It is worth noting that Maharashtra's total pearl millet area is only about one-third of that of Rajasthan. Interestingly, the 6% land allocation to IPM across both states produced 6% of the total pearl millet grain production, indicating no yield advantage for IPM varieties relative to conventional pearl millet.

Overall, a household harvested approximately 600 kg of IPM and 1,000 kg of conventional pearl millet in the 2023 season. IPM farmers allocated 58% of their harvested IPM for their own household consumption and sold 32% to the market. Only a small share (0.08%) of the IPM harvest was reserved as farm-saved seed, confirming that there is minimal to zero use of farm-saved seed, and any growth in the area share depends largely on the seed production and distribution capacity of the IPM seed system. Notably, 100% of IPM-growing households consumed part of their IPM harvest, and 57% sold a portion of it. While 46% of the households interviewed consumed pearl millet-based foods (all varieties) 24 hours preceding the interview, only 5% had consumed foods made from IPM in the same period. This proportion varied significantly ($p>0.001$) between the two states, with Maharashtra reporting nearly 10% while Rajasthan reported only 0.7% of the households that had eaten IPM food in the last 24 hours preceding the interview. Based on the current production and consumption level results, we estimate that IPM currently contributes an estimated 1% of household dietary iron intake and 2% of zinc intake across the two states. In contrast, conventional pearl millet contributes 22% and 30% to iron and zinc intake, respectively, underscoring its role as a key dietary iron and zinc delivery vehicle, and the need to increase IPM production to enable consumers to switch from the low iron and zinc non-IPM varieties. Overall, soil analysis revealed a mean iron content of 47.9 ppm across both states, with significantly higher levels in Maharashtra compared to Rajasthan. Analysis of pearl millet grain samples confirmed higher mean iron levels (53.0 ppm) for IPM varieties compared to non-IPM varieties (45.7 ppm). However, despite the different soil iron levels between Maharashtra and Rajasthan soil samples, there were no significant differences in iron levels for IPM grain samples from the two states. Overall, limited supply, low awareness and knowledge on nutrition and the financial constraints that make IPM growers sell their IPM to raise cash for other uses.

1. Introduction

Micronutrient deficiency is a major global public health challenge, affecting over two billion people worldwide (Vos et al., 2020). Among these deficiencies, for example, iron, zinc, selenium, vitamin A, and folate, iron deficiency is the most prevalent, frequently leading to iron deficiency anemia (Bailey et al., 2015). In India, the burden is particularly acute, with 55.3% of women and 58% of children under five estimated to be anemic (NFHS, 2015–16). The consequences of these prevalences extend far beyond health to negative economic impacts. Stein and Qaim (2007) estimated that micronutrient deficiencies cost India between 0.8% and 2.5% of its GDP annually. More broadly, childhood stunting linked to malnutrition has been found to cost the private sector in low- and middle-income countries at least US$135.4 billion, equating to up to 1.2% of national GDP across affected countries (Akseer et al., 2022). Health impacts are profound, including cognitive impairment, increased risks of child and maternal mortality, and reduced work productivity (Bailey et al., 2015). These deficiencies are largely attributed to inadequate dietary intake of essential micronutrients (Umugwaneza, 2017; Grosshagauer et al., 2020).

In response to the micronutrient deficiency challenges, the Government of India and development partners such as HarvestPlus have pursued multiple strategies to improve micronutrient intake across the population. One key approach is the development and dissemination of biofortified crop varieties through commercial delivery models to increase production and consumption of biofortified foods. Biofortification, a process of enhancing micronutrient content of staple crops through conventional plant breeding, is widely recognized as a sustainable, cost-effective, and food-based strategy to reach populations with limited access to diverse diets, fortified foods, or supplements (Meenakshi et al., 2010; Bouis & Saltzman, 2011). Randomized controlled trials have demonstrated their efficacy, for instance, consumption of iron-biofortified beans in Rwanda (Haas et al., 2016) and iron pearl millet in India (Pompano et al., 2022) improved hemoglobin levels and total body iron stores, respectively, suggesting their potential to address micronutrient gaps at scale.

1.1 Delivery of Iron Pearl Millet in India

Pearl millet is a vital staple crop in the arid and semi-arid regions of India. According to ICAR and the Department of Agriculture & Farmers Welfare (DA&FW), the national pearl millet area is approximately 7.5–8 million hectares, with an average annual production of 10 million tons and productivity of about 1,400 kg/ha. Major producing states include Rajasthan (45% of the national area), Uttar Pradesh (20%), Gujarat (9%), Haryana (9%), Maharashtra (6%), and Tamil Nadu (2%). Pearl millet production and consumption offer a potential for addressing malnutrition (Louhar et al., 2020; NFHS-4, 2015–16). To combat the nutritional gap, HarvestPlus, in collaboration with ICRISAT and the Indian Council of Agricultural Research (ICAR), developed eleven iron-biofortified pearl millet (IPM) varieties between 2014 and 2024 (Annex 1). To ensure farmer access, structured seed production and dissemination efforts began in 2015. Initially, IPM seed was commercialized as truthfully labeled (TFL) seed by both public and private entities, including Nirmal Seeds and the Maharashtra State Seed Company (MSSC), with HarvestPlus playing a catalytic value chain coordination role in stimulating market demand. Since then, this initiative has achieved significant scale. By December 2022, a cumulative total of 2,500 tons of certified and TFL IPM seed had been produced and disseminated. It is estimated that by 2023, over 360,000 farmers across India were cultivating IPM, bringing nutritious food to an estimated 1.8 million individuals within farming households (HarvestPlus data, 2023). While primarily grown for household consumption, an early outcome survey in 2018 indicated that a portion of the harvest (5% of production) was sold by farmers. This suggests a growing commercial pipeline where IPM reaches consumers beyond farming families, broadening its public health impact (HarvestPlus, 2018).

1.2 Rationale

Existing literature on the production and consumption of pearl millet and iron pearl millet (IPM) in India is limited in scope and representativeness. Nambiar (2012) identified pearl millet as a staple, consumed by over 90% of households in the studied regions and prepared in various forms for different groups; for instance, *kuler* and *raab* are specifically given to breastfeeding women to boost milk production. Reddy et al. (2013) found that 46% of pearl millet grain produced by farmers is allocated for human consumption, a figure that rises to 94% for iron pearl millet (HarvestPlus, 2018). While Reddy et al. (2018) projected rapid growth in non-food uses of pearl millet, these studies provide localized insights that are not state-level representative. Crucially, however, they offer little detail on the production, consumption, and commercialization of iron-biofortified pearl millet specifically. Furthermore, except for HarvestPlus modeling estimates, there is no evidence of studies or findings detailing the coverage of IPM — the proportion of a population that is eating IPM — nor the adoption — the number/proportion of farmers that are growing iron pearl millet. Documented coverage studies exist for fortified products (Osendarp et al., 2018) and, to some extent, other biofortified crops like cassava in Nigeria (FGN, 2022), but not for IPM in India.

The success of biofortification depends on the premise that widespread cultivation and consumption of biofortified staples will increase micronutrient intake, improve nutritional status and yield positive health and economic outcomes (Qaim et al., 2007). However, a program's impact is determined not only by biological efficacy but also by high coverage and effective implementation (Osendarp et al., 2018). Ultimately, the potential of biofortification is largely determined by the scale of farmer adoption, production and consumer consumption levels (Bouis et al., 2011). The current limited availability of recent, reliable data on biofortification coverage presents a dual challenge. First, it hinders the assessment of ongoing programs, and secondly, it complicates the planning of new policies. This gap, however, also represents an opportunity for new research to inform the effective scaling of nutritional interventions.

1.3 Overall Objective

This study assessed the coverage and adoption of iron-biofortified pearl millet (IPM) in rural and urban households across Maharashtra and Rajasthan, India. To achieve this, we evaluated the pathways to consumption, specifically investigating farm-level production patterns, household consumption behaviors, and the commercialization of IPM. The goal was to determine the extent to which the IPM promotional activities have translated into increased farm-level production and dietary intake of iron pearl millet foods by key nutritionally vulnerable groups like Women of Reproductive Age (WRA), adolescent girls, and children under five in these two states.

1.3.1 Specific Objectives

The specific objectives of the study were to:

a) Estimate the farm-level adoption and population-level consumption of iron pearl millet (IPM) varieties and foods, respectively, in Maharashtra and Rajasthan.

b) Quantify the contribution of IPM to the dietary iron intake of the target populations in these regions.

c) Analyze the iron content in IPM grain samples collected from both household and market sources.

d) Identify the key drivers and barriers influencing the consumption of IPM-based foods among urban and rural households.

2.0 Research Design and Methods

This study employed a mixed-methods design, integrating quantitative and qualitative data to examine the coverage and determinants of iron pearl millet (IPM) within food systems in Maharashtra and Rajasthan, India. The research was operationalized across two interdependent units of analysis: (1) farm households as sites of production and consumption, and (2) market systems governing the distribution of IPM products. Quantitative methods (surveys) provided estimates of scale and association, while qualitative methods (interviews, focus groups) generated explanatory depth on behavioral and structural factors, helping to explore the barriers and drivers of adoption and consumption. The household survey questionnaire has modules like (i) household demographics and assets; (ii) food security; (iii) cropping patterns and land allocation, with separate sections for conventional pearl millet (PM) and iron pearl millet (IPM); (iv) seed sources and input use; (v) 24-hour dietary recall for women of reproductive age, adolescent girls, and children under five; (vi) post-harvest allocation (home consumption, sales, gifts, seed saving, losses); and (vii) awareness and perceptions of IPM traits relative to preferred non-IPM varieties."

2.1 Study Context and Site Selection

Pearl millet in Maharashtra and Rajasthan is predominantly grown during the Kharif (rainy) season, with planting in June–July and harvest in September–October. The survey was conducted in March–April 2024, approximately 5–6 months post-harvest. Data was collected from key stakeholders across the pearl millet value chain, including 3,342 farming households, 315 *Mandi* traders, 73 processors, and 277 retailers. The two states were selected purposively based on three criteria: (1) their status as major pearl millet-producing regions, representing a significant share of national output; (2) documented high prevalence of iron deficiency among target populations; and (3) sustained investment in IPM varietal dissemination – IPM delivery footprint, allowing for the assessment of a matureing intervention. Within these states, districts were stratified by agro-climatic zones and level of pearl millet cultivation to ensure the sample captured ecological and production heterogeneity.

2.2 Sampling Framework and Data Collection

2.2.1 Household Survey: Sampling and Implementation

A multi-stage, stratified cluster sampling design was used to select households, ensuring representativeness for rural and urban populations. Primary Sampling Units (PSUs) were villages in rural strata and Census Enumeration Blocks in urban strata, selected with probability proportional to size. Figure 1 shows where the villages were sampled in the two states. A household listing was generated for each selected PSU, of which 15 households were randomly chosen. The sample size was calculated to detect a minimum acceptable prevalence of key indicators with 95% confidence and a design effect of 2.0, inflated by 20% to account for non-response. The final sample included 3,342 households.

Trained enumerators administered a structured questionnaire via Computer-Assisted Personal Interviewing (CAPI) using the KoBoToolbox platform. The instrument collected data on: Socioeconomics such as demographics, asset ownership, and food security; Agricultural Production including cropping patterns, input use, adoption of varietals (with an emphasis on IPM), yields, and post-harvest allocation; and consumption through a 24-hour dietary recall for key demographic groups (women of reproductive age, adolescent girls, children under five), covering food sources (own production, purchase) and detailed preparation methods.

2.2.3 Qualitative Component

All qualitative sessions were audio-recorded, transcribed verbatim, and translated into English for analysis. Twenty-four FGDs (twelve per state, segregated by gender) with farmers to examine decision-making processes related to seed adoption, perceived benefits, and consumption preferences. Key Informant Interviews (KIIs): Forty-five semi-structured interviews with agricultural extension officers, seed company agents, agro-dealers, and leaders of Farmer-Producer Organizations (FPOs). These interviews investigated systemic factors affecting seed access, quality assurance, and market development.

2.2.4 Bio-physical Sampling

To contextualize nutritional impact claims, composite grain samples were collected from a subsample of households and market actors. We put grain samples into two groups, namely IPM and non-IPM. To decide which group a sample belonged to, we did two things. First, we asked the farmer what kind of grain it was and checked if the type was on the list of IPM grains. Second, if there was a seed packet or label, we looked at that too. If we couldn't tell what kind of grain it was, we didn't put it in either group. We gave each sample a special code number so we could match it to the farmer's answers. To make sure our results were correct, we tested samples twice and used special reference materials for comparison. Concurrently, soil samples were taken from the associated fields of surveyed farm households. Using a detailed grain/soil Sample Collection Protocol, all samples were collected, preserved, transported and analyzed for iron and zinc content using inductively coupled plasma mass spectrometry (ICP-MS) at an accredited laboratory to assess actual micronutrient density and potential soil-crop linkages.

2.3 Ethical Protocols

The study protocol received approval from the Institutional Review Board of the International Food Policy Research Institute (IFPRI). Written informed consent was obtained from all participants. Data was anonymized, and the consultant staff completed mandatory research ethics training.

2.4 Analytical Strategy

We conducted both quantitative and qualitative analyses. The quantitative analysis details descriptive statistics (means, proportions), summarized adoption, allocation, and consumption patterns. Multivariate regression models identified factors linked to iron in soil and grain. The dietary contribution of IPM to nutrient intake was estimated using conversion factors from 24-hour recall data. The qualitative Analysis involved thematic analysis of transcripts, applied a framework approach, deriving codes both deductively (from research questions) and inductively (from data), to triangulate and explain survey results. The data integration process combined quantitative and qualitative findings during interpretation to determine "what" is occurring and "why," offering strong evidence for policy considerations.

3. Results

3.1 Household Demographic Profile

The demographic characteristics of the surveyed households in Maharashtra and Rajasthan are summarized in Table 1. The average household size was 4.1 members, slightly below the national average of 4.4, with a significant disparity between states. This suggests notable differences in household structure and dependency ratios that may influence production and consumption patterns. Household heads were, on average, 48 years old in both states, indicating a predominantly economically active population (Katungi et al., 2017). Most households (82%) were male-headed, though the proportion of female-headed households was significantly higher in Rajasthan (22%) than in Maharashtra (15%) ($p<0.001$). Critically, the sample composition aligns well with the target demographic for nutritional interventions. A large majority of households (82%) included at least one woman of reproductive age (WRA), with nearly a quarter (23%) including an adolescent girl—both groups prioritized for iron deficiency interventions. The presence of target beneficiaries (children aged 6–59 months, WRA, and adolescent girls) was significantly higher in Rajasthan across all categories ($p<0.01$), confirming that the intervention areas encompass households with the highest potential nutritional need. This demographic alignment underscores the relevance of the sample for assessing the reach and consumption of iron pearl millet among its intended beneficiaries.

Table 1: Household Characteristics by State

Variable	Maharashtra	Rajasthan	Pooled	P-value
Proportion (%) of Households with at least one WRA	0.83 (1697)	0.81 (1701)	0.82 (3398)	0.05
Proportion (%) of Households with at least one adolescent girl	0.18 (1697)	0.28 (1701)	0.23 (3398)	0.00
Proportion (%) of Households with at least one child 6-59 months	0.07 (1697)	0.12 (1701)	0.09 (3398)	0.00
Average age of the household head	48.06 (1697)	48.01 (1645)	48.03 (3342)	0.92
Proportion (%) of Female-headed households	0.15 (1697)	0.22 (1645)	0.18 (3342)	0.00
Average household size	3.68 (1697)	4.55 (1645)	4.11 (3342)	0.00

Sample sizes (n) are in parentheses. P-values test for significant differences between states.

3.2 Awareness of IPM and its products by value chain actors

Respondents were asked whether they had ever heard about or seen IPM or its products. Table 2 shows that 47% of Farmer Producer Organizations (FPO), 13% of retailers and 5% of the *Mandi* traders and 11% of the households were aware of IPM and its products. The level of awareness varied across value chain actor categories. It is important to note that FPOs have a higher proportion that are aware of IPM and its products compared to other VCA.

Table 2: Proportion of VCA that are aware of Awareness IPM and its products

Category of Value Chain Actor	Frequency/n
Mandi traders	5% (315)
Farmer-Producer Organization (FPOs) leaders	47% (45)
Retailers	13% (277)
Households	11% (3336)

3.3 Adoption of Pearl Millet and Iron Pearl Millet

Analysis of cultivation patterns for pearl millet and IPM varieties shows significant differences between Maharashtra and Rajasthan, as shown in Table 3. Overall, 64.5% of all households surveyed grew pearl millet in 2023, but only 5.0% grew IPM. The state-level contrast is that in Rajasthan, 79.3% of households grow pearl millet, yet only 0.9% of those pearl millet growers had planted IPM in 2023. In Maharashtra, by contrast, 50.1% of farmers grew pearl millet, but a much higher 9.1% of those pearl millet growers had planted IPM. In Maharashtra, the most widely grown IPM variety among surveyed households was Dhanshakti, while the few IPM-growing households in Rajasthan reported growing RHB 234. The varietal portfolio in Rajasthan—only two released IPM varieties compared to five or six in Maharashtra—partially explains this lower adoption rate. However, direct state-to-state comparisons should be made with caution because Maharashtra and Rajasthan fall under different pearl millet growing zones (Zone B and Zone A1, respectively), which have distinct agro-ecological conditions, varietal adaptation requirements, and release histories. Therefore, the differences in adoption reflect not just promotional efforts but also underlying varietal availability and what can actually grow well in each region.

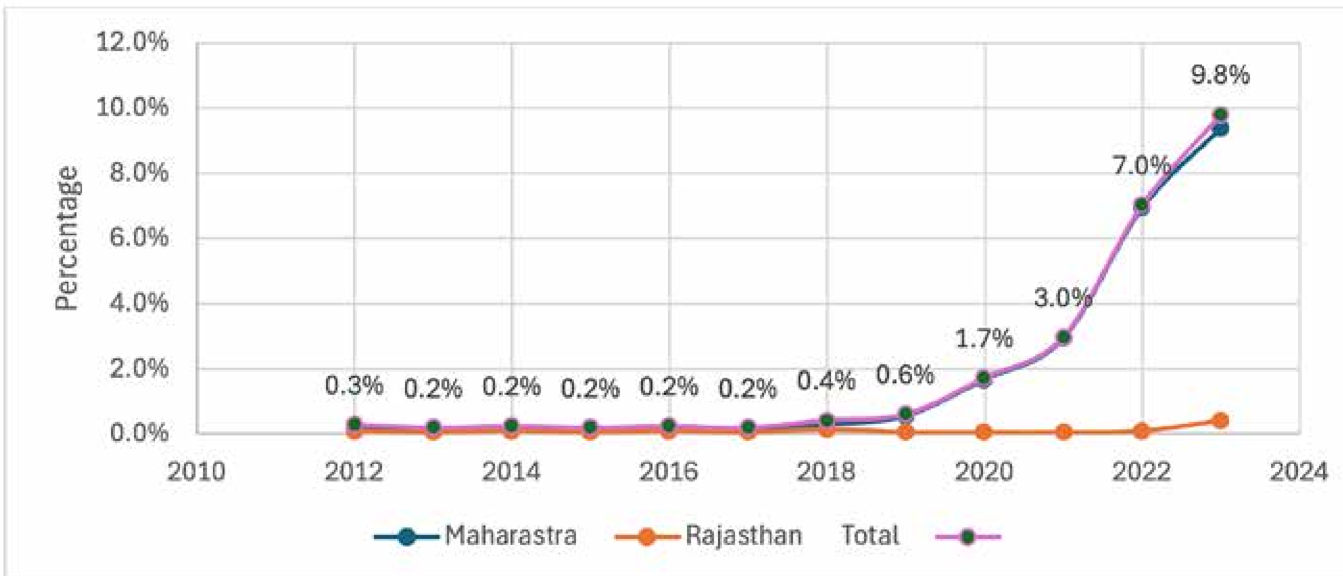
Table 3: Proportion of Farmers Growing Pearl Millet and Iron Pearl Millet (IPM), 2023

Variety	Maharashtra	Rajasthan	Pooled	P-value
Pearl Millet	50.09% (1697)	79.27% (1645)	64.45% (3342)	0.00
Iron Pearl Millet (IPM)	9.07% (1697)	0.88% (1645)	4.97% (3342)	0.00

3.4 Trends in Iron Pearl Millet Adoption Over Time

Pearl millet in Maharashtra and Rajasthan is planted during June–July and harvested in September–October, the Kharif (rainy) season. Working with several public and private partners, HarvestPlus led active promotion of IPM varieties in 2012. As shown in Figure 1, adoption has steadily increased, with the proportion of households growing IPM rising from 0.2% in 2013 to 9.8% in 2023. This indicates steady growth/expansion, mainly driven by Maharashtra, where active promotional efforts are anchored on a well-established and functional IPM seed system — adoption has remained low in Rajasthan. While the overall adoption rate looks good, the result clearly shows the significant interstate differences, emphasizing the need for tailored strategies to overcome local geographic-specific barriers.

Figure 1: Proportion of Pearl Millet Farmers Growing Iron Pearl Millet (IPM), 2013–2023



3.5 Input Use in Pearl Millet Production

Input use level indicates cultivation intensity and willingness to adopt production technology (Table 4). In 2023, 80% of pearl millet farming households used fertilizer, 56% used hired labor, and 13% used pesticides or herbicides, with notable differences between Rajasthan and Maharashtra. Rajasthan had more farmers using fertilizer (82%) than Maharashtra (76%), while Maharashtra farmers used hired labor more than those in Rajasthan (81% compared to Rajasthan (40%). These patterns suggest widespread investment in fertilizer, and improved production technology, and may point to the likelihood of adopting new technologies like IPM varieties. The reliance on hired labor in Maharashtra suggests a more commercial system, and IPM scaling could integrate soil fertility and pest management to enhance crop performance.

Table 4: Use of Other Inputs Among Pearl Millet-Growing Households

Input Type	Maharashtra (n=850)	Rajasthan (n=1304)	Pooled (n=2154)
Use of Fertilizer (%)	76	82	80
Use of Pesticide/Herbicide (%)	16	11	13
Hire Labor (%)	81	40	56

3.5.1 Fertilizer Use Among Pearl Millet Farmers

Fertilizer application signals agricultural intensification. Among pearl millet farmers, urea (32.2%) was more common than DAP (22.2%). Organic inputs like compost were rarely used (0.6%). Patterns vary greatly between Maharashtra and Rajasthan. In Maharashtra, farmers used a mix of fertilizers, including DAP (32.8%) and Sulphur (3.4%). Rajasthan mostly used urea (41.6%), with 42.7% using "other" fertilizers, possibly traditional soil amendments. Low and varied fertilizer use suggests pearl millet cultivation isn't highly input-intensive, impacting yield and returns from new varieties like IPM. The frequent "other" inputs in Rajasthan need further study to understand local soil practices. IPM promotion should include tailored nutrient management advice to improve yield and nutrition.

Table 5: Fertilizer Use Among Pearl Millet-Growing Households (%)

Fertilizer	Maharashtra (n=649)	Rajasthan (n=1070)	Pooled (n=1719)
Urea	16.8	41.59	32.23
DAP	32.82	15.7	22.16
Sulphur	3.39	0	1.28
Yuriya	44.07	0	16.64
Compost	1.54	0	0.58
Others	1.39	42.71	27.11

"Yuriya" is likely a local term for a specific fertilizer, most likely urea. The high "Others" category in Rajasthan suggests the use of unlisted, traditional, or compound fertilizers.

3.6 Sources of Pearl Millet Seed

Understanding where and how farmers source their seed is important for evaluating the existence and functionality of seed systems and the respective seed supply/distribution pathways for improved varieties like IPM. Table 6 shows that 44.5% of the farmers sourced pearl millet seed from the local market and 38.4% sourced from agrodealers, with only a few (12.8%) using their own/recycled seed. This result shows that nearly all farmers of PM buy their seed, indicating that PM seed is largely commercial and there is very little reliance on farm-saving seed. Regardless of the high purchase, there are differences between states because, in Maharashtra, most farmers (83.2%) acquired PM seed from agro-dealers, reflecting a formalized network, whereas in Rajasthan, 66.5% of farmers bought their seed from the local market, often involving grain merchants, for which questions on seed quality or purity may be raised. These differences highlight the need for tailored dissemination strategies, paying attention to the category of institutions that act as the key interface between seed companies and farmers. Integrating IPM seed into these channels is strategic and promising because farmers are used to buying seeds. Maharashtra's strong agro-dealer network offers a clear entry point for certified IPM seeds. In Rajasthan, local grain traders are a strategic seed distribution pathway, but this will require improved labeling and traceability to ensure that farmers get true-to-type and good-quality IPM seed.

Table 6: Sources of Pearl Millet Seed Used by Farmers in 2023 (%)

Source	Maharashtra (n=795)	Rajasthan (n=1411)	Pooled (n=2206)
Purchased from Agro-dealers	83.18	12.19	38.35
Purchased from the local market	6.7	66.49	44.46
Purchased from Other Farmers	6.44	4.6	5.28
Farmers' Group/Cooperative	0.39	0.84	0.68
Free from Relatives/Friends	2.76	3.6	3.29
Own/Recycled Seed	4.86	17.48	12.83
Subsidy	0.13	2.91	1.89
Other	0	0.08	0.05

3.7 Land Allocation to Pearl Millet and Iron Pearl Millet

We assessed land allocation patterns to understand how farmers value the pearl millet enterprise among other enterprises in their cropping systems and how they value the biofortified IPM varieties within the PM enterprise. In 2023, surveyed households cultivated an average of 1.67 hectares of all crops, with 0.64 hectares (38%) dedicated to pearl millet (PM). Among households that adopted iron pearl millet (IPM), they allocated 0.45 hectares (nearly 70%) to the biofortified IPM variety, showing that a switch to the IPM varieties may be due to government or NGOs' subsidies. Interstate differences were notable and significant, with Rajasthan households allocating more land to PM (0.68 ha) than Maharashtra (0.58 ha). While the overall area share of IPM stood at 6.3%, nearly 12% of the total household PM area in Maharashtra was allocated to IPM, while only 0.2% of the total household PM area in Rajasthan was allocated to IPM. This share of PM land to IPM in Maharashtra signals good scaling progress for IPM. This success in Maharashtra is a clear testimony to the IPM scaling potential. In Rajasthan, emphasizing the critical role of local markets as a major interface for delivering seed to farmers could help accelerate scaling. However, with small sample size this should be interpreted with caution.

Table 7: Land Allocation to Pearl Millet and Iron Pearl Millet, 2023

Variable	Maharashtra	Rajasthan	Pooled	p-value
Avg. Cultivated Land/HH (Ha)	1.63 (850)	1.70 (1304)	1.67 (2154)	0.32
Avg. Area to PM/HH (Ha)	0.58 (850)	0.68 (1295)	0.64 (2145)	0.00
Avg. Area to IPM/HH (Ha)	0.46 (244)	0.30 (13)	0.45 (257)	0.10
Total Area to PM (Ha)[1]	496.36	880.86	1,377.22	–
Total Area to IPM (Ha)	111.43	3.86	115.29	–
% of PM Area Allocated to IPM	12.45 (850)	0.21(1304)	6.3 (2154)	0.00

Figures in parentheses indicate the sample size (number of households). In 2023, the area under PM was 4.2 million hectares in Rajasthan and 0.5 million hectares in Maharashtra.

3.8 Production of Pearl Millet and Iron Pearl Millet in 2023

Farmer harvest data from 2023 shows clear differences between regular pearl millet (PM) and iron-biofortified pearl millet (IPM). On average, households produced about 1,005 kg of regular PM but only 602 kg of IPM (Table 8). Part of this difference comes from farmers planting IPM on smaller areas of land. Production also varied by state: Rajasthan households produced more regular PM (1,124 kg) than Maharashtra (823 kg). However, IPM production was higher in Maharashtra (627 kg) compared to Rajasthan (388 kg), which reflects Maharashtra's relative success in promoting IPM adoption. Interestingly, even though IPM covered 6% of the total PM growing area across both states, it only made up 6% of the total PM grain produced. This matters because while the nutritional and market benefits of IPM are important selling points for getting farmers to adopt it, breeding programs also need to focus on developing high-yielding IPM hybrids. Why? Because farmers care more about yield than almost any other trait when choosing which varieties to grow. Under current farmer management practices and without special agronomic advice, IPM varieties showed a lower average yield (about 1,469 kg per hectare) compared to conventional pearl millet (about 1,725 kg per hectare). That said, on-farm trials in other locations have shown that with good nutrient management, IPM can match the yields of regular millet. This gap between what is possible and what farmers actually achieve suggests that simply giving out seeds is not enough, seed distribution needs to be bundled with agronomic support and recommendations to help farmers get the best results from IPM.

Table 8: Pearl Millet and Iron Pearl Millet Production, 2023

Variable	Maharashtra	Rajasthan	Pooled	p-value
Avg. PM Production/HH (kg)	822.88 (850)	1124.26 (1294)	1004.78 (2144)	0.00
Avg. IPM Production/HH (kg)	626.62 (139)	387.50 (16)	601.94 (155)	0.00
% of Total PM Production that is IPM	16.01	0.22	6.24	0.00
Avg. Yield: IPM (kg/Ha)	1452.80 (136)	1640.39 (13)	1469.17 (149)	0.42
Avg. Yield: PM (kg/Ha)	1639.92 (850)	1780.36 (1293)	1724.66 (2143)	0.01

Sample sizes (n) are in parentheses.

1 The total area figures reported (e.g., 496 ha PM in Maharashtra) are derived from the survey sample and are not extrapolated to state-level population estimates. Extrapolation would require appropriate survey weights. The percentage of PM area allocated to IPM (16% in Maharashtra) refers to within-sample allocation, not state-level cropped area.

3.9 Utilization of Iron Pearl Millet Harvest

We assessed how households were allocating their harvested IPM grain to understand the extent to which IPM growing households prioritize iron pearl millet for home consumption (Table 9. Overall, IPM-growing households allocated about 58% of their harvested IPM for their own consumption, and sold 32% of the grain, while 0.08% was allocated as farm-saved seed, 4% was given as gifts, and 1% was accounted for as postharvest losses. This is a shift from the findings from the 2018 study in Maharashtra, where over 94% was allocated to consumption. The change in proportion allocated to home consumption and sales demonstrates that with increasing production, farmers are likely to sell an increasing proportion of their harvested IPM, improving household income while allowing non-growers to access it from the market. In Rajasthan, IPM farming households consumed 72% of the harvested IPM compared to those in Maharashtra who consume 51% of their harvest — more IPM is therefore sold to the market in Maharashtra. This changing pattern from a subsistence focus in 2018, to a more market sales orientation in 2023, indicates the growing commercial viability of IPM, increased production and improved market links in Maharashtra. Promotional strategies should aim to sustain this growth while maintaining household nutrition.

Table 9: Proportion of Harvested Iron Millet Allocated to Various Uses

Use category/type	Maharashtra (n=139)	Rajasthan (n=16)	Pooled (n=155)	p-value
Home Consumption (%)	50.76	72.31	57.95	0.00
Avg. Per Capita Consumption (kg/year)	51.9	49.79	50.8	0.00
Sold (%)	43.2	10.76	32.11	0.00
Avg. Quantity Sold (kg)	270.69	41.73	193.25	0.00
Seed (%)	0.12	0.00	0.08	0.00
Gifts (%)	5.38	0.77	3.85	0.00
Loss (%)	1.42	1.54	1.46	0.01

3.10 Allocation of Iron Pearl Millet Harvest

We assessed the proportion of IPM farming households that allocated IPM to each of the various possible uses, Table 10. The proportion of households that consume IPM can be a proxy indicator of the extent to which messages about the nutritional and health benefits of IPM were understood and are being applied, or maybe the traditional value farmers place on pearl millet. Overall, all (100%) IPM farmers allocated some IPM for their own household consumption, while 57% of them were selling some of their IPM, reflecting possible dietary and income benefits. Notably, 2% reported using IPM grain as Farm Saved Seed (FSS) for the next season, highlighting the high availability and affordability of IPM certified seed, at least for the farmers who have adopted IPM, in India. Up to 80% of IPM farmers in Maharashtra sold their surplus IPM vs a paltry 15% of the IPM farmers in Rajasthan who sold their surplus. The results show a higher economic benefit potential for IPM farmers in Maharashtra compared to Rajasthan IPM farmers. Further analysis of what the economic benefits are and how they differ by state will be useful.

Table 10: Proportion of IPM farmers allocating harvested IPM to various uses (%)

Use	Maharashtra (n=139)	Rajasthan (n=16)	Pooled (n=155)
Household Consumption	100	100	100
Sale	80	15	57.89
Farm Saved Seed	3.8	0	2
Gift	54	8	39
Other Uses	23	15.4	20.51

Percentages exceed 100% as households allocate harvest to multiple uses.

3.11 Market Channels for Pearl Millet Sales

The choice of buyer affects price, transaction costs, and market access for farmers (Vroegindewey et al., 2018). Table 11 shows the different markets (buyers) to which farmers sell their harvested PM grain. Market availability and the ease with which farmers can access them are crucial drivers or barriers to selecting new varieties that farmers can grow (Kihimba, H.A., Alphonce, R., Ngaiza, M., & Ochieng, J., 2026; Barnes, A.P., Hammond, J., & Duncan, A., 2026). Overall, nearly 68% of farmers sold their surplus to *Mandi* traders, emphasizing the role of formal wholesale markets, while 18% sold to neighbors or fellow farmers, and another 18% sold to roadside traders or middlemen. A robust strategy for engaging Mandi traders to raise their awareness about the value proposition of IPM could be strategic for achieving large-volume grain movement and creating an impactful demand-pull that can accelerate adoption of IPM varieties. However, local sales, which show a decentralized community-level trade network, can also be crucial for promoting IPM consumption in rural areas, by households that do not grow IPM. Promoting farmer-to-farmer or farmer-to-neighbor sales of IPM could introduce biofortified grain into local diets, fostering familiarity and demand within the community.

Table 11: Proportion of Farmers Selling Pearl Millet by Buyer Type (%)

Buyer Type	Maharashtra (n=1149)	Rajasthan (n=400)	Pooled (n=1549)
Mandi Traders	74.59	53.06	67.75
Individual Trader	28.12	22.16	26.23
Middleman (Roadside)	12.77	13.99	13.16
Neighbor / Fellow Farmer	39.94	27.11	35.87
Other	0.54	0.00	0.37
Don’t Remember	0.14	0.29	0.19

Note: Percentages exceed 100% as farmers could report multiple buyer types. “Neighbor / Fellow Farmer” combines the original “To the neighbor” and “Farmers” categories.

3.12 Farm Level Revenue from Pearl Millet and Iron Pearl Millet

Revenue from crop sales motivates farmers to adopt varieties and expand the area under those crop varieties. Table 12 shows the average income from pearl millet (PM) and iron pearl millet (IPM) during 2023. Overall, farm households earned an average of ₹13,955 (~USD154) from PM and ₹8,627 (~USD95) from IPM, reflecting larger planting areas and higher production of PM. Sales differed significantly across states: Rajasthan farmers earned ₹18,577 (~USD204) from PM, higher than Maharashtra's ₹11,799 (~USD130). This difference aligns with Rajasthan's larger PM area and production. For IPM, Maharashtra farmers earned an average of ₹8,641 (~USD95), while those in Rajasthan earned an average of ₹8,145 (~USD90). Lower IPM revenue resulted from smaller cultivated areas. To promote IPM, strategies should ensure a price premium that offsets yield trade-offs, along with reliable market channels. Better market links and consumer awareness are essential for making IPM economically attractive.

Table 12: Average Household Revenue from PM and IPM Sales (Indian Rupees ₹)

Variety	Maharashtra	Rajasthan	Pooled	Pvalue
PM	11,799 (735)	18,577 (343)	13,955 (1078)	0.00
IPM	8,641 (133)	8,145 (4)	8,627 (137)	0.23

Note: Sample sizes (n) indicate the number of households that sold each variety. The very small number of IPM sellers in Rajasthan limits statistical comparison.

3.13 Farmer Access to Institutional Support Services

Access to support services like training, extension, credit, and farmer groups is crucial for improved adoption of agricultural innovations (Ashrit & Joshi, 2024). The survey revealed a very low access to services among pearl millet farmers—less than 8% in both states. Only 2% reported receiving training, while 2%, 7% and 1% reported having accessed extension, credit, and being part of groups, respectively — there were significant differences in access to services between Maharashtra and Rajasthan. This lack of support can potentially hamper the adoption and scaling of IPM varieties. Access to training and credit are key for achieving accelerated and sustained adoption — these services are part of the crucial toolkit of drivers for adoption, without which, adoption could rely only on the demand-push pillars that pump seed of new varieties into the market, risking low sales, profit, and slow adoption or even disadoption of new technologies, like IPM varieties. Bundling services like credit, extension, markets and training with IPM inputs like seed has the potential to create a strong demand push that can accelerate adoption, sustainably.

Table 13: Proportion of Pearl Millet Farmers with Access to Institutional Support

Variable	Maharashtra (n=850)	Rajasthan (n=1304)	Pooled (n=2154)
Training	2%	2%	2%
Extension	2%	1%	2%
Access to Credit	6%	7%	7%
Member of a Group	2%	1%	1%

3.14 Farmer Perceptions of IPM Traits

Farmers assess new technologies to determine whether they try/test them and ultimately whether they can continue growing them. We used a Likert scale to assess farmers' perceptions of selected traits comparing IPM to the farmers' preferred non-IPM variety, Table 14. Overall, most farmers rated IPM as better (higher) or the same as their most preferred non-IPM variety, for most traits. About 50% rated IPM higher for yield —important for productivity and income. Over 66% of the respondents rated IPM taste as better than that of their most preferred non-IPM variety — a key trait to drive adoption. Perceptions were more moderate for drought and flood resistance, with less than 50% rating IPM higher. The positive ratings for yield and marketability are different from the earlier findings of the yield disadvantage of IPM, requiring further investigation. The slightly mixed views on resilience suggest a need for agronomic support or better communication. Importantly, strong perceived marketability and price potential indicate farmers see an economic benefit in IPM, supporting its wider adoption. Reinforcing market linkages and clear price signals will help turn positive perceptions into increased cultivation.

Table 14: Farmer Ratings of IPM Traits Relative to their Preferred Non-IPM Variety (% of Respondents)

	Don't know	Higher	Lower	Same
Yield	3.07 (8)	50.57 (132)	1.92 (5)	44.44 (116)
Disease resistance	3.07 (8)	50.19 (132)	6.13 (16)	40.61 (106)
Drought resistance	3.07 (8)	47.13 (132)	5.75 (15)	44.06 (115)
Resistance to flood	3.83 (10)	42.91 (112)	6.9 (18)	46.36 (121)
Taste	3.07 (8)	66.28 (132)	1.92 (5)	28.74 (75)
Marketability	2.68 (8)	53.64 (132)	1.92 (5)	41.76 (109)
Price	3.07 (8)	52.49 (132)	1.15 (3)	43.3 (113)

Sample sizes (n) for each category are in parentheses

3.15 Households Experiencing Food Insecurity

Food insecurity is evaluated on a continuum scale ranging from moderate to severe. Moderate food insecurity manifests when households compromise on dietary quality, often reducing food intake by skipping meals or decreasing portion sizes. Severe food insecurity involves more critical deprivation, including experiencing hunger, exhausting food supplies, or abstaining from eating for entire day(s) due to scarce resources and inability to secure food one way or the other. The prevalence of these conditions among surveyed households is detailed in Table 15. The vast majority (98.6%) of the respondents reported no food insecurity. Nonetheless, 1.4% of the households surveyed that experienced food insecurity across both states is of concern. There was a higher prevalence in Rajasthan (2.0%) compared to Maharashtra (0.8%). Although the overall percentage remains low, this still signifies a vulnerable segment of the population for whom access to adequate and nutritious food persists as a challenging issue.

Table 15: Percentage of Households Experiencing Food Insecurity

State	Maharashtra	Rajasthan	Total
No Food Insecurity	99.18% (1,683)	98.05% (1,613)	98.62% (3,296)
Moderate or Severe Food Insecurity	0.82% (14)	1.95% (32)	1.38% (46)

Figures in parentheses indicate the number of households

3.16 Consumption of Pearl Millet and Iron Pearl Millet

The study showed that while the consumption of pearl millet was generally high, the consumption of IPM remained limited. Overall, nearly 47% of households reported having consumed PM foods in the 24 hours preceding the interview, while just over 5% had consumed IPM foods in the same period. However, PM food consumption varied significantly between states, with more (55.6%) households in Rajasthan and fewer (38.5%) households in Maharashtra reporting having eaten PM foods in the 24 hours preceding the interview. Additionally, nearly 10% of households in Maharashtra reported having eaten IPM food 24 hours preceding the interview compared to only 0.7% in Rajasthan. Most respondents who did not consume PM or IPM in the 24 hours preceding the interview had also not consumed it either in the past six months, especially in Rajasthan, Table 16. Results from the qualitative data revealed that low production constrained household IPM consumption. As such, it is important to accelerate scaling of IPM, to increase production volumes and improve access to IPM food by people in farm and off-farm households. Maharashtra's higher production results in moderate consumption, but Rajasthan's low production leads to just under 1% of the households consuming IPM despite high acceptance and consumption of PM. Boosting IPM cultivation in high-consumption states and channeling increased production into farm household diets and markets are necessary.

Table 16: Proportion (%) of Households Reporting Consumption of PM and IPM, by Recall Period

Recall Period	Pearl Millet (PM)			Iron Pearl Millet (IPM)		
	Maharashtra	Rajasthan	Pooled	Maharashtra	Rajasthan	Pooled
24 hours	38.48	55.56	46.89	9.92	0.71	5.41
7 days	15.62	17.69	16.64	7.55	0	3.85
30 days	24.93	22.67	23.82	4.58	0.53	2.6
6 months	10.61	3.1	6.91	2.54	0.09	1.34
Not consumed	10.72	12.28	11.49	75.91	98.76	87.11

3.17 Sources of Iron Pearl Millet Consumed in the Household

To understand how consumers were accessing IPM for consumption, we asked households that had reported having eaten IPM foods in the 24 hours preceding the interview where the IPM they consumed was sourced from. Table 17 shows that overall, IPM consumed at home mainly came from own production (52.5%) and market purchases (55.8%). A small share was received as gifts (3.7%). Data reveal significant differences between states: Rajasthan had more IPM from its own production (68.8%), while Maharashtra had more market-purchased IPM (56.5%), aligning with earlier adoption and market development trends. High iron content is invisible; the accuracy of household reports on market purchases depends on clear labeling and trader awareness. As such, results should be interpreted cautiously, as some respondents may have misidentified the pearl millet they purchased from the market, confusing it for IPM.

Table 17: Sources of Iron Pearl Millet Consumed at Home (% of Consuming Households)

Source	Maharashtra (n=317)	Rajasthan (n=19)	Pooled (n=336)
Own Production	51.59	68.75	52.51
Purchased from the market	56.54	43.75	55.85
Gift	3.53	6.25	3.68
Don't Know	0.35	0	0.33

Note: Percentages exceed 100% as households could use multiple sources.

3.18 Primary Forms in which Pearl Millet is Consumed

Understanding how pearl millet is consumed is crucial for designing effective promotion and processing strategies. Respondents were asked to identify various types of foods that use PM/IPM as the primary/dominant ingredient. As shown in Table 18, roti is the most predominant form in which PM/IPM is consumed, with nearly 100% of consumers in both states using it. This makes roti the main vehicle for delivering IPM benefits. Apart from roti, patterns vary by state, reflecting regional preferences. In Maharashtra, papad (a thin, crisp disc) is the second most common for PM (11.5%) and IPM (24.9%). In Rajasthan, upma (a savory porridge) is a secondary form for PM (21.1%) and dominant for IPM (43.8% among a few consumers). Smaller proportions consume laddu (sweet ball) and porridge.

Table 18 Proportion (%) of respondents who consumed PM/IPM foods, by type

	Pearl millet			Iron pearl millet		
	Maharashtra (1785)	Rajasthan (2012)	Pooled (3797)	Maharashtra (412)	Rajasthan (24)	Pooled (436)
Roti	99.67	99.72	99.7	100	100	100
Ladu	2.77	5.82	4.26	10.32	6.25	10.1
Porridge	1.71	0.07	0.91	5.69	0	5.39
Papad	11.54	0.21	6.01	24.91	0	23.57
Upma	1.65	21.07	11.11	5.69	43.75	7.74
Others	0.33	12.54	6.28	0	0	0

Note: Sample sizes (n) are in parentheses in the header row. Percentages are based on consumers of PM/IPM, not total respondents.

3.19 Consumption Frequency of Pearl Millet and Iron Pearl Millet

Understanding the frequency of consumption of PM and IPM food can provide useful insights about the contribution of PM and IPM to iron and zinc supply to the diet. We assessed the number of days on which PM/IPM had been consumed in the participating households. Table 20 shows households ate conventional PM more often than IPM—11 days in 30, or roughly every third day, versus 6 days for IPM. Significantly more households in Maharashtra reported having eaten IPM on 6 days in the last 30 days preceding the interview than those in Rajasthan, indicating that higher production in Maharashtra led to higher consumption. Rajasthan's high PM use and low IPM intake reveal an untapped opportunity. The interstate differences show that the main barrier to IPM consumption is availability, not demand. Increasing IPM production and supply to the food system is, therefore, a no-brainer if we are to see a substantial increase in its consumption.

Table 19: Estimated Household-Level Daily Intake of Iron and Zinc from Pearl Millet Sources

Metric	Maharashtra (n=1697)	Rajasthan (n=1701)	Total (n=3398)
Iron Intake from PM (mg/day)	13.5	9.8	11.7
Zinc Intake from PM (mg/day)	4.3	3.2	3.7
Reference EAR (Women of Reproductive Age)	~22 mg Fe/ day~9.8 mg Zn/ day		

Table 20: Average Number of Days Pearl Millet was Consumed in the Last 7 and 30 Days

Frequency per period	Pearl millet			Iron pearl millet		
	Maharashtra	Rajasthan	Pooled	Maharashtra	Rajasthan	Pooled
Number of days in the last 7 days	3 (265)	4 (291)	3 (556)	3 (0)	1 (3)	1 (3)
Number of days in the last 30 days	8 (423)	13 (373)	11 (796)	6 (16)	6 (7)	6 (23)

Figures in parentheses for the 7-day data represent the sample size of households consuming, highlighting the very low base for IPM.

3.20 Per Capita Consumption of Iron and Zinc from Pearl Millet

To assess the nutritional contribution of pearl millet, we estimated daily intake of iron (Fe) and zinc (Zn) from conventional PM and biofortified IPM varieties for key groups using 24-hour dietary recall data. The intake was calculated by multiplying each food item's micronutrient content. Overall, Table 19 shows a low mean daily iron intake of 11.7 mg (compared to an EAR of 22mg Fe/day for WRA). There were significant differences between Rajasthan (9.8 mg) and Maharashtra (13.5 mg). The estimated daily iron intake from all sources (11.7 mg) is approximately 50% of the Estimated Average Requirement (EAR) for women of reproductive age (22 mg/day). To meet the full EAR from IPM alone, a woman would need to consume approximately 180–220 grams of IPM grain per day (assuming 53 ppm iron and 10–15% bioavailability). This is consistent with the 150–200g range reported in clinical feeding trials (Pompano et al., 2022; Haas et al., 2016). Zinc intake averaged 3.7 mg, compared to an EAR of 9.8 mg. Current pearl millet consumption meets the EAR for iron and zinc partly, highlighting opportunities to increase overall intake and shift to more nutrient-rich IPM, if production is increased.

3.21 Nutritional Contribution of Pearl Millet to Dietary Intake

To quantify the nutritional impact of PM and IPM foods, we estimated their contribution to household dietary intake of iron and zinc by: (1) using 24-hour recall data to estimate consumption; (2) multiplying these by their average nutrient concentrations; (3) summing total micronutrient intake; and (4) calculating the percentage contributed by PM and IPM. Results show conventional PM contributes 22% iron and 30% zinc, while IPM's contribution is minimal—1% iron and 2% zinc—due to limited production and consumption. This highlights a large potential. Fully replacing PM consumption with IPM could boost iron and zinc intake by 15-20%. Achieving this requires increasing IPM production and consumption to displace conventional millet. Among IPM-growing households, IPM contributes 12% to iron intake, indicating the potential if scaled.

Table 21: Percentage Contribution of Pearl Millet to Household Dietary Iron and Zinc Intake

Source	Maharashtra (1697)	Rajasthan (1701)	Pooled (3398)
% Iron from IPM	3%	0%	1%
% Iron from PM	19%	25%	22%
% Zinc from IPM	3%	0%	2%
% Zinc from PM	26%	33%	30%

3.22 Barriers and Drivers of Iron Pearl Millet Consumption

Understanding the constraints and enablers influencing household food choices is critical for designing effective policies to enhance the consumption of nutritious foods like IPM. Existing evidence indicates that adoption is influenced by a complex interplay of awareness, accessibility, affordability, and cultural preferences (Muthini et al., 2020; Bellon et al., 2020). To identify these factors in our study context, we conducted thematic analysis of qualitative data from Focus Group Discussions (FGDs) and Key Informant Interviews (KIIs) with both IPM growers and non-growers. Data were analyzed to categorize recurring themes into distinct barriers and potential drivers.

The analysis revealed three primary, interconnected barriers to consumption, which are summarized in Table 22 alongside illustrative quotes

1. Limited Awareness and Knowledge of the Nutritional importance of millets

A key obstacle was a fundamental lack of knowledge about the nutritional importance of millets, especially their role as a source of iron. Discussions revealed that pearl millet is often seen merely as a filler food rather than a nutritious staple. This knowledge gap also reflects a broader misunderstanding of balanced diets. Representative Quote: "There is a lack of knowledge of the parents... They eat porridge the whole day, without anything to support a balanced diet." (FGD Participant). This theme appeared in over 80% of FGD sessions.

2. Financial Constraints and Market Orientation

Households face substantial financial pressures that lead them to prioritize cash income over nutritional self-sufficiency. Participants explained that they often sell nutritious food items, such as pearl millet and animal products, to cover urgent expenses related to education, healthcare, and household needs. A representative quote was: "They sell everything to get a different commodity... I am telling my people here, if you have a cow with milk, why can't you leave a cup for your family?"

3. Cultural Beliefs and Practices

Deep-rooted cultural beliefs often restrict food intake for certain household members, especially girls. Foods such as eggs, chicken, or liver are considered culturally forbidden for children or women, which limits dietary variety and micronutrient consumption. A typical quote: "In this area girls are not supposed to eat chicken or liver, or they will die, but it is a myth, so there is a need for education." (KII Respondent). This belief was mentioned in about 40% of discussions, with significant regional differences.

4.Private sector role is limited in IPM breeding and seed marketing

While initial IPM variety development was led by public sector institutions (ICAR, ICRISAT) with HarvestPlus support, private sector involvement in IPM breeding and seed marketing has been very limited. Notable exceptions include Nirmal Seeds and the Maharashtra State Seed Company (MSSC). Expanding private sector participation through licensing agreements, royalty models, and public-private partnerships will be essential for achieving scale, particularly in states like Rajasthan where private seed companies dominate conventional pearl millet seed supply.

Table 22: Key Barriers to IPM Consumption from Qualitative Analysis

Barrier Category	Key Description	Prevalence in FGDs/KIIs	Illustrative Quote
Nutrition Knowledge	Lack of awareness of the nutritional value of millets and balanced diet principles.	High (>80%)	*"There is a knowledge gap in knowing how to mix different types of food..."*
Financial Resilience	The sale of nutritious produce for cash limits household availability.	High (~70%)	*"They need money to buy soap... They eat vegetables, and that is for the whole year without changing."*
Cultural Beliefs	Food taboos restrict consumption, especially for women and girls.	Moderate (~40%)	*"It's forbidden."* (regarding children eating eggs)
The private sector role is missing	Increase production and consumption through demand pull	Moderate (40%)	

Themes of climate vulnerability and low production volumes were also discussed but were more frequently framed as barriers to production rather than direct barriers to consumption when grain was available.

3.23 Micronutrient Analysis of Soil and Pearl Millet Grain

Soil micronutrient availability affects the concentration of micronutrients in harvested grain (Li et al, 2007). This applies to biofortified varieties too (Bouis & Saltzman, 2017), which have an inherent high genetic ability to utilize available soil minerals to increase grain MN levels. To test this, paired soil and grain samples were collected from farmers' fields, preserved, transported, and analyzed using ICP-MS and DTPA extraction. Results in Table 23 show that soil iron (Fe) and zinc (Zn) were significantly higher in Maharashtra than in Rajasthan. Grain Fe averaged 47.9 ppm and Zn 33.4 ppm overall, with Maharashtra's samples higher than Rajasthan's samples. The positive link between soil and grain micronutrients aligns with previous findings (e.g., Cakmak, 2008; Bouis & Saltzman, 2017), indicating that soil health influences genetic potential expression. Although the target iron content for IPM varieties is 50-75 ppm in grain, results show that soil context affects actual levels. Enhancing soil micronutrient availability by applying recommended fertilizers, in deficient regions like Rajasthan, can complement breeding efforts, maximizing biofortification and the genetic potential of IPM seeds.

Table 23: Mean Mineral Content in Soil and Pearl Millet Grain by State

Variable (Unit)	Maharashtra (n=80)	Rajasthan (n=82)	Total (n=162)
Soil Analysis			
Available Zinc (ppm)	0.61	0.43	0.52
Available Iron (ppm)	9.36	2.94	6.11
Available Copper (ppm)	2.52	0.34	1.42
Manganese Available (ppm)	10.02	6.16	8.07
Grain Analysis			
Iron (ppm)	51.3	43.12	47.92
Target Range for IPM	(50-75 ppm)	(50-75 ppm)	(50-75 ppm)
Zinc (ppm)	33.91	32.76	33.44

3.24 Mineral Content of Grain Across the Value Chain

To assess if pearl millet's nutritional quality remains as it moves from farm to market, samples were collected from various actors and analyzed for iron (Fe) and zinc (Zn). Results in Table 24 show the highest iron levels in samples from farmers (47.9 ppm), followed by retailers (45.0 ppm) and Mandi traders (44.3 ppm), with the lowest at the processor level (42.1 ppm). Zinc levels were consistent, ranging from 31.8 to 33.4 ppm. ANOVA analysis indicated no significant differences in micronutrient levels across the chain. The slight decline in iron may suggest minor nutrient dilution or variability, but zinc levels remained stable. Importantly, the results suggest the grain's nutritional quality is largely preserved in the market system. This is promising for IPM scaling, as a segregated supply chain could deliver biofortified grain with its nutrient profile intact if cross-contamination is avoided.

Table 24: Mean Iron and Zinc Content in Pearl Millet Grain Samples by Value Chain Actor

Value Chain Actor	Iron (Fe) ppm	Zinc (Zn) ppm
Farmer	47.92	33.44
Mandi Trader	44.3	31.81
Retailer	45.01	32.28
Processor	42.08	32.96
Target for IPM (Breeding)	50 - 75	N/A

3.25 Comparison of micronutrient content in IPM and Conventional Varieties

A core objective of biofortification is to develop crop varieties with demonstrably higher micronutrient density than conventional counterparts. Our grain analysis confirms that IPM varieties had higher iron levels (average 53.0 ppm across hybrids and OPVs) compared to non-IPM varieties (average 45.7 ppm). The highest iron concentration was found in IPM OPVs (55.0 ppm). Among IPM varieties, OPVs showed a higher mean iron content (55.0 ppm) than hybrids (51.1 ppm), though both were higher than that of conventional varieties. Zinc content was also elevated in IPM OPVs (38.0 ppm) compared to other groups. This analysis validates the biological success of the breeding program and provides a clear, evidence-based value proposition. The superior iron content, particularly in OPVs, is a tangible asset for communication with farmers and consumers. However, the parallel existence of high-performing OPVs and hybrids presents a strategic consideration: OPVs may offer a nutritional edge and allow seed saving, while hybrids might provide higher yield potential. Scaling strategies should consider this varietal portfolio, potentially targeting OPVs for higher nutritional impact in subsistence-oriented systems and hybrids for market-oriented production where yield is a primary driver of adoption.

Table 25: Mean Iron and Zinc Content by Pearl Millet Variety Type

PM variety	Fe (ppm)	Zn (ppm)
IPM hybrid	51.06 (23)	32.4 (23)
IPM OPV	54.97 (28)	37.96 (28)
Non-IPM hybrid	44.42 (79)	32.074 (79)
Non-IPM OPV	48.15 (30)	33.59 (30)
All varieties	47.92 (160)	33.43 (160)

3.26 Association Between Soil and Grain Micronutrient Content

Understanding how soil micronutrient levels relate to the nutrient content of grains is really important for planning farm management strategies and for evaluating how well biofortification programs work, since these programs aim to boost nutrient levels in crops even when soil conditions are poor. To investigate this relationship, researchers collected soil and grain samples from farmers' fields and tested them for iron and zinc using standard lab methods. They then ran a regression analysis to see if higher soil nutrients led to higher grain nutrients, and if that connection was strong enough to matter. However, when they included all the factors in a full statistical model, the relationship lost its significance. This doesn't necessarily mean there is no real connection; it may simply mean the study didn't have enough samples to detect one. Going forward, future research should collect paired soil and grain samples from at least 300 farmers to reliably detect moderate-sized effects.

The regression analysis results, shown in Table 26, reveal how soil iron levels relate to grain iron content. In the simplest model (Model 1), soil available iron had a statistically significant positive correlation with grain iron, meaning that a 1 mg increase in soil iron was associated with a 0.57 mg increase in grain iron. When soil pH was added as a control in Model 2, the relationship stayed significant and nearly unchanged, showing that pH did not affect this connection in the study sample. However, once other soil properties like electrical conductivity, organic carbon, and soil texture were included in the full model (Model 3), the direct correlation between soil and grain iron became non-significant. This suggests that the apparent link was likely being influenced or "confounded" by other soil factors that affect how plants take up nutrients. The fact that the soil-to-grain correlation for iron is weak and easily disrupted by other variables actually highlights the success of plant breeding for biofortification. In other words, the high iron content in IPM varieties comes mainly from their genetics, not just from rich soil. This means IPM can deliver nutritional benefits across many different soil types, even those low in available iron. That said, good agronomic practices to keep plants healthy still matter for getting the best yields and grain quality.

Table 26: Regression Models for Association Between Soil Available Iron and Grain Iron Content

Variable	Model 1	Model 2	Model 3
Soil Available Fe (mg/kg)	0.567* (0.226)	0.562* (0.226)	0.068 (0.559)
Soil pH	–	0.94 (1.313)	-0.84 (1.266)
Soil EC (ds/m)	–	–	2.018 (1.314)
Soil OC (%)	–	–	0.591 (4.419)
B.F. Varietal Trait (Dummy)	–	–	14.483 (10.357)
Soil Texture Variable (a1)	–	–	6.24 (4.384)
Interaction: Fe * Soil texture	–	–	-0.078 (0.659)
Interaction: Fe * B.F.	–	–	-0.642 (1.081)
Intercept	44.063** (1.807)	36.953** (10.555)	46.368** (9.471)
Number of Observations	128	128	127

*Standard errors in parentheses. ** $p < 0.01$, * $p < 0.05$. EC=Electrical Conductivity, OC=Organic Carbon, B.F.=Biofortified.*

4 Conclusion

This study assessed the adoption, consumption, and barriers and drivers of iron-biofortified pearl millet (IPM) adoption in Maharashtra and Rajasthan, India. During the 2023 season, only 5% of all pearl millet-growing households cultivated IPM, but adoption varied significantly between states: 6% of farmers grew IPM in Maharashtra compared to just 1% in Rajasthan, indicating the late start of promotion and seed system development in Rajasthan compared to Maharashtra. On average, adopters allocated nearly 70% of their pearl millet land (about 0.45 hectares) to IPM. However, across all pearl millet farmers, IPM accounted for only 9% of the total pearl millet area, with state-level differences, with IPM covering 12% of the pearl millet area in Maharashtra but a mere 0.2% in Rajasthan. Though state-level differences, with IPM breeding being mandatory across all state breeding centers, a pearl millet variety release policy of the Indian Council of Agricultural Research (Government of India) would increase adoption of IPM in Rajasthan

In terms of productivity, IPM-growing households produced an average of 600 kg of grain, which made up only 6% of their total pearl millet harvest. This is significantly lower than the 1,000 kg average for conventional pearl millet, meaning that under current conditions, IPM varieties do not offer a clear yield advantage. Since high yield is one of the main reasons farmers choose to grow a crop, this lack of yield benefit presents a major challenge for scaling up IPM and highlights the urgent need to develop and release higher-yielding varieties. However, looking at how farmers use their harvested IPM reveals its dual role in supporting both nutrition and income. On average, IPM-growing households allocated 57% of their harvest for home consumption and 32% for market sales. Notably, every single one of these households consumed at least some of their IPM grain, and more than half (57%) sold a portion, showing that farmers both rely on IPM for their own nutritional needs and engage with markets to earn income. Only very small shares were kept for seed (0.08%) or given away as gifts, reinforcing that IPM is grown primarily for eating and selling. The near absence of farm-saved seed for IPM implies that scaling depends entirely on a functional certified seed system. This is both a strength (quality control) and a vulnerability (supply shocks). Policymakers should invest in decentralized seed production through FPOs and agro-dealers, especially in Rajasthan where local grain markets dominate.

For Rajasthan, a major barrier to IPM adoption is the very limited number of adapted varieties available as of 2023; only two varieties (RHB-233 and RHB-234) were released for the state. Rajasthan, being Zone A1, requires crops that can tolerate drought and extreme heat, whereas Maharashtra, which falls under Zone B, already has five to six released IPM varieties suited to its conditions. To speed up IPM adoption in Rajasthan, three things are needed: First, the development and release of more IPM varieties specifically bred for Zone A1 conditions; second, active involvement of private seed companies to multiply and sell these seeds; and third, scaling up the existing two varieties through targeted seed subsidies and on-farm demonstration trials. Preliminary monitoring and evaluation data also suggest that where formal government extension services are weak, farmer-to-farmer seed exchange and visible yield demonstrations become key drivers of adoption.

At the time of the survey, IPM consumption levels were relatively low in both Maharashtra and Rajasthan. Only about 5% of households had eaten IPM-based food in the 24 hours before being interviewed. In contrast, 46% of households consumed pearl millet-based foods of any variety during that same period, showing that conventional pearl millet remains far more common in daily meals. This low level of IPM consumption may be correlated to limited production, which in turn means consumers simply do not have easy access to IPM grain. As a result, the current nutritional contribution of IPM is very small, providing only an estimated 1% of total dietary iron and 2% of total dietary zinc at the household level. By comparison, conventional pearl millet contributed much 22% of iron intake and 30% of zinc intake. Athough growers of IPM allocated about 68kg per capita of IPM for consumption. This highlights its role as a staple food and also shows the huge potential for improving nutrition if biofortified varieties could replace even a portion of the conventional pearl millet currently being consumed.

Laboratory analysis confirmed that the biofortification breeding program has been effective, with IPM varieties containing 16% more iron than regular pearl millet. Specifically, IPM varieties had an average iron content of 53.0 parts per million (ppm), compared to just 45.7 ppm in conventional varieties. Among the different types of IPM, open-pollinated varieties (OPVs) showed the highest iron density at 55.0 ppm, which validates the core nutritional benefit of growing and eating IPM. The analysis also found that these higher micronutrient levels were largely preserved as the grain moved through the value chain, meaning that from the farmer all the way to the local retailer, IPM grain retained its nutritional advantage and did not lose significant iron content along the way.

Our study has a few limitations. First, we only collected data from certain districts in Maharashtra and Rajasthan, so our results might not apply to all of India. Second, we visited farmers 5–6 months after they harvested their crops, which means they might not remember exactly how much grain they ate or how well they stored it. Third, our numbers for crop area and production come from our sample of farmers, not from counting every farm in the state or country. Fourth, we asked farmers to tell us if they used Integrated Pest Management (IPM), but some might have gotten it wrong, especially if they bought it from a market instead of making it themselves. Fifth, Maharashtra and Rajasthan have different types of farmlands, different weather zones, and different histories of when IPM seed varieties were released, so comparing the two states may have intrinsic differences. Finally, because we only visited farmers at one point in time, we can't report causation but only correlations.

The study establishes that IPM is nutritionally superior to other crops and that households cultivating it consume and sell significantly higher proportions of their harvest, positioning IPM as a strategic crop for improving both smallholder nutrition and income. However, the current scale of production and consumption remains limited. Therefore, achieving meaningful health and economic impacts at the population or food-system level will require highly targeted scaling models. These models must rest on three interconnected pillars: first, the widespread availability of competitive, high-performing IPM varieties; second, an effective demand-push strategy driven by a robust seed system that ensures farmers can access quality planting materials; and third, a strong demand-pull strategy anchored on consistent market demand for IPM grain. Together, these elements can accelerate adoption, expand production, and ultimately increase consumption.

5 References

Akseer, N., Tasic, H., Onah, M. N., Wigle, J., Rajakumar, R., Sanchez-Hernandez, D., ... & Hoddinott, J. (2022). Economic costs of childhood stunting to the private sector in low-and middle-income countries. *EClinicalMedicine*, *45*.

Ashrit, R. R., & Joshi, S. (2024). Farmer's understanding and adoption of agricultural practices in southern part of India. *Discover Agriculture*, *2*(1), 5.

B.Y. Li, D.M. Zhou, L. Cang, H.L. Zhang, X.H. Fan (2007). Soil micronutrient availability to crops as affected by long-term inorganic and organic fertilizer applications. https://doi.org/10.1016/j.still.2007.05.005

Bailey, R. L., West Jr, K. P., & Black, R. E. (2015). The epidemiology of global micronutrient deficiencies. *Annals of nutrition and metabolism*, *66*(Suppl. 2), 22-33.

Bellon, M. R., Kotu, B. H., Azzarri, C., & Caracciolo, F. (2020). To have or to eat? The value of biofortified crops for nutrition and health. *Appetite*, 148, 104580.

Bouis, H. E., & Saltzman, A. (2017). Improving nutrition through biofortification: a review of evidence from HarvestPlus, 2003 through 2016. *Global food security*, *12*, 49-58.

Bouis, H. E., Hotz, C., McClafferty, B., Meenakshi, J. V., & Pfeiffer, W. H. (2011). Biofortification: a new tool to reduce micronutrient malnutrition. *Food and nutrition bulletin*, *32*(1_suppl1), S31-S40.

Cakmak, I. (2008). Enrichment of cereal grains with zinc: Agronomic or genetic biofortification? *Plant and Soil*, 302(1-2), 1-17.

Federal Government of Nigeria (FGN) and the International Institute of Tropical Agriculture (IITA). 2022. National Food Consumption and Micronutrient Survey 2021. Preliminary Report. A

Grosshagauer, S., Milani, P., Kraemer, K., Mukabutera, A., Burkon, A., Pignitter, M., ... & Somoza, V. (2020). Inadequacy of nutrients and contaminants found in porridge- type complementary foods in Rwanda. *Maternal & Child Nutrition*, *16*(1), e12856.

Haas, J. D., Luna, S. V., Lung'aho, M. G., Wenger, M. J., Murray-Kolb, L. E., Beebe, S., ... & Egli, I. M. (2016). Consuming iron biofortified beans increases iron status in Rwandan women after 128 days in a randomized controlled feeding trial. *The Journal of nutrition*, *146*(8), 1586-1592.

HarvestPlus. (2018). *India's pearl millet seed industry: Prospects for high-iron hybrids* (HarvestPlus Working Paper No. 28). Washington, DC: International Food Policy Research Institute (IFPRI).

HarvestPlus. (2023). *IPM seed dissemination and coverage report*. Unpublished internal data. International Food Policy Research Institute.

International Institute for Population Sciences (IIPS) and ICF. National Family Health Survey (NFHS-4), 2015–16: India. Mumbai: IIPS; 2017. [Cited 2021 January 15]. http://rchiips.org/NFHS/NFHS-4Report.shtml

Katungi, E., Farrow, A., Chianu, J., Sperling, L., & Kadege, E. (2017). *Common bean in Eastern and Southern Africa: A situation and outlook analysis* (CIAT Occasional Publication). Cali, Colombia: International Center for Tropical Agriculture.

Louhar, G., Bana, R. S., Kumar, V., & Kumar, H. (2020). Nutrient management technologies of millets for higher productivity and nutritional security. *The Indian Journal of Agricultural Sciences*, *90*(12), 2243-2250.

Meenakshi, J. V., Johnson, N. L., Manyong, V. M., DeGroote, H., Javelosa, J., Yanggen, D. R., ... & Meng, E. (2010). How cost-effective is biofortification in combating micronutrient malnutrition? An ex ante assessment. *World Development*, *38*(1), 64-75.

Muthini, D., Nzuma, J., & Nyikal, R. (2020). Farmer adoption and willingness to pay for biofortified crops: A case of high-iron beans in Kenya. *[Journal title to be confirmed]*.

Nambiar, V. S., Dhaduk, J. J., Sareen, N., Shahu, T., & Desai, R. (2012). Potential functional implications of pearl millet (Pennisetum glaucum) in health and disease. Journal of Applied Pharmaceutical Sciences, 1(10), 62–67.

Osendarp, S. J., Martinez, H., Garrett, G. S., Neufeld, L. M., De-Regil, L. M., Vossenaar, M., & Darnton-Hill, I. (2018). Large-scale food fortification and biofortification in low-and middle-income countries: a review of programs, trends, challenges, and evidence gaps. *Food and nutrition bulletin*, *39*(2), 315-331.

Pompano, L. M., Luna, S. V., Udipi, S. A., Ghugre, P. S., Przybyszewski, E. M., & Haas, J. (2022). Iron-biofortified pearl millet consumption increases physical activity in Indian adolescent schoolchildren after a 6-month randomised feeding trial. *British Journal of Nutrition*, *127*(7), 1018-1025.

Qaim, M., Stein, A. J., & Meenakshi, J. V. (2007). Economics of biofortification. *Agricultural Economics*, *37*, 119-133.buja and Ibadan, Nigeria: FGN and IITA. 288 pp.

Reddy, A. A. (2018). Agricultural productivity growth in Orissa, India: Crop diversification to pulses, oilseeds and other high value crops. *African Journal of Agricultural Research*, *8*(19), 2272-2284.

Umanath, M., Balasubramaniam, R., & Paramasivam, R. (2018). Millets' consumption probability and demand in India: an application of heckman sample selection model. *Economic Affairs*, *63*(4), 1033-1044.

Umugwaneza, M. (2017). The development of food based dietary guidelines (FBDGs) for 6 to 23 month old Rwandan children (Doctoral dissertation, North-West University (South Africa), Potchefstroom Campus).

Vos, T., Lim, S. S., Abbafati, C., Abbas, K. M., Abbasi, M., Abbasifard, M., ... & Bhutta, Z. A. (2020). Global burden of 369 diseases and injuries in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. *The lancet*, *396*(10258), 1204-1222.

Vroegindewey, R., Theriault, V., & Staatz, J. (2018). Coordinating cereal farmers and buyers: evidence from Mali. *Journal of Agribusiness in Developing and Emerging Economies*, 8(2), 234-255.

Annex 1: Iron Pearl Millet (IPM) Varieties Released in India (2014–2024)

Variety Name	Year Released	Recommended State(s)	Iron Content (ppm)	Type (OPV/ Hybrid)	Updated Iron content (PPM) as per source - AICRP India
AHB 1200 Fe	2017	Rajasthan, Gujarat, Haryana, Punjab, Delhi, Maharashtra, Telangana, Andhra	77	Hybrid	same
AHB 1269 Fe	2018	Rajasthan, Gujarat, Haryana, Punjab, Delhi, Maharashtra and Tamil Nadu	73	Hybrid	91
Chakti	2018		65	...	Niger Africa
CO 10	2023	Tamilnadu	59		
Dhanashakti	2014	Maharashtra, Karnataka, Andhra Pradesh, Tamil Nadu, Rajasthan, Haryana, MP, Gujarat, UP, Punjab	72	OPV	81
HHB 299	2017	Rajasthan, Haryana, Gujarat, Punjab, Delhi, Maharashtra and Tamil Nadu	73	Hybrid	same
HHB 311	2018	Rajasthan, Gujarat, Haryana, Punjab, Delhi, Maharashtra and Tamil Nadu	62	Hybrid	83
Moti Shakti (GHB 1225)	2019	Gujarat	TBD	Hybrid	76
Phule Mahashakti (DHBH 1211)	2018	Maharashtra	78	Hybrid	85
RHB 233	2018	Rajasthan, Haryana, Gujarat, Punjab, Delhi, Maharashtra and Tamil Nadu	64	Hybrid	83
RHB 234	2018	Rajasthan, Haryana, Gujarat, Punjab, Delhi, Maharashtra and Tamil Nadu	62	Hybrid	84
Shakti 1201 (Dhoni)	2015		74		released as TFL but discontinued
PBH 1625	2024	Telangana	77.62	Hybrid	78

Figure 2. Location of Study Villages/Urban Blocks