Enhancing Crop Resilience: The Role of Participatory Plant Breeding

Abstract

The world faces increasing concerns over climate change's impact on global food security. Fluctuating climate conditions cause farming uncertainty, leading to food scarcity and higher prices worldwide. New strategies are crucial for enhancing food production and agricultural resilience. Participatory Plant Breeding (PPB) tailors crop varieties to specific ecological contexts, fostering collaboration between breeders, farmers, and stakeholders. It emphasizes participatory varietal selection (PVS) and explores long-term stability and genetic diversity implications. PPB aims to increase crop production, profitability, and adoption of context-specific varieties, benefiting targeted users and enhancing farmer skills. PPB advances crop genetics by integrating biotechnology, conventional breeding, marker-assisted selection (MAS), and organic farming. Multidisciplinary activities within PPB drive its potential to revolutionize crop genetics, promoting sustainable production and reducing hunger.

Keywords: Climate change, food security, participatory plant breeding, genetic diversity, agricultural resilience

Introduction

In recent times, changing climate patterns from year to year have caused uncertainty in farming, sometimes leading to insufficient food and higher prices for food worldwide[1]. New strategies are necessary to meet the goals of increased food production. One of the acknowledged factors involves enhancing genetic diversity within fields, which leads to improved disease control, increased resilience to climate fluctuations, and enhanced ecosystem functionality.

Plant breeding plays a significant role in developing cultivars with increased yield potential and improved adaptation to various ecosystems. Genetic variability, crucial for populations to adapt to environmental conditions, is often limited in conventional breeding (CPB), which prioritizes genetic uniformity for variety registration and plant breeder rights. To address this, alternative breeding methods, like decentralized approaches, aim to create more diverse varieties suitable for organic and low-input agriculture.

Participatory Plant Breeding (PPB) is gaining prominence[2]. Decentralized breeding focuses on creating varieties tailored to the unique conditions of various environments, considering the interactions between genotype and environment. This approach involves directly breeding crops within the specific target environment to enhance adaptation and performance in those specific ecological contexts [3]. Varieties created in PPB programs often show variation, as farmers prioritize stability and suitability for their local conditions. While specific studies validate the stability of mixed varieties, there remains a gap in our comprehensive understanding of the long-term stability of evolving populations or mixtures arising from Participatory Plant Breeding (PPB) initiatives and their potential associations with genetic diversity [4].

PPB represents establishing a plant breeding initiative that partners with diverse stakeholders. This collaboration involves breeders working alongside farmers, marketers, processors, consumers, and policymakers, all with various interests spanning food security, health, nutrition, employment, and more. PPB represents a distinctive approach to plant breeding. It is particularly suitable when there is a limited understanding of the traits desired by farmers, traders, industries, and consumers for their crops and when conventional market research falls short in providing these insights. PPB is divided into two primary types: "farmer-led" and "formal-led."[5].

In traditional plant breeding (CPB), new varieties are brought into use without evaluating their appropriateness for farmers, and the availability of new varieties usually drives this approach. On the contrary, Participatory Plant Breeding (PPB) flips this delivery process, beginning with farmers' initial approval after a comprehensive selection cycle. As a result, PPB follows a demand-driven approach right from the start.[6,7 and 8].

Participatory research is seen by many as a solution to the challenges faced in various agricultural research programs. Participatory Plant Breeding (PPB) expects to generate specifically tailored, relevant, and well-suited varieties. The objectives of PPB involve improving crop production and profitability through the development and broader adoption of appropriate, often improved, varieties. This approach aims to provide benefits to a specific user group or deliberately address the needs of a broader user community.

Moreover, it aims to augment farmers' abilities to enhance their selection and seed production endeavors. Participatory Plant Breeding (PPB) can incorporate biotechnological approaches and other traditional plant breeding methods. This integration leads to heightened biodiversity and sustainability in the enhancement of crops[8].

Participatory plant breeding involves various tasks such as defining breeding goals, generating genetic diversity, choosing from diverse populations to develop experimental varieties, assessing these experimental varieties, releasing chosen varieties, encouraging the acceptance of released varieties, and supporting seed production [7].

Participatory plant breeding

Participatory Plant Breeding (PPB) entails the establishment of a collaborative plant breeding initiative involving cooperation among breeders, farmers, marketers, processors, consumers, and policymakers. Within the framework of PPB, there is a cooperative effort between farmers and researchers, with farmers assuming a primary role in the planning, executing, and assessing the breeding materials. PPB is based on the principle that farmers and professional plant breeders contribute valuable knowledge and expertise, synergistically enhancing the plant breeding process by involving diverse participants in different breeding stages [5]. Participatory Plant Breeding (PPB) encompasses various terms that are often used interchangeably, such as collaborative plant breeding (CPB) and farmer participatory breeding (FPB). The term "participatory" in PPB signifies that stakeholders can actively contribute to all significant plant breeding and variety selection phases.

According to Atlin [9] , Participatory Plant Breeding (PPB) methodologies are becoming increasingly popular. These encompass farmer-driven selection, on-farm evaluation, and the utilization of locally adapted landraces. The scope and methods of PPB programs vary, commonly utilizing farmer visual assessment and phenotypic mass selection for traits governed by simple genetics. Furthermore, they incorporate limited replicated yield testing through multiple-environment trials (MET), a crucial tool in formal plant breeding.

Bellon [10] found that the historical effectiveness of the centralized approach to germplasm improvement is currently leading to a transformation. This transformation is driven by integrating decentralized local breeding methods considering end users' viewpoints. In today's context of germplasm improvement, there is a noticeable shift away from the long-standing centralized model. This shift is characterized by the inclusion of decentralized local breeding methods, actively considering the perspectives and requirements of end users.

According to Merga [11], Participatory Plant Breeding (PPB) has the potential to boost production and profitability, improve farmer skills in selection and seed production, create adapted germplasm tailored to marginalized user groups, optimize the cost-effectiveness of breeding programs, and contribute to the preservation of biodiversity and germplasm. Rahman [12] highlighted the importance of Participatory Plant Breeding (PPB) in enhancing the livelihoods of subsistence farmers globally, elevating adoption rates, and establishing a connection with the practical realities on the ground.

Goals of PPB

The goals of Participatory Plant Breeding (PPB) encompass addressing pressing agricultural challenges while empowering farming communities. PPB aims to enhance crop resilience, increase food production, and promote sustainable agricultural practices through collaborative efforts between breeders, farmers, and stakeholders.

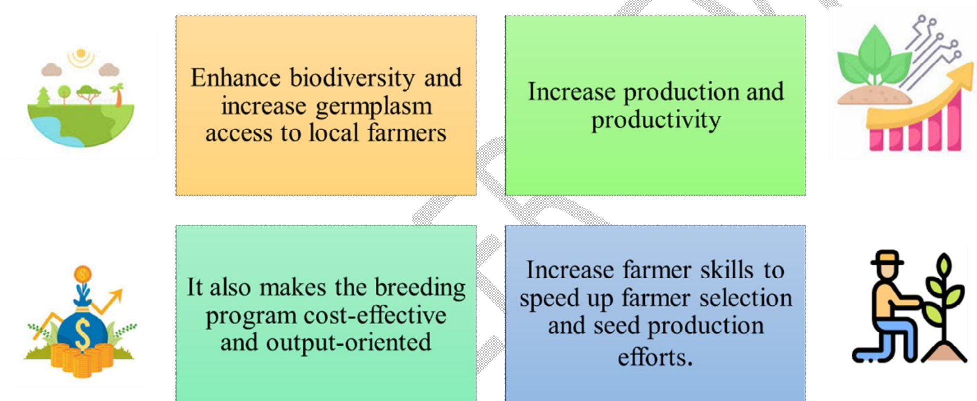

Fig 1. Goals of PPB

Kinds of Participation in PPB

Various modes of participation are positions on a spectrum representing varying degrees of interaction. Each mode of participation can be defined by how farmers and plant breeders engage in establishing goals, making decisions, sharing accountability for decision-making and execution, and producing outcomes[13] . In practical terms, typically recognize three distinct forms of participation: consultative, characterized by the sharing of information; collaborative, involving the distribution of tasks; and collegial, where responsibility, decision-making, and accountability are shared among stakeholders[14,15].

Functional participation:

Plant breeders can customize research for diverse farmer groups, incorporating insights from women, men, and varied economic backgrounds. Farmers contribute crucial input, assessing trait trade-offs accurately. On-farm research, managed by researchers, farmers, or collaboratively, ensures varieties excel in authentic conditions. Participatory Plant Breeding (PPB) boosts farmers' adoption of innovations [7].

Empowering participation: Elevating farmers' knowledge and skills enables them to actively engage in collaborative breeding initiatives and enhances their proficiency in individual breeding endeavors.

Genotype × environmental interaction effects

Selected and targeted environments are the same in PPB and different in CPB [16, 17]. They found that the genotype × environment is widely acknowledged as a critical factor in plant breeding and forms the basis for the adoption of PCI. Nevertheless, there has been limited analysis of the implications of G × E interaction for developing selection systems incorporating farmer participation and the full potential of Participatory Plant Breeding (PPB).

Participatory varietal selection

Engaging partners in on-field testing of finalized or nearly finalized varieties characterizes Participatory Variety Selection (PVS), usually involving a limited group. This process holds a crucial role in every breeding program, given that selection is a fundamental activity across all phases of the breeding process. Consequently, PVS consistently forms an essential component of PPB but can also function independently as a standalone process [12]. Engaging partners in the concluding phase of a breeding program that is otherwise not participatory brings about both notable benefits and drawbacks [2]. Integrating partners' preferences, post-on-farm trials speed up adoption as only their favored varieties are proposed for release. However, seeking partner opinions late in the program may result in none aligning with expectations, prompting consideration for earlier involvement. Participatory varietal selection effectively identifies farmer-accepted varieties, addressing challenges leading to cultivating outdated types [12]. Additionally, Participatory Variety Selection (PVS) can function as a preliminary phase, acting as an exploratory trial to assist partners in evaluating the level of commitment required for a fully developed Participatory Plant Breeding (PPB) program in terms of land and time. As stated by Ceccarelli [2] , PVS can be conducted using two approaches:

A) Mother trails

The trials contain several cultivars (generally 6–10) and a local check. The design could be led by researchers, managed by farmers, or involve inputs from their level. Farmers' involvement in assessing varieties during the maturity period of crops is highly favored in mother trials.

B) Baby trails

Typically, each farmer is provided with one or two new cultivars, which are then compared to local ones or subjected to numerous trials. A standard practice involves having 4-5 baby trials within various mother trials for each location or village. Farmers carry out the management, input, and supervision of these trials. The data collected mainly relies on perception, with minimal emphasis on quantitative measures like yield.

In farmer PVS, the goal is to identify cultivars that align with farmers' preferences. This involves defining farmers' criteria, searching for suitable released and unreleased cultivars, and testing them in participatory trials managed by farmers [18]. While farmer-acceptable cultivars have been found among released varieties, there is a lack of such cultivars in officially recommended regional varieties. This limited adoption is due to resource-constrained farmers not being exposed to the most suitable options. To boost adoption, measures like increased farmer participation, zonal trials to define suitable regions for preferred cultivars, a more flexible release system, and easier access to new cultivar seeds can be implemented [19].

The process of PVS was carried out at the Central Soil Salinity Research Institute, Regional Research Station, located in Lucknow, Uttar Pradesh, India, from 2001 to 2007. The primary objective was discovering rice varieties, genotypes, and breeding accessions with salt tolerance characteristics. The overarching goal was to pinpoint high-yielding, versatile, and well-received rice cultivars suitable for cultivation in sodic soil conditions, all achieved through active participation from local farmers [20].

PPB contributes to farmers' rights in several ways

Participatory Plant Breeding (PPB) supports farmers' rights by allowing them to shape technological advancements, leveraging the traditional knowledge of involved farmers, influencing decision-making, and fortifying farmer seed systems [21].

Steps of PPB

Step 1: Setting criteria to identify target environments and target users

When establishing criteria, it is beneficial to prioritize various categories of environments and users. Ensuring the effectiveness of participatory research involves meticulously selecting research objectives, identifying target environments, and actively involving the pertinent user communities. Additionally, a systematic understanding of the various forms of participation remains essential for selecting appropriate participatory research techniques and tools [22]. As per Ceccarelli [3,43] , the primary criteria for farmers' identification can be categorized into three overarching groups:

- **Farmer Characteristics:** Characteristics of farmers span a wide range of elements, such as the language they speak, religious beliefs, ethnicity, age, gender, income levels, educational background, market involvement and orientation, participation in farmer organizations, and the complex network of relationships among different groups within the same community and between communities [3].
- **Farmer Expertise:** Identifying if farmers are involved in plant improvement practices is crucial, as this information is essential for selecting the most appropriate breeding approach based on their needs and circumstances [2].
- **Farmer Needs:** This includes addressing diverse farmer needs, risk perceptions, desired variety traits, and preferences for specific crop quality attributes. Understanding constraints like fertilizer use, crop rotations, and irrigation is crucial. Identifying farmers' seed supply preferences impacts their reliance on personal versus formal sector sources [3,43].

Step 2: Choice of the target environment and users

In this stage, potential biases can impact PPB's success. Critical decisions include choosing individual or group participation, selecting experts or representatives for the wider community, and determining if equity should be the primary goal in user identification.

Step 3: Choice of Genetic Material

The selection of genetic material for the program should be discussed with the farmers. Initially, scientists might find that farmers lack awareness of the diversity within the crop. In such instances, we recommend commencing with a diverse set of genotypes representing a broad range of diversity. However, in some situations, farmers possess prior experience with different germplasm types and may have strong preferences for specific types.

Step 4: Choice of Parental Material

The selection of parental material is crucial in a breeding program and is primarily influenced by the number of target environments and objectives. It is noteworthy that, similar to conventional plant breeding (CPB), the parental material in a Participatory Plant Breeding (PPB) program is, with few exceptions, the best material farmers choose in the preceding cycle. Haugerud [23] found that divergence in the assessments of new crop varieties between scientists and farmers does not arise due to a lack of formal scientific knowledge among farmers. Instead, it often occurs because scientists neglect to incorporate farmers' knowledge and consider their limitations. Farmers' preferences for cultivars differ based on factors like farm size, family structure, gender roles, economic status, and market outlook. The disparity between scientists' and farmers' evaluations of new varieties arises from scientists not tapping into farmers' insights and accommodating their specific situations.

Step 5: Choice of Breeding Method

In Participatory Plant Breeding (PPB), selecting breeding methods requires assessing how farmers manage genetic diversity. The choice of breeding method is also contingent upon the preferred genetic structure of the end product, such as pure lines, mixtures, hybrids, or open-pollinated varieties.

Step 6: Naming of Varieties

The community should be involved in the naming process, which may involve using the village name, the name of a prominent farmer's child, or symbolic names like peace and unity. The naming of varieties significantly influences the sense of ownership and carries legal implications when officially releasing PPB varieties.

Step 7: Sharing and Disseminating Findings

After consolidating the PPB trial results for each location, it is essential to disseminate the information to all stakeholders. This can be achieved through various means, such as organizing a field day where participating farmers explain and present their work, utilizing radio and television for documentation, conducting stakeholder meetings to share results, training participating farmer groups, and creating descriptive sheets for each farmer's selected variety.

On-Farm Trials

On-farm trials facilitate collaboration between farmers and researchers in technology development. In participatory research, ranking and scoring exercises are expected to assess farmer preferences for various agricultural aspects, but they often lack input from numerous individual farmers. Gathering opinions from more farmers is crucial for establishing the repeatability and generalizability of study findings. Integrating the ranking of evaluation criteria with evaluation scores can help generate broadly applicable results regarding farmers' overall preferences [14,24]. Active farmer involvement in on-farm experimental activities is widely recognized as crucial in evaluating new technologies for sustainable agriculture in households with limited resources. These assessments and more formal evaluations conducted on experimental plots within farmers' fields provide a solid basis for formulating recommendations for new interventions [44,45].

Participatory plant breeding strategies

Within the PPB model, the initial step of generating genetic variability typically falls under the purview of the research institution. However, it is important to note that this responsibility can vary. The essential components of the biological model of plant breeding encompass the following: genetic variation, environmental variation, and how it interacts with genetic variation, as well as the process of crop plant selection [25,42].It is essential to differentiate between the technical procedure of creating crosses and the strategic choices in selecting parents and planning the crosses. Making a cross is purely technical, while parent selection and cross-design decisions are critical within a breeding program.

In Participatory Plant Breeding (PPB), most parental material employed in crosses comprises the finest breeding material selected from the prior breeding cycle. With the involvement of both breeders and farmers in the selection process, farmers play an active role in deciding which parents to use in initiating a new breeding cycle. Multiple selection stages occur in farmers' fields, where farmers and other stakeholders actively participate. This process ensures continuous interaction with the research institute and involves additional farmers in the PPB program.

Selection is independently carried out at each location, often leading to the choice of distinct entries in different locations. However, it remains possible to select the same material in different locations [24] . Farid [26] found that combining morphological approaches, drone imaging, and PPB helped select the best corn cultivation technology package. Frank [27] documented wheat population varieties' genetic diversity and performance stability created through Participatory Plant Breeding (PPB).

PPB for self-pollinated crops

Farmers cultivate large F2-derived populations in their fields from single crosses. Selection begins once selfing progresses, emphasizing high between-plant heritability. Less productive populations are swiftly discarded. The selection spans multiple generations, with many farmers preferring naturally propagated, well-selected bulks. These varieties, chosen in on-farm trials, often outperform later selections by breeders from the same bulk. Higher participation occurs with more promising bulks, making collaborative breeding cost-effective, even without formal training.

The success of collaborative breeding hinges on different resource requirements compared to on-station breeding, making its cost-effectiveness subject to varying circumstances [28]. It can enhance the likelihood of selecting segregants that perform well across diverse environments by employing techniques that aggregate bulks selected by different farmers. Furthermore, it is highly beneficial for the decentralization of breeding programs. In cases where the pedigree method is employed for breeding, the selection in farmer fields can commence with segregating populations, such as F2-derived F3 families. Field testing can initiate as early as the F3 bulks in breeding programs that utilize the bulk-pedigree method.

In both scenarios, evaluating yields for at least four consecutive seasons is crucial for informing farmers' adoption decisions and the variety release process. Initially intended for small-scale farmers in developing nations, Participatory Plant Breeding (PPB) is now widely adopted in U.S. organic breeding projects, backed by literature supporting its quantitative genetic selection theory [29].

PPB Model for Population Improvement of Cross-Pollinated Crops

The recombination phase generates genetic variability, typically conducted on a station, while selection and testing occur in farmers' fields. For hybrid development, producing inbred varieties in farmer fields offers the advantage of conducting selection during the inbreeding process in the actual production environment, ensuring unbiased selection without being affected by field heterogeneity. Shelton [30] discovered that modifications in open-pollinated sweet corn populations employing recurrent selection and Participatory Plant Breeding (PPB) demonstrated notable linear trends in quantitative and qualitative traits.

PPB Model for Vegetatively Propagated Crops

Following the initial crosses, all subsequent generations are appropriate for testing and selection in farmers' fields.

Biotechnology-Assisted PPB

Biotechnology can enhance Participatory Plant Breeding (PPB) with resource-poor farmers, creating tools that significantly boost the efficiency of their breeding endeavors in the field. Likewise, conducting needs assessments for Farmer Participatory Breeding (FPB) could enhance biotechnology research, offering a crucial reality check to refine its focus on the requirements of resource-poor farmers.

Success Stories of Biotechnology-Assisted PPb

Thro and Spillane [31] detailed a proposed Participatory Plant Breeding (PPB) initiative utilizing another culture to introduce rainfed rice in eastern India. The sequential steps involved in this scheme commenced with the characterization of parent varieties, followed by hybridization to generate F1 progeny through 20-30 crosses. Subsequently, anther culture produced double haploids (DH) from F1 and F2. Farmers actively evaluated the DH, contributing to the overall performance assessment. The most promising DH underwent replicated yield trials, marking a comprehensive approach to integrating PPB with biotechnological methods to improve and disseminate rainfed rice varieties in the specified region.

Combining Participatory Plant Breeding with Molecular Marker Technology

Steele [50] researched marker-assisted backcrossing (MABC), revealing its capability to generate pure and partial pyramids incorporating root QTLs and aroma from Azucena into a Kalinga III genetic background. Bulks were selected through a modified SLS-MAS approach for Participatory Plant Breeding (PPB), indicating the presence of target regions from Azucena. The PPB products, namely Ashoka 228 and 200F, and their parents and control lines, were systematically screened for root traits and flowering time. Notably, the root systems of these two varieties closely resembled those of the bulks selected for root QTLs, comprising 40% IR64 but 9 AFLP markers and 1 SSR from IR64. The study initially utilized SSRs and SNPs to screen 44 PPB products from various crosses, all featuring Kalinga III as one parent. Advanced lines and bulks, incorporating aroma, were successfully developed through the combined use of Marker-assisted selection (MAS) and PPB methodologies.

Participatory Plant Breeding and Women's Empowerment

In Syria, a six-year study (2006–2011) revealed the significant role of participatory breeding in empowering women. A case study involved 12 women from three villages during a PPB program by ICARDA. Initially, local women's strong interest led to the appointment of a young female as part of the PPB team in 2006. Seven women farmers actively participated in PPB trials, contributing to evaluation, variety selection, nomenclature, and conference participation. The study underscores the crucial empowerment of women farmers, especially in societies where the feminization of agricultural labor makes them critical contributors to small-scale farming development [3].

Participatory Plant Breeding Across Continents

Typically, PPB projects revolve around one or two national or international breeders and their teams based at an agricultural research facility. Support is provided by various extension agents, farmer paraprofessionals, and personnel from non-governmental organizations (NGOs) [32]. PPB across various continents is shown in Table 1.

A) Eastern India Rainfed Farming Project

The Eastern India Rainfed Farming Project (1995–2005) aimed to assist resource-poor farmers, constituting 19,000 households in the Chota Nagpur Plateau region. The project employed approaches such as Participatory Variety Selection (PVS) and Participatory Plant Breeding (PPB) to improve rice farming. PVS entailed farmers selecting germplasm from diverse varieties, while PPB concentrated on the ongoing enhancement of the chosen varieties identified through PVS.

B) ICRISAT

ICRISAT, established in 1972 and headquartered in Hyderabad, India, ICRISAT has offices across African countries like Mali, Nigeria, Niger, and Kenya. A key goal of ICRISAT is to create innovative techniques that enhance research impact on the nutritional and economic well-being of low-income individuals. Bridging the gap between farmers and scientists is a strategic approach, ensuring research outcomes are highly relevant to specific farming communities. Recognizing farmers' priorities is pivotal for directing research effectively. Enabling farmers to choose, adapt, and improve from various options creates more practical and valuable agricultural technologies [33].

C) CENESTA

The Centre for Sustainable Development (CENESTA), headquartered in Iran, is a non-governmental, non-profit organization that fosters sustainable development in indigenous and local communities. CENESTA collaborates actively with local communities in Iran, local and national government agencies, academic and research institutions, and non-governmental organizations (NGOs).

Crop name	Country	Institution(s)	Year initiated
Barley	Italy	Italian Association for Organic Agriculture	2013
Peas	Italy	Italian Research Institute CREA	2013
Buckwheat	United States	Organic Seed Alliance	2014
Cauliflower	France	French National Research Institute INRAE	2014
peas	United States	United States Department of Agriculture/ Agricultural Research Service USDA-ARS	2016
Pepper	United States	Cornell University/Seed Change	2016
Clover, Yellow Sweet	United States	United States Department of Agriculture/ Agricultural Research Service USDA/ARS	2017
Maize	France	Organic Food and Farming Institute ITAB	2017
Tomato	Italy	Rete Semi Rurali	2018
Buckwheat	France	French National Research Institute INRAE	2018

Table 1. PPB projects identified in the United States, Canada, and Europe [34,46.47].

Advantages of Participatory Plant Breeding

Participatory Plant Breeding (PPB) offers numerous advantages for agricultural development and crop improvement. By actively involving farmers in breeding, PPB ensures crop varieties are tailored to local needs and environmental conditions, enhancing agricultural resilience and sustainability.

A) saves time

As per the World Development Report, Participatory Plant Breeding (PPB) and plant varietal selection expedite the varietal development and dissemination process, reducing the timeline to 5–7 years. This represents nearly half the time compared to the 10–15 years typically needed in Conventional Plant Breeding (CPB) programs.

B) Improving Farmer Seed Systems and Seed Provision to small-scale Farmers

Challenges in providing quality seeds to small-scale farmers include high production costs and limited adaptability of cultivars. Farmers' seed management strategies in western

Rajasthan are being examined in their social and environmental context. Despite efforts to improve seed access, success remains limited. However, cultivars tailored to farmers' needs through Participatory Plant Breeding (PPB) offer new opportunities. A robust seed system, characterized by diversity, high-quality seeds, efficient distribution, and knowledge sharing, is crucial for sustainable agriculture [35,36].

C) Enhancement of Biodiversity

Ceccarelli [37] highlighted the recognition of Participatory Plant Breeding (PPB) for its selection efficiency, increased variety adoption, farmer empowerment, and social equity, contrasting it favorably with Conventional Plant Breeding (CPB). Beyond its traditional association with organic agriculture, PPB is suggested as a viable breeding opportunity for conventional agriculture in light of climate change. The replacement of varieties in PPB contributes to increased biodiversity, as Smith [38] noted, with participatory methods expected to accelerate the replacement rate of cultivars, ultimately leading to a reduction in the average age of cultivars and promoting more extraordinary biodiversity over time.

D) Amelioration in farmers' conditions

Participatory Plant Breeding (PPB) boosts farmers' organizational and social capital and individual farmers' knowledge, skills, and ability to learn and experiment [48].

E) Improves research efficiency

During the ICARDA barley breeding program in Syria, a case study revealed that breeders were more efficient in high rainfall conditions, while farmers were more efficient in water-deficient conditions. By the sixth year, Participatory Plant Breeding (PPB) made certified varieties accessible [49].

E) Accelerates Adoption

In Syria, farmers prefer PPB-derived varieties, cultivating 69% more land and achieving a 26% higher yield than conventional varieties.

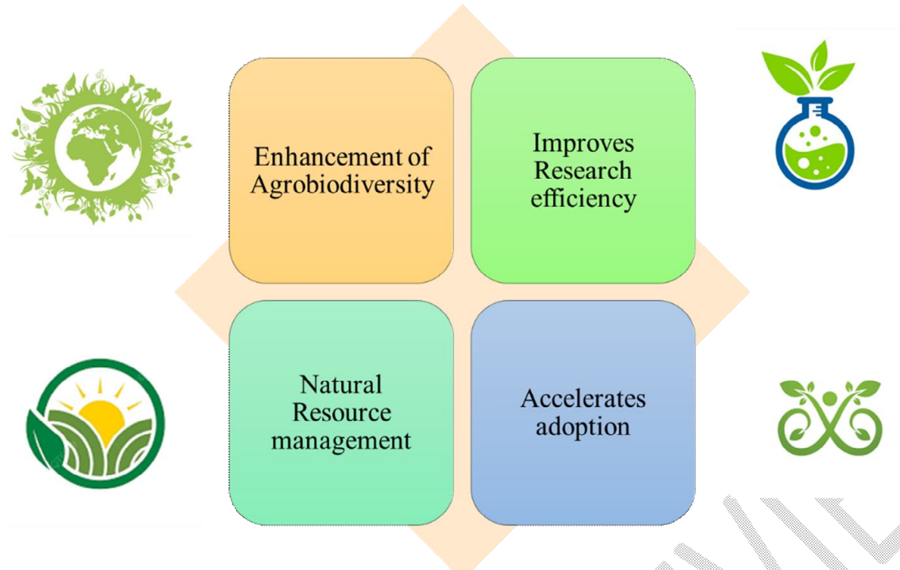

Fig 2. Benefits of PPB

Challenges of PPB

Despite significant investments from the public and private sectors in improving crop varieties, the utilization of Participatory Plant Breeding (PPB) is increasing to address cropping system requirements. However, various challenges impede the advancement of PPB. These include securing consistent funding and navigating regulatory obstacles linked to the commercial dissemination of PPB-developed varieties [34]. The heightened complexity associated with PPB further exacerbates these challenges, increasing time and costs. This complexity involves factors such as the training of farmers, the need for earlier and more comprehensive testing of varieties, a larger quantity of seeds, conducting trials beyond experimental fields, and the necessity for diverse manpower to communicate effectively with farmers, all leading to an inflation of costs. Despite these challenges, recent research has shown promising approaches to overcome them.

Case studies and success stories of PPB

The case studies and success stories of Participatory Plant Breeding (PPB) exemplify its effectiveness in addressing agricultural challenges through collaborative efforts. These real-life examples showcase how PPB empowers farmers, enhances crop resilience, and fosters sustainable agricultural practices. From diverse regions worldwide, these stories highlight the transformative impact of PPB on livelihoods and food security, as shown in Table 2.

Crop	**Year**	**Mode of PPB**	**Varieties**	**Reference**
Rice	2007	Combining Participatory Plant Breeding (PPB) with Molecular Marker Technology	Two varieties were released: Birsa Vikas Dhan 110 and Birsa Vikas Dhan 109.	[50]
	2013	Organic PPB	Jaiva	[39]
Potato	2018	Collaborative PPB	R8, R9, Rpi-blb2, Rpi-cap1, Rpi-chc1, and Rpi-edn2 lines of potato resistance against late blight disease	[40]
Tomato	2019	Organic, MAS, PPB	Tomato lines of multiple disease resistance against *Fusarium oxysporum f.sp. Lycopersici*, race 2 (FOL) and *Pseudomonas syringae pv.* Tomato	[8]
Maize	2003	PPB	GDRM-187, released as Gujarat Maize-6 (GM-6) Gujarat state, India.	[41]
	2020	Drone Imaging and PPB	selecting the best corn cultivation variety technology package.	[26]
Wheat	2020	PPB	Wheat Population Varieties have genetic diversity and stability	[27]

Table 2. PPB in various crops

Future perspectives

Advances in technology will play a pivotal role in streamlining data collection and sharing among researchers and farmers. The future of participatory breeding relies on evaluating a more comprehensive array of impacts, especially concerning rural innovation capacity and poverty reduction. Continued efforts will empower farmers to actively participate in breeding decisions and shape the development of crop varieties. Future endeavors will prioritize breeding for resilience to climate change and addressing emerging environmental challenges. PPB will increasingly align with market demands, ensuring crop varieties meet consumer preferences and economic needs. However, this agricultural breakthrough has had limited applicability in marginal areas, where breeders primarily concentrated on homogenous agroecological and socioeconomic conditions.

Conclusion

In conclusion, biodiversity loss, climate change, and global hunger present challenges that Participatory Plant Breeding (PPB) can address effectively. PPB emerges as a vital approach within this framework, emphasizing the critical role of enhancing genetic diversity in crop fields to tackle these pressing issues. By collaborating with diverse technologies like Marker-Assisted Selection (MAS) and organic farming, PPB fosters agrobiodiversity and ensures widespread food access and resilience to climate change. Despite challenges such as securing funding and navigating regulatory obstacles, recent research showcases innovative approaches to overcome these barriers and maximize the impact of PPB initiatives. Through integration with advanced technologies and a steadfast focus on genetic diversity, PPB holds immense potential to revolutionize crop genetics and foster sustainable agricultural practices globally. Moving forward, prioritizing inclusivity, knowledge exchange, and empowering farming communities will ensure our agricultural systems' continued resilience and adaptability in the face of evolving environmental and socio-economic pressures.

Statements and declarations

Data availability

Data is provided in the manuscript

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