Potential Vegetable Crops for Hybrid Seed Production and its Strategies in Nepal

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Abstract

Nepal's horticulture sector holds significant potential for growth, yet remains heavily reliant on imported hybrid vegetable seeds. This strategic paper evaluates the prospects and challenges of developing a robust domestic hybrid seed industry, with a focus on six key vegetable crops: tomato, hot and sweet pepper, brinjal, cucumber, brassicas, and cucurbits. These crops were selected based on technical feasibility, agro-ecological adaptability, seed market demand, and potential for import substitution.

The study combines a desk review, key informant interviews, and expert consultations with seed companies and researchers. Findings revealed both the strengths such as growing market demand, successful pilot programs, and youth engagement potential and critical barriers including limited RandD capacity, inadequate infrastructure, lack of skilled breeders, and regulatory challenges.

- To address these issues, the paper presents a three-tiered strategy roadmap:
- Short-term (0-2 years): Simplify seed licensing and variety registration, pilot production of feasible hybrids, and strengthen basic infrastructure and extension services.
- Mid-term (2-5 years): Establish a hybrid seed production unit (HSPU), integrate advanced breeding technologies (e.g. cytoplasmic male sterility, marker assisted selection, double haploid), and strengthen public-private collaborations among research, extension and academia.
- Long-term (>5 years): Position Nepal as a regional hub for custom hybrid seed production, claim GI tags for native varieties, and build mega seed enterprises with strong IPR protection.

The study concluded that a coordinated national effort anchored in science, policy, and market intelligence is vital for transforming Nepal's vegetable seed sector. By investing in innovation and building institutional capacity, Nepal can achieve seed sovereignty, reduce import dependency, and become a competitive player in the regional seed market.

Keywords: Diverse geography, Hybrid seed, Phenotypic selection, Strategy road map

Introduction

Agriculture is the backbone of Nepal's economy, supporting around 60% of the population (Yogi et al., 2025). Vegetable production is crucial for food security and nutrition, and with rising urbanization and changing dietary preferences, the demand for high-quality vegetables is increasing. Nepal's diverse geography and climate provide excellent opportunities for vegetable crop research and hybrid seed production (Devkota and Mishra 2020)mean comparison, correlations, and biodiversity indices were used for data analysis. On the basis of biodiversity index, evenness, the adequate number of species, and Sorenson's coefficient, open-pollinated (OP. The country's different agroecological zones support numerous vegetable species, making it ideal for developing hybrid varieties that can improve crop yields, enhance disease resistance, and provide farmers with greater income stability (Reddy et al., 2011).

Vegetables can generate 3 to 5 times more income than cereal crops, enabling farmers to buy at least three times more food than if they grow traditional cereals (Pandey, 2013). The importance of high-quality seeds is crucial, as they are the foundation of successful vegetable cultivation, impacting yield, disease resistance, and overall crop performance (Tiwari et al., 2023). Hybrid seeds, known for their superior traits such as increased productivity and enhanced resilience, are particularly beneficial. The current market for hybrid seeds in Nepal is expanding, driven by both local demand and advancements in cultivation practices (Keller 2024, Chakrabarty et al., 2023). In such background, vegetable research initiatives should focus on developing hybrid varieties for key crops of Solanaceae, Brassicaceae, and Cucurbitaceae families.

The characteristics of Nepalese fresh vegetable production play a crucial role in shaping the size and demand of the vegetable seed market. Despite the sector's considerable potential, it faces multiple interconnected challenges that hinder its growth and sustainability. One of the primary issues is the limited awareness and access to quality seeds among farmers, many of whom continue to rely on traditional varieties with lower yield potential and resistance to pests and diseases. This contributes to a significant yield gap and restricts productivity (Joshi, 2017a). Inadequate infrastructure further compounds the problem; poor transportation networks, lack of secure market linkages, and insufficient storage facilities make it difficult for farmers to sell their produce efficiently, often resulting in post-harvest losses (Yogi et al., 2025). Price volatility due to seasonal supply fluctuations and market demand, combined with unhealthy competition among traders and the dominance of middlemen, reduces farmers' profitability and makes the adoption of high-quality seeds less affordable for smallholders (Poudyal et al., 2023). Additionally, production and transaction costs remain high due to limited mechanization, fragmented landholdings, and poor road access. Labor shortages, driven by the migration of youth away from agriculture, have also led to an expansion of fallow lands, while increasing human-wildlife conflict continues to damage crops and dissuade farming activity (Rai et al., 2019). Overlaying all of these issues is the growing threat of climate change, with unpredictable weather patterns and extreme climatic events posing significant risks to both the stability and productivity of vegetable farming (Sapkota et al., 2023, Ghimire et al., 2023). Together, these factors create a complex environment that challenges last-mile seed delivery and limits the overall development of the vegetable seed market in Nepal.In countries with strong seed systems, the private sector significantly contributes to national agricultural gross domestic product. Nepal should follow the example of neighboring South Asian countries, for instance India, that have successfully adopted modern hybrid breeding technologies by inviting joint ventures and implementing robust plant variety protection (PVP) laws (Gauchan, 2016). Currently, the size of the Nepalese seed enterprise is estimated at around $45 million, with about 20 seed companies and over 70 foundation seed producers (SQCC, 2025).

Hybrid seeds are produced by crossbreeding two different parent lines to develop new variety with desirable traits. Over 20,000 hybrid varieties are available to farmers globally, with seed companies investing 15–25% of their turnover in RandD (Keller, 2024). This investment fosters innovation to incorporate essential traits such as higher yield potential, improved disease and pest resistance, and better adaptability to diverse environmental conditions. Countries like Vietnam, China, and India have made significant progress in their seed sectors by adopting modern hybrid breeding technologies supported by robust plant variety protection (PVP) laws and investment-friendly policies. However, the adoption of hybrid seed technologies in Nepal faces various challenges. This paper aims to discuss these opportunities and challenges, identify potential vegetable crops, explore innovative production techniques, and propose strategic recommendations for hybrid seed production.

Methodology

1. Study site and data collection

The study tried to cover Nepalese seed sub-sector across the country. Special focus given to areas producing hybrid seeds of tomato and cucumber like Chandragiri, Kathmandu; Pawati, Dolakha and Khatigaunda, Dailekh. Seed companies based in Kathmandu were consulted, particularly scientists looking after RandD activities of private sector seed companies (PSCs), e.g. SEAN SEED CO. LTD., Gorkha Seed Co. Pvt. Ltd., and Karma Seed Co. Pvt. Ltd., were consulted. The study used a rapid, mixed-methods approach, combining both qualitative and quantitative tools for data collection.

2. Desk review

The initial phase involved a desk review of relevant secondary data, reports, and publications. This included information on status of seed import, hybrid seed production, the agro-ecological suitability, climatic requirements, and market trends for hybrid seed production of vegetables. Sources included PowerPoint presentations, government reports, newspapers, peer-reviewed journal articles, policy documents, manuals, and official information from Ministry of Agriculture and Livestock Development of Nepal.

3. Key informant interviews (KIIs)

Field data collection consisted of KIIs with farmers from the Dolakha, Dailekh, Kathmandu and with scientists from the PSCs. Total 6 KIIs were conducted, providing an in-depth understanding of seed companies aim and their current activities and plans on hybrid seed production of vegetables.

4. Analytical approach

The study team comprised experts from both the public and private sectors, representing research, quality control, extension, and academia. Each member independently collected data relevant to their area of expertise. The selection of potential vegetable crops for hybrid seed production was primarily guided by seed import-export data maintained by the Seed Quality Control Center, alongside the technical feasibility of hybridization within the Nepalese context. Insights from scientists at seed companies and farmers regarding hybrid seed production technologies and potential market demand were gathered through personal consultations. Additionally, the authors have incorporated their insights and experiences during the data analysis where relevant. Based on information collected through desk reviews and key informant interviews (KIIs), a SWOT analysis highlighting the strengths, weaknesses, opportunities, and threats was conducted for the selected vegetable crops using established criteria (Section 2.5).

5. Selection criteria of vegetable crop for hybrid seed production

The selection of vegetable crops for hybrid seed production was guided by a set of strategic and technical criteria aimed at ensuring both viability and long-term sustainability. Market demand was a key consideration, assessed through formal seed import data to determine economic potential and commercial interest. Germplasm access was also critical, focusing on the ease of acquiring or developing genetic resources, with particular attention to the challenges faced by the private sector in accessing proprietary germplasm. The technical feasibility of hybridization, including the capacity to maintain generation-wise seed supply, was evaluated to ensure practical implementation. Adaptability of crops to Nepal's diverse agro-climatic zones was prioritized to maximize agro-ecological suitability and success rates. In addition, emphasis was placed on import substitution and identifying opportunity crops that could not only reduce dependency on foreign seeds but also create local income and employment. Finally, the potential for custom seed production was explored to address specific market needs and preferences.

Current Scenario of Hybrid Seed Research and Production

1. Status of vegetable production

Nepal's diverse geography and climatic conditions allow for the cultivation of a wide range of vegetables, from root crops to leafy greens. In FY 2022/023, the total area under vegetable cultivation was 302,135 hectares, with a production of 4,370,77 metric tons, an increase of 4% and 5.4%, respectively, compared to the previous year (MoALD, 2024)Agriculture, forestry and fishing contributed 24.1% to the gross domestic product in FY 2022/023, where vegetables contributed 13.4 % to the agricultural GDP, with significant contributions to rural incomes and local diets (MoALD, 2024).

Key vegetable crops registered in Nepal consist of over 277 varieties from more than 41 different species (SQCC 2024), all recommended for cultivation by the National Seed Board (Table 1).

Table 1: Number of vegetable crop varieties notified by the Nepal government till 2024

S. N.	Vegetables	Registered	Released	Total notified varieties	Hybrids
1	Cauliflower	24	4	28	24
2	Tomato	18	6	24	20
3	Cabbage	23	1	24	23
4	Cucumber	23	1	24	22
5	Hot pepper	15	1	16	15
6	Radish	10	4	14	6
7	Squash	11	1	12	10
8	Bitter gourd	10	1	11	10
9	Sweet pepper	2	1	3	1
10	Brinjal	5	1	6	4
11	Broccoli	7		7	7
12	Others	108	28	76	32
	Total	277	170	224	53
Among 277 varieties	National hybrid varieties	3	2	5	
	Imported hybrid varieties	170	-	170	

Extension services are offered by 753 local government units and 77 provincial agricultural knowledge centers or development offices. Nepal's top vegetable-producing regions include the Terai plains, known for their fertile soils and favorable climate, as well as hilly areas where farmers grow a diverse range of crops, including vegetables. Due to the scarcity of locally bred hybrid vegetable varieties, extension service centers often recommend seeds of imported crop varieties for commercial use.

2. Research activities

The National Horticulture Research Centre, in collaboration with different research centers and their stations under the Nepal Agricultural Research Council (NARC), is spearheading variety development activities in the country. To date, a total of 277 varieties across 41 vegetable crops have been developed. Of these, 53 varieties have been released and 224 registered in Nepal (Table 1). A significant majority of the registered varieties (89%) are exotic, with only 11% developed locally. In contrast, among the released varieties, 95% are locally developed in Nepal (SQCC 2024).

The Seed Act 2045 and Seed Rules 2081 of Nepal mandate both public and private sectors to participate in crop research and variety development. Notably, no hybrid varieties from the private sector have been released or registered in the country to date. Among the domestic varieties, only five are hybrids (two released and three registered), while out of the 224 registered exotic varieties, 75.9% are hybrids. NARC has developed several hybrids: Srijana (registered in 2010), Khumal Tomato Hybrid-2 and Khumal Tomato Hybrid-3 (both released in 2021) for tomatoes, as well as Madhu and Krishna (both registered in 2022) for cucumbers. The National Seed Vision 2013-2025 (NSV) aimed to develop 30 hybrid varieties of vegetable crops (20 from public and 10 from private research institutes), but current progress has fallen short of this target (SQCC, 2013).

In Nepal, variety improvement traditionally relies on phenotypic selection of parent plants and their offspring, resulting in a slow process that does not meet the demands of modern commercial agriculture. Agro-morphological characterization dominates crop research and a variety improvement activity. Additionally, this phenotypic selection can be unreliable, as phenotypes can be changed due to age, environmental influences, and agro-ecological conditions. Moreover, phenotypic traits often arise from the interaction of multiple genes, resulting in complex inheritance patterns that may not be immediately apparent (Miko 2008).

Nepalese vegetable breeders are not getting the advantage of modern 'omics' approaches (Joshi and Ayer 2020). Genotyping approaches like quantitative trait loci mapping, association mapping, markers assisted selection and genomic selection, which are crucial for trait discovery, inbred development and parent selection. Optimization of hybridization protocols, use of cytoplasmic male sterility (CMS) and thermosensitive genic male sterile (TGMS) lines is necessary for potential vegetable crops to accelerate the hybridization process which is currently limited around manual emasculation and pollination (Simko et al. 2021). National agriculture research systems lag in participatory plant breeding and variety selection activities in the case of vegetables. Involvement of farmers in the variety development process right from the beginning of trait and parent selection is important. At later stage, seed increase of promising pre-released vegetable varieties facilitates large-scale participatory variety selection in target environments. However, increasing the F1 seed production for a portfolio of pipeline varieties requires more time, dedicated manpower, and guaranteed financial resources (De Jonge et al., 2021).

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In Nepal, investment in research and development remains relatively low. The Nepal government allocates approximately 1% of its budget to research activities, reflecting limited prioritization of innovation and long-term productivity gains within the sector (Dhakal 2024, TKP 2024). In contrast, the private sector's contribution to research is even more modest, with allocations estimated to be less than 1%, often described as merely traceable. This disparity highlights a critical gap in sustained research investment needed to drive advancements in technologies, including agricultural research and development, crop diversification, and climate-resilient practices. Strengthening public-private partnerships and increasing funding for research are essential steps toward achieving sustainable agricultural growth (Sokona et al. 2013).

3. Hybrid seed research and production activities in Nepal

Hybridization in Nepal was first initiated in 1964 with potato by Gopal R. Rajbhandari, a scientist at the NARC.

Later, in 1999, formal crop breeding program at Agriculture Botany Division began in rice. Beyond NARC, involvement from academia and the private sector in hybridization and hybrid seed research and production began only much later (Joshi 2017b). Universities in Nepal have initiated basic research activities focused on testing hybrid varieties of vegetable that are better suited to local climatic conditions and market demands. Current curricular activities often emphasize the theoretical knowledge of the use of basic breeding techniques at the undergraduate level and advanced breeding techniques, including molecular markers and genomic selection at postgraduate and doctorate levels. However, hybrid-focused practical activities on research and variety development are still lacking in almost all universities. The academic landscape is still static, positioning the universities merely as a tuition center for hybrid seed production techniques. Advanced field-testing facilities, climate chambers, greenhouses, and laboratories equipped with modern molecular facilities at Nepalese agricultural universities are still a distant reality. Private sector seed companies share the same situation as universities in Nepal. Recently seven seed companies were permitted for hybrid seed production of crops and vegetables (SQCC, 2025).

4. Status of seed import

With the increasing demand for organic and high-quality produce in both domestic and international markets, the potential for vegetable exports has also grown. In Nepal, the total area under vegetable cultivation was 302,135 hectares, producing 4,376,077 metric tons of fresh vegetables (MoALD 2024). Based on this acreage, the estimated annual requirement for vegetable seeds is around 2,500 metric tons. Hybrid seeds contribute to over 80% of total fresh vegetable production, while the remaining share is met by non-hybrid, open-pollinated varieties. A significant number of seeds are being imported to Nepal to fulfill the demand for high-quality seeds. Table 2 summarizes the status of hybrid seed imports in FY 2022/23 (SQC,C 2025).

In the fiscal year 2022/2023, the total value of formally imported hybrid seeds amounted to 5,022 thousand USD (Table 2). Of this total, cauliflower accounted for 27.1%, followed by cabbage with a 10.2% share. Radish contributed 9.1%, bitter gourd 9%, and tomato 8.6% to the overall import value. During the same FY, Nepal has formally imported 569.93 MT of vegetable seeds of value 6,795 thousand USD where hybrid seed contributed by 12% to the quantity and 74% to the value (SQCC 2025).

Table 2: Status of seed import/export in the FY 2022/023

S.N.	Vegetables	Seed quantity, kg	Hybrid seed import, value in USD	Percent share in total value
1	Cauliflower	5,385.90	1,359,766.66	27.1%
2	Tomato	717.50	430,733.00	8.6%
3	Cabbage	3,148.85	513,476.50	10.2%
4	Cucumber	2,025.00	366,220.41	7.3%
5	Hot pepper	723.20	179,167.78	3.6%
6	Radish	23,800.00	452,725.00	9.0%
7	Squash	1,076.00	96,382.00	1.9%
8	Bitter gourd	3,956.00	457,462.62	9.1%
9	Sweet pepper	110.00	32,312.78	0.6%
10	Brinjal	110.00	14,421.05	0.3%
11	Broccoli	353.00	121,822.00	2.4%
12	Other vegetables	28,863.00	997,580.19	19.9%
	Total	**70,268.45**	**5,022,069.99**	

5. Private sector in hybrid seed production

The private sector's involvement in hybrid seed crop research and development in Nepal is limited. Despite global success in hybrid seed production, the private sector in Nepal has made limited contributions to crop research and hybrid seed development, focusing primarily on the trade and distribution of imported hybrid seeds. The National Seed Vision (NSV) aimed to develop 10 vegetable hybrids from the private sector but did not outline a clear strategy to achieve this goal (SQCC, 2013).

Four seed companies have been granted licenses for hybrid seed production in Nepal, with five others awaiting approval from the National Seed Board (NSB). Additionally, three companies have received licenses for research for development (RandD) activities, but their scope remains minimal. Initial optimism around these licenses has not resulted in significant progress due to constraints such as limited human resources, insufficient RandD investment, and lack of infrastructure.

Private companies also face challenges in accessing public germplasms and modern facilities, including laboratories and field trials, which are vital for effective research. At the International Seed Conference 2024 in Kathmandu, some private seed companies entered Memorandums of Understanding (MoU) with foreign counterparts to collaborate on custom seed production and joint research for developing new vegetable hybrids. However, the success of these collaborations might be challenging due to the Nepalese private sector's weak market intelligence and networking capabilities, hindering their ability to leverage international partnerships, access advanced technology, and respond to global market demands effectively. Sanitary and phytosanitary requirements in the exchange of seeds and planting materials can pose a significant hurdle to custom seed production in Nepal. Globally, practices such as Pest Risk Assessment (PRA) and the issuance of phytosanitary certificates supported by advanced laboratory facilities are standard in international seed trade. However, in Nepal, limited institutional capacity, poor infrastructure, and insufficient technical expertise will hinder timely compliance with these international standards. This may result in slow growth of Nepalese seed sub-sector.

6. Promising Vegetable Crops for Hybrid Seed Production

This study has selected few most promising vegetable crops for hybrid seed production. This is done based on the selection criteria mentioned in the methodology of the study. Starting with a selected number of successful varieties will be advantageous, as it enables the gaining of experience and promotes adoption among farmers. Once the seed production for these initial crops is established, other crops can be explored for hybrid development.

6.1. Tomato

The consumption of tomatoes has risen significantly, both in local markets and for export purposes. The cross-border Indian market, along with some global demand for fresh and processed tomato products, presents valuable opportunities for Nepalese farmers. Strong seed demand in the local market is evident from the import statistics (Table 2).

Hybrid tomato seed production has become a success story in Nepal, demonstrating both technical feasibility and economic viability. For over a decade, many farmers have been producing seeds of the hybrid tomato variety Srijana F1. In addition, several seed companies have developed and marketed their hybrid tomato varieties. For example, SEAN SEED CO. LTD. has introduced Chandragiri and Malika F1, while Gorkha Seed Co. Pvt. Ltd. markets Samjhana, Tirsana, and Jharana hybrids. However, all varieties developed by PSCs have to be registered with the National Seed Board. Hybridization technology is accessible and particularly suited for young farmers. Recently, custom seed production for tomatoes has been successfully tested in Dolakha and Lamjung districts of Nepal. This approach offers a dual benefit: farmers can earn income while gaining valuable experience. Additionally, it provides opportunities to enhance capacity in virus screening and phytosanitary measures.

6.2. Hot and Sweet pepper

Urbanization has led to an increased demand for fresh vegetables, including hot and sweet (bell) peppers. The trend towards healthy eating continues to drive their popularity. Seed demand for both crops is notable in the Nepalese seed market (Table 2).

Hybrids can provide improved fruit size, color, and taste while enhancing resistance to pests like aphids and thrips, thereby reducing losses. Hybridization techniques for sweet pepper are similar to those used in tomato, making them easier to learn and well-suited for youth engagement. In fact, custom seed production of sweet pepper has already begun in Nepal, particularly in Thankot, Kathmandu.

6.3. Brinjal

The data (Table 2) showed that there is good demand for brinjal seed in the domestic market. Hybridization techniques are easier like tomatoes and peppers. Custom seed production of wild brinjal is tested in Nepal targeting export to Japan, however it is still in the piloting phase. This needs to be expanded in the future.

6.4. Cucumber

Cucumber demand peaks during the summer months, and its popularity continues to rise in urban areas. The total annual sales value of cucumber seeds (Table 2) highlights the crop's market potential. Hybrid cucumber varieties, known for their faster growth, higher yields, and uniform fruit size, are particularly appealing to both consumers and retailers.

The NARC has already developed two hybrid cucumber varieties: Madhu and Krishna, which are ready for commercial seed production. Additionally, the hybridization technique is well established, making it easily transferable to young farmers for widespread adoption.

6.5. Brassicas

Seeds of brassicas (e.g. cauliflower, cabbage, radish, broccoli, etc.) are being supplied in Nepal via import and share quite large amount of import values. This indicates huge market potential. Suitable hybridization techniques need to be researched and applied for the production of hybrid seeds in the country and substitute the imports.

6.6. Cucurbits

Like brassicas, hybrid seed of cucurbits (e.g., bitter gourds, pumpkins, gourds, etc.) possess good market demand and scientists working on them are required to start breeding programs.

7. SWOT analysis of six selected vegetables for hybrid seed production

A strength, weaknesses, opportunities, and threats (SWOT) analysis was conducted for hybrid seed production of vegetable crops discussed in section 3.6. The SWOT associated with hybrid seed production of vegetable crops tomato, hot and sweet pepper, brinjal, cucumber, brassicas and cucurbits are tabulated in Table 3.

Table 3: Strengths, weaknesses, opportunities and threats assessed for hybrid seed production of vegetables from the Solanaceae, cucurbitaceae, *and* Brassicaceae families

Strengths		Weaknesses	
Proven success in hybrid seed production (e.g. Srijana, Madhu)	Growing vegetable demand due to urbanization and health trends	Domestically developed hybrids need to be registered with National Seed Board	Shortage of skilled labor and limited extension services
Technically feasible and economically viable venture	Hybrids improve fruit quality and pest resistance	Limited skilled breeders and molecular lab facilities	Weaker law enforcement and field monitoring
Accessible hybridization techniques, suitable for youth	High demand for custom seed production	Increasing infestation of insect pests and diseases	Custom seed production is still in pilot stage
Seed companies have developed own hybrids (e.g. tomatoes)	High yield and uniformity in hybrids	Illegal inflow of sub-standard seeds from outside	Lack of dedicated breeding programs
Wide range of crops within Brassicaceae and Cucurbitaceae family		Limited market information and extension support	
Opportunities		Threats	
Strong local demand and potential for export	Opportunities for import substitution	Climate change and pest/disease pressure	Cross-pollination risks and lack of zoning
Custom seed production tested in Dolakha and Lamjung	Easy to transfer hybridization skills to youth	Policy and regulatory uncertainty	Unpredictable climate may affect yield and quality
Scope for youth employment and skill-building	Potential to scale up for export (e.g., to Japan)	Risk of seed purity loss due to poor isolation	Uncertainty in success of piloting phase and seed export
Potential to produce and distribute local hybrids	Could engage local producers in niche export markets	Sanitary and phytosanitary measures and issuance of phytosanitary certificate compliance to international standard	Low investment in infrastructure and technical support in academia, publica and private research institutions
Learning opportunities for agricultural graduates		Tough price competition in the local seed market	

Hybrid Seed Production Techniques

Hybrid seed production involves complex breeding techniques and technological innovations that require specialized expertise and careful field management (Chakrabarty et al. 2023)harnessing the advantage of heterosis between two diverse genotypes to achieve maximum hybrid vigour, is widely recognized and commercially used for crop variety improvement both in field and vegetable crops. Hybrids can be developed using appropriate technology, irrespective of the mating and pollination system in the plant species. Production of hybrid seed depends on plant, pollinator and environmental factors, which influence it individually or in interactive ways. Hence, an understanding of these components is important to undertake hybrid seed production of a given crop species. The basic requirements for hybrid seed production at a commercial scale are (a. These three components, breeding techniques, technological innovations, and field management, play a critical role in ensuring the success of hybrid seed production and marketing programs. Their use and importance are briefly discussed in the following subsections, with reference to Nepalese context.

1. Breeding techniques

1.1. Inbred line development

Inbreeding is used to develop stable inbred lines which are then used in hybrid production. This is a common method to expand the gene pool. This involves self-pollination and repeated self-pollination over several generations to stabilize the desired traits in line to ensure genetic purity and stability. This will be followed by line selection. Line selection identifies and selects lines with consistent performance and desirable traits for hybridization.

1.2. Controlled pollination

Controlled pollination is essential in hybrid seed production. It involves deliberately cross-pollinating two distinct parent plants to combine desirable traits from both. The primary steps include:

- Selection of parent lines: Choosing two genetically distinct parent lines that exhibit desirable characteristics.
- Isolation: Preventing unwanted pollen from contaminating the flowers of the selected plants, often using physical barriers or spatial separation.
- Pollination: Transferring pollen from the male parent to the female parent, either manually or through controlled mechanical means.
- Seed harvesting: Collecting seeds from the fertilized flowers, which will carry the hybrid genetic material.

1.3. Hybridization

Hybridization is the process of crossing two different varieties or species to produce hybrids with specific traits:

- Interspecific hybridization: Crossing between different species within the same genus (e.g., different tomato species).
- Intraspecific hybridization: Crossing between different varieties within the same species (e.g., different varieties of tomatoes).

1.4. Selection methods

- Phenotypic selection: Based on morpho-physio and agronomical responses, a commonly used method in Nepal, time-consuming and costly.
- Marker-assisted selection (MAS): Using molecular markers linked to desirable traits to select parent plants for crossing. MAS accelerates the breeding process by identifying beneficial traits at the DNA level.
- Genomic selection: Utilizing high-throughput genomic data to predict the performance of hybrids based on the genetic makeup of the parents.

1.5. Field testing and evaluation

Performance metrics such as yield per hectare, disease resistance, climate resilience, nutritional content, seed production economy, and market competitiveness should be assessed. Comparisons are made between new and market-leading hybrid varieties to determine the advantages and limitations of each. Distinctness, uniformity and stability (DUS) testing and characterizations (genotyping and phenotyping) of each variety are imperative. Once hybrids are developed, they undergo rigorous field testing:

- Performance trials: Testing hybrids in various environmental conditions to evaluate their performance, including yield, disease resistance, and adaptation.
- Selection and optimization: Selecting the best-performing hybrids and optimizing production practices based on trial results.

Each technique is essential for developing hybrids that combine beneficial traits from different parent plants, leading to enhanced crop varieties with improved performance and resilience. It's important to ensure meaningful participation from farmers, traders, and extension workers at every stage, fostering a participatory approach that promotes shared ownership of the newly developed products.

2. Technological innovations

Adopting modern technologies can significantly enhance hybrid seed production in Nepal by improving breeding efficiency, accuracy, and speed. Although still in very early stages of adoption in Nepal, methods such as genome-wide association studies (GWAS) and CMS are some potential tools to identify desirable traits and streamline hybrid development. Advanced genomic tools like MAS, double haploid (DH) technique, and gene editing can reduce the time and cost associated with conventional breeding by enabling early selection of superior genotypes. Furthermore, breeders can use information shared over digital sequence information (DSI) platform to access genomic data and shorten the breeding cycle.

2.1. GWAS: A GWAS is a method used to identify associated genomes of interest. When genome sequences are mapped to individual genes, GWAS can help preliminarily identify candidate genes that control these traits based on both genotypic and phenotypic data (Samineni et al. 2022).

2.2. CMS: CMS is a method used to produce hybrids by preventing the production of functional pollen in one parent. Hybrids are produced from crossing CMS lines with donor lines (producer of viable pollen).

2.3. Resequencing and decoding: Resequencing involves periodic gene sequencing to uncover potential genetic variants or polymorphisms within individuals and across groups.

2.4. Genomic-assisted breeding/Marker-assisted selection and gene editing: The use of genomic tools in plant breeding, known as genomics-assisted breeding, has evolved significantly over the past few decades. Nowadays Single Nucleotide Polymorphisms (SNPs), Diversity Arrays Technology (DArTs), Genotyping-by-Sequencing (GBS), and Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) and CRISPR-associated protein 9 (CRISPR-Cas9) are being used to select genotypes with desirable traits early in the breeding process, reducing the time and cost of field trials while improving selection accuracy (Kumar et al. 2023, Li et al. 2022, Zafar et al. 2020) which poses serious threat to food security. Both heat and drought stress affects the production and productivity of wheat crop. The present study was undertaken to evaluate 34 landraces and elite cultivars of Triticum spp. for phenological and yield-related traits under optimum, heat, and combined heat–drought stress environments during 2020–2021 and 2021–2022. The pooled analysis of variance showed significant genotype × environment interaction, suggesting an influence of stress on trait expression. The trait performance of genotypes exhibited significant reduction under combined heat–drought stress as compared to optimum and heat stress environments. The maximum seed yield penalty was observed under combined heat–drought stress environment as compared to heat stress alone. Regression analysis indicated significant contribution of number of grains per spike towards stress tolerance. Based on Stress Tolerance Index (STI.

2.5. Haplotype-assisted breeding: It is a form of genomic assisted breeding (GAB), accelerates the breeding process and helps address issues related to linkage drag, enabling a more efficient selection of desirable traits (Sivabharathi et al. 2024). A haplotype refers to a specific combination of alleles at multiple loci that are inherited together (He et al. 2023). This method assists in targeting specific genetic markers associated with desirable traits, hence enhancing the likelihood of achieving favorable outcomes and reducing the resources and time needed to develop new varieties (Bailey-Serres et al. 2019).

2.6. Use of double haploid technique: This technique involves producing homozygous lines from haploid cells, which contain only one set of chromosomes. By inducing these haploids to double their chromosome number, researchers can create double haploids that are completely homozygous. This is particularly advantageous in plant breeding, as it allows for the immediate fixation of desirable traits in a uniform genetic background, reducing the number of generations typically required to achieve homozygosity through traditional breeding methods (Karkee et al. 2022, Dwivedi 2015). One common application of the double haploid technique is in the development of hybrid crops where breeders can quickly assess traits of interest (Karkee et al. 2022).

2.7. DSI: DSI refers to the nucleic acid sequence data obtained from genetic resources. It serves as a valuable research tool rather than a final product, aiding in securing patents and proprietary rights for innovations. Most DSI is freely accessible online, facilitating the exchange of information among academic researchers in studying hard-to-measure attributes during crop improvement and breeding. The ultimate aim is to produce innovative plant genetic resources in the form of seeds and other planting materials for farmers. DSI offers significant time and cost savings for plant breeders, as it streamlines the process of developing new crop varieties.

3. Field management practices

Effective input management is a crucial strategy for advancing vegetable crop research and hybrid seed production. Field management plays crucial roles while optimizing breeding techniques, using technological innovation and mobilizing various inputs. Upon efficient management of research plots and seed bulking zones, researchers and producers can enhance crop yields, improve seed quality, and streamline operations. Interconnected discussion at key inputs involved in this field is explained in subsequent subsections.

3.1. Infrastructure

Controlled environment greenhouses offer optimal conditions for stock seed maintenance, plant growth, and hybridization. Conditional storage ensures seed quality for a longer time. These facilities use advanced climate control systems to regulate temperature, humidity, and light, ensuring ideal growing conditions and storage year-round. Molecular laboratories equipped with cutting-edge technology enable detailed genetic analysis and gene editing facilities.

3.2. Irrigation

Efficient irrigation systems are vital for maintaining optimal soil moisture levels. Advanced techniques like drip irrigation and precision irrigation technologies ensure that water is delivered directly to plant roots, reducing waste and improving crop performance.

3.3. Soil health and fertilizer

Good soil health always keeps plants growing well and ensures higher production. The application of fertilizers must be managed carefully to provide the right nutrients at the right time. Precision agriculture tools help in tailoring fertilizer applications based on soil nutrient levels, thereby enhancing crop growth and minimizing environmental impact. The use of organic fertilizers and getting the produced hybrid seed certified organically will help in value addition. Organic fertilizers help increase soil organic matter, which can enhance carbon sequestration. This contributes to mitigating climate change by storing carbon in the soil.

3.4. Pest control

Integrated pest management (IPM) strategies combine biological, cultural, and physical methods to control pests while reducing reliance on harmful pesticides. Regular monitoring and the use of pest-resistant vegetable crop varieties also play a crucial role.

3.5. Skilled labor

Expertise in various aspects of vegetable crop research and hybrid seed production is essential. Skilled labor is needed for tasks such as plant breeding, gene editing, DH line development, disease diagnosis, data analysis, and precise handling of experimental procedures.

3.6. Mechanization

Modern mechanization, including planting machines, harvesters, processing equipment, seed coating, and pelleting facilities, increases efficiency and reduces labor costs. Automated systems also help in precise and consistent operations.

3.7. Software for data recording

Data management software is indispensable for recording and analyzing research data. It helps track crop performance, monitor experimental results, and make informed decisions based on comprehensive data analysis.

Challenges and Opportunities

Strengths, weaknesses, opportunities, and threats in the hybrid seed production of targeted crop varieties have been tabulated under the section 3.7 above. Here, overall challenges and opportunities were assessed and presented under this section for further clarity and recommendation.

1. Challenges

1.1. Technical know-how

There is a shortage of skilled labor and technical expertise including scientific manpower in hybrid seed production in Nepal. Almost all seed companies are running a shortage of full-time breeders in their RandD activities. Many farmers lack access to training and resources, limiting their ability to adopt new technologies. Research institutions are using traditional breeding methods instead of advanced genetic techniques, limiting the potential for yield improvements. There is a lack of agricultural extension workers to provide farmers with the necessary training and support in hybrid seed production and promotion. Nepal's seed sub-sector lacks a modern molecular seed laboratory to profile DNA, screen viruses, and provide efficient phytosanitary services to the seed companies.

1.2. Economic barriers

The high initial investment required for hybrid seed production can deter small-sized seed companies and research institutions. Hybrid seed production demands high input costs from the very beginning of the activities. Access to credit and financial resources is often limited, making it difficult for them to invest in quality seeds and inputs. The poor economic status is well reflected in very low investment in infrastructure, transportation, processing, and storage facilities.

1.3. Quality assurance

Inadequate human resources and knowledge deficiency are well reflected in seed quality assurance. Seed quality control agencies also lack sufficient resources to keep the whole seed value chain on the right track. Inefficient seed certification systems can allow substandard seeds to enter the market, affecting overall crop performance. There exists a high risk of seed contamination at production fields and threshing floors. Inadequate measures to control cross-pollination can result in the mixing of hybrid and non-hybrid seeds, compromising purity. A lack of coherent policies supporting hybrid seed production can create uncertainty for investors. Lacking policies in seed zoning, germplasm acquisition, and foreign investment is another hindrance to hybrid seed production and long-term agricultural practices.

1.4. Environmental factors

Most of the seed production activities are dispersed in many small pockets, posing challenges in maintaining isolation. Proper zoning for seed production is lacking. Climate change poses significant risks to hybrid seed production in Nepal. Unpredictable weather patterns, such as erratic rainfall and increased temperatures, can adversely affect seed yields and stability. High pressure of pests and diseases exists in the seed production plots. A lack of integrated pest management practices can lead to significant crop losses due to pests and diseases.

1.5. Socio-economic factors

This also play roles in the seed production environment. Most of the youth from households are not in farming. Lack of market information about market trends and the demand for specific hybrid varieties, impacting their production choices. Many farmers may prefer traditional varieties, leading to resistance against adopting new hybrids, even when they are potentially more productive. Women are often involved in seed production but face additional challenges in accessing resources and training. Traditional agricultural practices and beliefs may hinder the acceptance and adoption of hybrid seeds.

2. Opportunities

2.1. Emerging markets

The increasing demand for fresh, organic, and high-quality vegetables, both domestically and internationally, provides a significant opportunity for Nepalese farmers to capitalize on the hybrid seed market. Export of fresh and dried vegetables to Arabian countries and abroad has already been initiated. There are also higher possibilities to substitute the seed import from local breeding programs. Similarly, Nepal can be a custom seed production hub for international seed companies, for example, Japan. Testing for custom seed production of tomatoes has already been initiated.

2.2. Government support

The Nepal government has recognized the importance of agricultural innovation and has implemented policies to promote hybrid seed production. Newly formulated seed regulation (insert name/reference here) has opened the avenue for custom seed production and simplified the variety registration procedures of vegetables. Moreover, the Nepalese seed system is becoming digitalized where seed demand and supply can be placed, and breeders can apply for their variety registration (insert reference). There is a provision for hybrid seed production and RandD licenses for capable seed companies who are willing to invest in the sector. Nepal government has accepted the involvement of plant breeders and seed technologists from the public sector in the private firms as part-time service providers.

2.3. Scope for collaboration

Collaboration in the seed sub-sector is now a widely discussed concept and drawing multi-sectoral interests. Strengthening partnerships between the Department of Agriculture, Nepal Agricultural Research Council, Tribhuvan University, NGOs, and private sector players can enhance knowledge sharing and resource allocation, leading to more effective hybrid seed production initiatives. NARC and PSCs can jointly or individually develop new varieties that DoA and Universities can use in their extension and teaching programs. Universities can utilize the opportunities to focus on market-led seed production curricula, where fresh graduates can be encouraged to start-ups with seed entrepreneurship. Expertise from academia and research institutes have scope for collaboration in hybrid seed production.

2.4. International funding and expertise

Engaging with international agricultural organizations can bring in technical expertise and funding to support research and development in hybrid seed production. Nepal seed sub-sector can collaborate to invite funds for hybrid seed production and technology transfer. Germplasm accessions and capacity-building programs with support from international line agencies seem possible.

Strategies

1. Short-term strategies

Some strategies are recommended as short-term strategies (0 – 2 years) anticipating their quick output in the field of hybrid seed production.

1.1. Policy and institutional reforms

- Simplify licensing and registration processes for hybrid seed producers. There are experienced farmers who do not have license for hybrid seed production. Seed act and rules demands long list of documents to fulfil the licensing requirement. Similarly, variety registration of locally bred hybrids should avoid registration processes and should allow to sale in market as research variety at commercial scale.
- Prioritize hybrid seed production in national agricultural policies. Government agencies should put local varieties in the list of subsidized seed mini-kits and household nutritional program.
- Provide tax breaks, soft loans, and revolving funds to private seed companies those actively engaged in variety development and hybrid seed production in the country.

1.2. Pilot hybrid seed production

- Begin with technically feasible crops like brinjal, sweet pepper, and brinjal for testing hybrid seed production in the specified location.
- Scale up the seed production of already tested crop varieties like tomato and cucumber at commercial scale.
- Implement contract seed production with buy-back guarantees.

1.3. Capacity building and extension

- Conduct hands-on training for agricultural students, farmers and technicians on hybrid seed production, pest management, soil revitalization techniques, socio-economic importance of seed business.
- Launch awareness campaigns and field demonstrations at model government and private sector farms showcasing performances, comparative tolerances to surroundings, and yield and quality potentials of hybrid varieties.

1.4. Infrastructure and lab development

- Establish a molecular lab for RT-PCR testing, genotyping, and quality assurance of produced seed before distribution.
- Improve basic infrastructure required for field trials, post-harvest handling of seeds and value addition, for instance, irrigation, net/poly houses, threshing floors, and compost pits.

2. Mid-term strategies

Some strategies are recommended as mid-term strategies (2 – 5 years) anticipating their impact for long run in the field of hybrid seed production.

2.1. Institutional strengthening

- Establish a hybrid seed production unit (HSPU) under Seed Quality Control Centre (SQCC) with representation from NARC, universities, and PSCs. Such a unit should aim at looking after hybrid seed production and monitoring activities, and facilitating the genetic resources management for the national hybrid seed production programs. The HSPU should maintain data related to hybrid seed production, import, export and marketing and provide support to PSCs for data analysis and interpretation. The team may also conduct training sessions for researchers and practitioners on hybrid seed production, data analysis, modern tools and techniques in the field of plant breeding.

- Set up demo farms or convert existing seed production farms of Nepal government as hybrid seed production learning centers in close collaboration with local governments.

2.2. RandD and technology adoption

- Initiate use of GWAS, CMS, MAS, and double haploid techniques at laboratories that were stablished under short-term strategy. Allocate sufficient human resources and lab equipment for the full functioning of molecular labs.
- Promote public-private breeding partnerships and incentivize breeders through bonuses and royalties.

2.3. Policy formulation for foreign investment and intellectual property rights (IPR)

- Introduce provisions for tax incentives and financial leverages to encourage investment in hybrid seed production.
- Formulate and implement a policy framework that attracts foreign direct investment (FDI) in Nepal's hybrid seed industry.
- Develop and enforce a Plant Breeders' and Farmers' Rights (PB and FR) Act to effectively manage intellectual property rights (IPR) in the seed sector.

2.4. Hybrid seed production expansion

- Extend hybrid seed production to moderately complex but highly market potential crops like cauliflower, cabbage, and gourds.
- Position Nepal as a custom hybrid seed production hub for international seed companies by facilitating phytosanitary and pest surveillance services by Nepal government.

2.5. Market development

- Promote locally bred hybrid varieties through public campaigns and integrate into government procurement/subsidy programs.
- Conduct market study and survey, understand the dynamics of seed market and create market for Nepal-produced hybrid seeds through advertising and championing.
- Encourage cooperatives to take up contract production linked to seed markets.
- Provide financial support or subsidy to PSCs for organizing market promotional visits like rewards, farmer's tours, traders' visits, etc.

2.6. Education and curriculum

- Integrate hybrid seed production into university and school curricula.
- Provide assistantships and scholarships for graduates to do research on hybrid seed production and value addition technologies.
- Establish non-degree seed entrepreneurship programs in seed production areas.
- Link theories of seed production and marketing with seed entrepreneurships via motivational classes, demos and visits to the national seed companies.

3. Long-term strategies

Some strategies are recommended as long-term strategies (>5 years) anticipating flourishing the Nepalese seed industry via advancement in hybrid seed production and marketing.

3.1. Advanced RandD and innovation

- Fully integrate genotype–phenotype mapping and use of DH technique, CMS, MAS, DSI in plant breeding programs.
- Develop species-specific reference genomes for key vegetable crops.
- Claim and secure geographical indication (GI) tag for developed vegetable varieties, existing landraces for their unique trade values, facilitating the 'trade of traits'.
- Extend hybrid seed production to complex crops like radish, onion, cowpea, carrot, soybean, etc.

3.2. Infrastructure and enterprise development

- Support the formation of mega seed companies to drive hybrid innovation and export.

- Invest in long-term infrastructure for seed processing, storage, and logistics.

3.3. Policy evolution and evaluation

- Regularly monitor and adjust/optimize hybrid seed policies based on field impact.
- Strengthen plant variety protection laws and IPR for breeder innovations.
- Optimize and execute the tax, FDI, and subsidy policies in favor of agricultural industry.

Conclusion

Hybrid seed production of vegetable crops holds immense potential to transform Nepal's vegetable seed sub-sector by enhancing productivity, improving seed sovereignty, and opening pathways for commercial horticulture and seed export opportunities. This strategic review identifies key vegetable crops such as tomato, pepper, cucumber, and brinjal as immediate candidates for hybrid seed development due to their technical feasibility, market demand, and past production success. Despite these opportunities, Nepal's hybrid seed industry remains in its infancy, hindered by limited investment in RandD, inadequate infrastructure, weak policy enforcement, and low private-sector innovation. However, the convergence of growing domestic demand, evolving seed policies, and international interest in custom seed production presents a critical window for intervention. To harness these prospects, Nepal must adopt a multi-tiered approach in seed sub-sector: investing in modern breeding technologies (e.g., CMS, MAS, DH), enabling public-private-academic partnerships, and fostering youth involvement through entrepreneurship and education. Establishing a strong institutional backbone such as a national hybrid seed coordination unit and molecular seed labs will be crucial. Ultimately, achieving seed security through hybridization requires more than technical solutions; it demands political will, collaborative leadership, and long-term strategic commitment. If aligned effectively, Nepal can reduce dependency on seed imports, empower farmers, and position itself as a regional hub for hybrid vegetable seed innovation.

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