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Going for Hybrid Crops Breeding in Nepal: Strategies and Policy Dimensions

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Abstract

Crop Breeding programs were initiated in Nepal in 1951 with a focus on the varietal improvement of cereal crops. These varieties, however, have limited impact in the farmers' field due to their low adaptation and low yield potential. Nepal annually imports hybrid seeds of cereals, vegetables, and flowers from India, China, and elsewhere costing billions of Rupees. It is estimated that approximately 73% of the vegetable seeds and over 60% of the hybrid seeds of maize and rice are imported annually. Hybrid seeds generally produce 20-25% more yield than conventional varieties. Despite this fact, only about 15% of maize and <10% of rice acreage in Nepal has hybrid seeds compared to over 50-60% in China. Nepal is behind in developing policies for genetic innovations, including genetics and breeding, utilizing genetic diversity, and using new biotechnological traits such as golden rice and drought-tolerant wheat, which could be important for Nepal in the future. Nepal has the technical knowledge, skilled human resources, and appropriate environment to produce hybrid and improved seeds for most of the crops in Nepal, but there is a lack of proper policies in place. Nepal can learn lessons from our neighboring countries, including India, China, Philippines, and Bangladesh, which are highly engaged in a new technology of crop genetics, hybrid breeding, proper Plant Variety Protection (PVP) laws, and private-sector entrepreneurship. In addition, Nepal should aim to be self-sufficient and export quality hybrid seeds of cereals and vegetables that can be produced in its diverse geographies and production niches.

Keywords: Hybrid crop breeding, Agriculture policy, Crop breeding strategy

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1. Introduction

Nepal is an agricultural country, and it is of utmost importance to be self-sufficient in seed production and supply systems for increased food production. Cereal crops are the most critical components of food systems, followed by legumes, vegetables, and fruit crops. With the rapidly growing population and shrinking agricultural lands, we have obligation to meet the increased demand for food by improving the yield potential.

Rice (*Oryza sativa* L.), maize (*Zea mays* L.), and wheat (*Triticum aestivum* L.) are the three most important cereal crops, followed by finger millet (*Eleusine coracana*), barley (*Hordeum vulgare*)), oat (*Avena sativa*) and buckwheat (*Fagopyrum esculentum*) accounting for over 95 percent of all cereal production in Nepal (Tiwari et al., 2020). Nepal has a diverse agroecosystem with three major agroecological zones, *Terai* (plains), hills, and mountains. The *Terai* region is often called the bread basket of Nepal due to its capability of producing most of the food for its population. The *Terai* region comprises only 23 % of the total land area and over 56% of national cereal production.

Plant breeding and crop improvement programs are essential to increase yield potential and feed the growing population. In Nepal, systematic breeding work was initiated in 1967 after the Agriculture Botany Division (ABD) was established under the Department of Agriculture although the initial rice research program was started in 1951 (Bhattarai, 1969; Joshi, 2017). Currently, the National Rice Research Program (NRRP) is headquartered in Hardinath, Dhanusha, National Maize Research Program (NMRP) is in Rampur, Chitwan, and National Wheat Research Program (NWRP) in Bhairahawa, Rupandehi. These programs have the national mandate to develop superior cultivars suitable for different cropping systems (Joshi, 2017). However, their primary focus has been developing open-pollinated (OP) cultivars despite hybrids being superior to open-pollinated ones.

Heterosis or hybrid vigor, the phenomenon where hybrids perform superior to their parents, has been exploited to improve the economic yields of major crops. This is more common with cross-pollinated species such as maize, sorghum (Troyer & Wellin, 2009) and canola (Rahman, Bennett, & Yang, 2016). With maize, hybrid cultivars have been shown to produce at least twice as much compared to inbred lines (Troyer & Wellin, 2009). In general, self-pollinated crops are not expected to produce the same level of heterosis as the cross-pollinated species. Nonetheless, hybrid cultivars of rice have been shown to substantially increase grain yield (Yuan & Virmani, 1998). In China, over 50 percent of the rice area is planted with hybrid cultivars, showing 20 percent higher yields than the inbred varieties (Yuan & Virmani, 1998). In recent years, Nepal's demand for hybrids and hybrid technology has increased tremendously. Hybrids are preferred over open-pollinated varieties because of their higher yields, greater uniformity in plant height, maturity, and other vital traits.

2. Research Methodology

This review paper was prepared using secondary data supported by Key Informant Interviews (KIIs) with major stakeholders in Nepal. We collected information from scientific literature available online, based on the experience of Nepalese researchers, and the Government of Nepal (goN) data sources. We collected national and international literature and analyzed the relevant information for the manuscript. Emphasis has been placed on generating new ideas and methodology utilizing global literature available. Authors have also expressed their own views, experiences, and knowledge to some extent where applicable.

3. Results and Discussions

Nepal has developed and adopted a ten-year agriculture development plan called Agriculture Development Strategy (ADS) of Nepal, and National Seed Vision (NSV) 2025. Both documents have emphasized various aspects of research and seed production to make it self-sufficient and explore market opportunities in Nepal and improve the economy of the country. The ADS describes farmers-oriented research by reforming the NARC and designing the breeding programs and variety evaluation process (Government of Nepal, 2014a). The ADS also plans to have real-time information on seed supply and seed demand so that farmers can get the input on timely basis to use quality seeds of improved varieties. It also emphasizes the capacity building for research, extension, and education, which includes seed production facilities in the country. It emphasizes the public-private venture to reduce the poverty by enhancing agriculture productivity (Government of Nepal, 2014a). The ultimate goal is to initiate commercial agriculture and create jobs in the country hence improving the economic conditions. For that, hybrid production will be invaluable.

Consistent with the ADS policies, the NSV envisions promoting domestic production of cereals and vegetable seeds by exploiting the local climatic conditions and available human resources in the country. It aims to increase crop productivity, raise income and generate employment opportunities through self-sufficiency, import substitution, and export promotion of quality seeds (Government of Nepal, 2014b). The document reports that the use of maize, rice, and vegetable hybrid seeds is on the rise, Seed replacement rate is also as high as 66%. Therefore, the NSV emphasizes the options to provide more varieties including open-pollinated as well as hybrids, which we discussed in the current manuscript. Rapid breeding cycle by using the modern breeding tools could be used to develop varieties in as short period of time (Government of Nepal, 2014b). Joint venture with a multi-national seed companies is emphasized to fulfill the national demand and to increase the export promotion by exploiting the unique available climatic conditions. Public-private working relationship is emphasized to address the national demand and to create job opportunities in agriculture.

Current breeding policy as such is not discouraging, particularly in cereal crops. They have developed a large number of new varieties in rice, maize and wheat in Nepal. However, there is a question in their adaptability and farmers preference. The variety selection approach can be changed to participatory so that farmers and the private sector seed traders can provide their input and select the variety of their choice. Slow variety replacement due to availability of farmers preferred variety is one of the issue in the current breeding system (Government of Nepal, 2014b). Low investment in demand-driven breeding is another issue leading to lack of unavailability of farmers preferred varieties on timely basis. Lack of competitiveness in seed production is another issue leading to the availability of quality seeds of improved varieties for growers. Poor performance of the varieties, which is not addressing the farmers expectations is a big gap, that needs to be addressed by implementing noble breeding as envisioned in Seed vision 2025 (Government of Nepal, 2014b). For that, we should encourage the active participation of the private sector actors including farmers in the varietal development and seed production. Plant breeders are not motivated to do a better job and develop better varieties, we should strengthen the human resources situation and motivate them by introducing incentive mechanism such as PVP act. Poor international collaboration is another factor causing poor performing varieties, linkages should be strengthened as outlined in this report.

3.1 Hybrid Rice

In Nepal, by 2020 National Seed Board (NSB) has released and recommended 87 varieties of rice. More than two-thirds of the genetic improvements in rice in Nepal came from the International Rice Research Institute (IRRI) followed by Nepal and India (KC et al., 2021). The establishment of a Hybrid Research Unit (HRU) under the National Commodity Programs and Divisions was recently proposed. It is envisaged that 40 hybrids, including eight rice hybrids, will be developed, and promoted by 2025. In addition, the private sectors expect to develop and promote 20 hybrids, including five rice hybrids (KC et al., 2021).

Although, some hybrid varieties are planted in some parts of *Terai* with seeds introduced mainly from India, the official registration of hybrid cultivars began in 2010 (Gauchan, Thapa Magar, & Gautam, 2010). These hybrids have shown up to 45 percent higher grain yields compared to main season inbred varieties released for the Terai and Inner Terai regions. In 2016, only 7.4 percent of the country's rice area was under hybrid cultivars. This shows that there is a huge potential for expanding hybrid cultivars to increase total rice production. Most hybrid cultivars currently available in Nepal are introduced from India and China. The procedure for hybrid seed production in rice has been established. Vernet et al. (2022) reported that synthetic apomixis can be achieved in an F1 hybrid rice by inducing inactivation of conversion of meiosis into mitosis (MiMe) mutations and egg cell expression of BABYBOOM1 (BBM1) in a single step. They generated hybrid plants that produce more than 95% clonal seeds across multiple generations. Clonal apomictic plants maintain the phenotype of the F1 hybrid along successive generations which allows farmers to use their seed for the following growing season. This is a significant milestone for hybrid crops where seed production can be expensive.

In addition to hybrid rice, Nepal should also be evaluating new technologies, including golden rice to enhance vitamin A content in our diet. The IRRI is developing new strains with significantly high levels of vitamin A content as compared to regular white rice. Results from confined tests in the Philippines and Bangladesh have shown that GR2E introgression lines matched the performance of the recurrent parents for agronomic and yield performance, and the key components of grain quality. Moreover, no differences were observed in terms of pest and disease reactions (Swamy et al., 2021). The Philippines has officially approved for cultivation and utilization of golden rice, and Bangladesh is expected for commercial release in the near future.

3.2 Perennial and Direct Seeded Rice

Nepal could benefit from using perennial rice, saving significant labor and time. Crop perennialization, the conversion of annual grains to perennial forms, has shown such a possibility (Figure1). Recently, a domesticated annual Asian rice (*Oryza sativa*) was hybridized with its perennial African relative (*Oryza longistaminata*) and PR23 was developed and is being cultivated on several thousand hectares in China (Zhang et al., 2022). From a single planting, irrigated perennial rice produced grain for eight consecutive harvests over four years, averaging 6.8 ton/ ha/ harvest versus the 6.7 tons/ha/harvest of replanted annual rice, which required additional labor and seed. Direct-seeded rice (DSR) is also making a comeback under a changing climate and labor shortages. The DSR saves water, reduces the duration to maturity as well as the labor required, and reduces negative environmental footprints, including Methane emissions (Shekhawat, Rathore, & Chauhan, 2020).

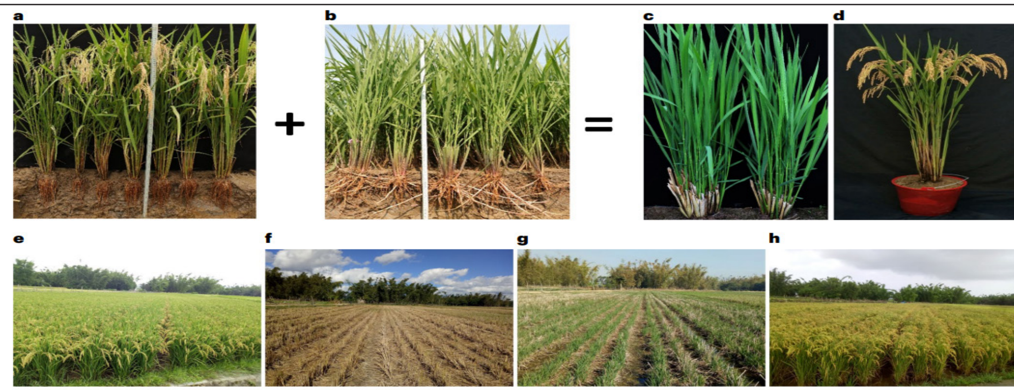

Fig. 1 | Innovation of PR for sustainable production. a, RD23, *Oryza sativa*, annual rice as female parent. **b**, *O. longistaminata*, perennial rice with strong rhizomes as male parent. **c**, PR23, perennial rice selection showing excellent regrowth above ground. Note both the numerous new green shoots and the cut brown shoots from the previous season. **d**, PR23 at maturity after regrowth. **e–h**, Performance of PR23 in Mengzhe, Yunnan, China (21° 57′ N, 100° 14′ E, 1,255 m). **e**, PR23 at maturity in the first year. **f**, PR23 overwinter in the first year. **g**, PR23 regrowth in the second year. **h**, PR23 at maturity in the second year. Note strong plant stand and high yield.

Figure 1. Innovation of Perennial Rice for Sustainable Production (Zhang et al., 2022).

3.3 Hybrid Maize

The NMRP initiated hybrid maize research in 1987 by testing nine maize hybrids developed by multinational seed companies based in India. The systematic inbred lines development was initiated in 1998 following continuous selfing from Arun-2 and Rampur Composite. The ABD also developed the 100 S4 (selfing generation-four) lines from Manakamana-2 and Arun-4 and their crosses are being evaluated in the mid-hill environments. A single cross hybrid named "Gaurav" was released in 2003 for commercial cultivation in *Terai*. The NMRP is evaluating multinational hybrids to identify high yielding hybrids (Tripathi, Shrestha, & Gurung, 2016). Several new hybrids have been recently released by NMRP - Rampur Hybrid-10, Rampur Hybrid-12, Rampur Hybrid-14, and Rampur hybrid 16. Yield potential, agronomics, and adoption need to be evaluated in the next few years.

Adopting hybrid technology is the best way to increase maize production to meet Nepal's ever-increasing demand for maize grains. There is a lack of reliable maize hybrids seeds production and distribution systems in Nepal. For this, the NMRP needs to emphasize hybrid breeding programs so that the programs could develop and release competitive inbreeds and hybrids. The other option would be to work together with the private sector, where the NARC may focus on inbred development and let the private industry focus more on seed production and marketing. It may be necessary to set up a royalty system for NARC or Universities to fund and encourage inbred development efforts. A smaller portion of breeding efforts may be continued for open-pollinated varieties. However, emphasis should be given to developing inbreeds and hybrids.

In Nepal, it is high time to go for hybrid maize technology to increase maize production. Hybrids are preferred over OPVs due to high yields, greater uniformity in maturity and plant height, ear height, and tolerance to abiotic stresses compared to OPVs. The current maize production can be doubled by utilizing hybrid seeds and appropriate inputs. To achieve this goal, a hybrid breeding program of the NMRP/NARC should be strengthened, well-funded, and energized. To meet seed production demands, private companies should be encouraged so hybrids can be developed and released regularly. In the US, hybrids have been extensively used since the 1930s, and currently, OPVs cover less than two percent of the land under maize production (Troyer & Wellin, 2009). Similarly, hybrids are extensively used in many Asian countries, including India, China, Pakistan, Thailand, the Philippines, and Vietnam. As evident from Figure 2, the US Corn yield increased significantly after adopting hybrid technology.

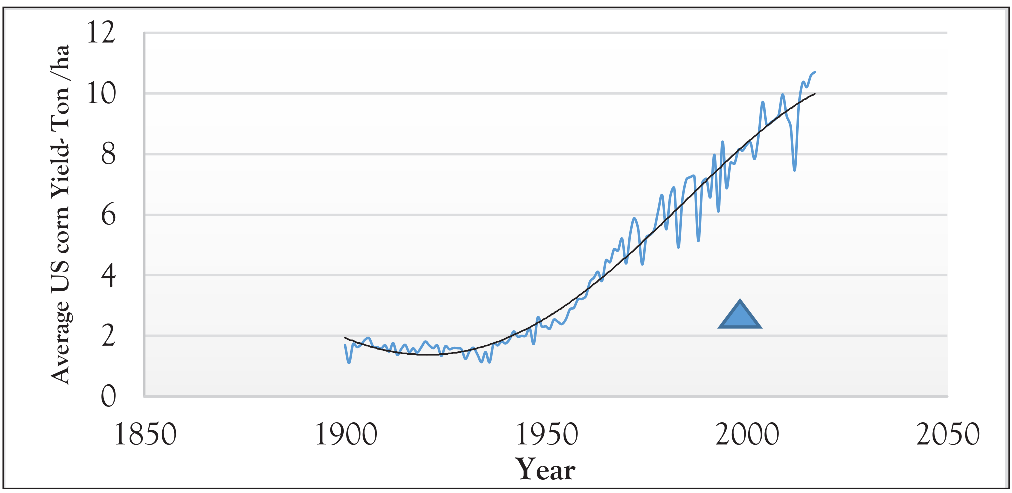

Figure 2. Average U.S. corn yields from 1900 to 2021. Source- United States Department of Agriculture, National Agricultural Statistical Services (NASS, 2021). ▲ Average corn yield in Nepal (~ 3 T/ha).

3.4 Wheat Improvement

Wheat crossing in Nepal started in the early 1970s at the ABD Khumaltar (Joshi, 2017). Later, the NWRP at Bhairahawa was charged with coordinating the country's overall wheat research. The NWRP focuses its breeding activities targeting four production environments: the irrigated ecosystem of Terai, Tars, and valleys under timely planting conditions, late-sown irrigated conditions, rainfed environment, and irrigated hill environment, while the ABD focuses on cultivar development for the irrigated and rainfed conditions of the mid and high hills and durum wheat for the far-western plains. The Lumle Agriculture Research Station is also involved in cultivar research for high-hill environments. Nepalese breed lines along with the advanced lines received from the CIMMYT, are evaluated at the NWRP, Bhairahawa, and the ABD, Khumaltar, and various NARC research centers, and the superior lines are proposed for release. CIMMYT has been an important part of wheat breeding in Nepal (Joshi, 2017). Several wheat varieties have been developed and released for different agro-climatic regions (Tiwari et al., 2020).

Recently, Molero et al. (2023) reported that wheat containing exotic DNA from wild relatives (*Aegilops tauschii)* benefits from up to 50 percent higher yields in hot weather compared with elite lines lacking these genes. They identified an *Aegilops tauschii* introgressed regions on these lines underlying the most significant of these associations with drought tolerance. Incorporating these exotic alleles into breeding programmes could serve as a pre-emptive strategy to produce high yielding wheat cultivars that are resilient to the effects of future climatic uncertainty (Molero et al., 2023). This is very important as there is growing uncertainty around the ability of major food crops to continue to meet global demand as temperatures rise and weather events become more extreme. Importantly, the exotic lines didn't perform any worse than the elite lines under normal conditions.

Despite the earlier failures, renewed efforts in recent years have been made for hybrid wheat, and hybrid varieties with desirable attributes have been produced and marketed (Matuchke, Mishra, & Qain, 2007). In Europe and USA, hybrid wheat production started in the 1990s, and over 60 hybrid wheat varieties have been marketed, with the majority of varieties released in Europe (Gupta et al., 2019). According to some reports, the area under hybrid wheat in Europe increased from ~ 100,000 ha in 2002 to 560,000 ha in 2017–2018 (Figure 3). In the public sector, wheat breeders from Texas A&M AgriLife Research and the University of Nebraska-Lincoln in the USA are jointly developing hybrid wheat varieties. Recently, Tucker et al. (2017) reported *Ms1*, a gene proposed for use in large-scale, low-cost production of male-sterile (*ms*) female lines necessary for hybrid wheat seed production. Lately, the CIMMYT is also initiating research work on hybrid wheat and making good progress. Nepal needs to plan and start organizing heterotic pools and developing CMS lines. In addition, transgenic wheat varieties are being developed in Argentina by introgressing a gene *(HaHB4)* from sunflower *(Helianthus annus),* which provides significantly better drought tolerance (Gonzalez et al., 2019; Sheridan, 2021).

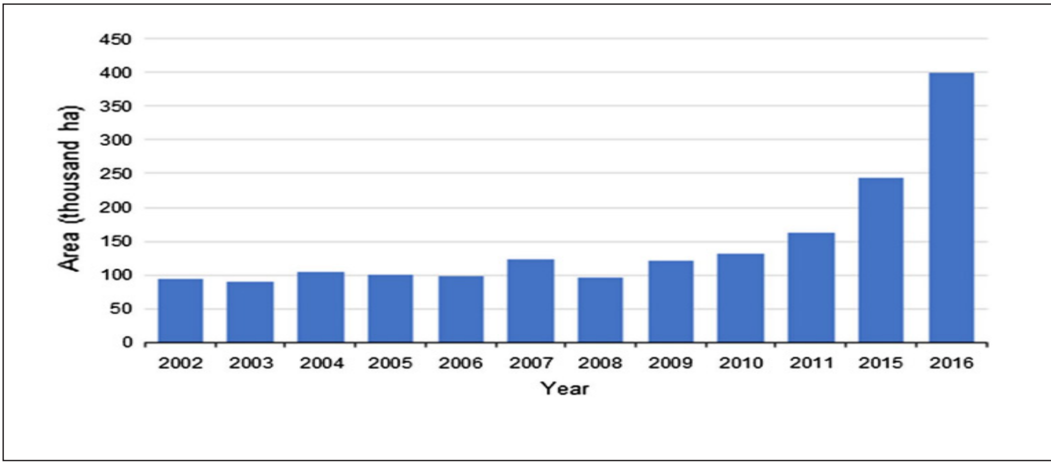

Figure 3. The area occupied by hybrid wheat in France during 2002–2016

3.5 Hybrid Vegetables

The use of hybrid varieties of major vegetable crops like cabbage, tomato, cauliflower, cucurbits, onion, carrot, is increasing every year in Nepal. About 73% of the vegetable production area is estimated to be covered by hybrid varieties in Nepal. A huge volume of hybrid seeds of vegetable crops is imported from India, China, Thailand, Japan, Korea, and the Netherlands (Gotame, Gautam, Shreshtha, & Pradhan, 2021). Hybrids have preferable characteristics, including high yield, better disease, and stress tolerance, therefore, higher demand by farmers. Demand for hybrids is increasing not only among commercial farmers but also small farmers.

Considering the urgent need to increase productivity and the high demand of Nepalese farmers, the National Horticulture Research Centre (NHRC), Khumaltar has started hybrid breeding in tomatoes since 2002/03 and hybrid tomato SRIJANA was released in 2010 (Gotame et al., 2021). In 2021, two tomato hybrids 'Khumal Hybrid Tomato-2' and 'Khumal Hybrid Tomato3' were released by the National Seed Board (NSB). Hybrid breeding of cucumber was also initiated in 2007/08 along with hybrid breeding in brinjal, hot pepper, and bitter gourd.

The seed sector in Nepal has a high comparative advantage, and the Government of Nepal has also emphasized developing and strengthening the seed supply system in Nepal (Regmi & Gauchan, 2012). Vegetable seeds are recognized as a lucrative enterprise for improving the livelihood of farmers and addressing the issues of self-sufficiency, food security, and economic development in remote areas (Timsina & Shivakoti, 2018). Vegetable seeds give 3–5 times higher income than alternative cereal crops, enabling farmers to buy at least three times more food than growing traditional food crops. Most of the socio-economic research studies reported that vegetable seed production is more profitable than food grain crops. Emphasis should be given to exploiting the micro-climate available throughout the country for vegetable seed production. This production should aim to fulfil the national demand and replace the foreign import. If seed production is launched in more systematic way, seed export is not difficult in Nepal.

4. Conclusions and Policy Recommendations

Hybrid cultivars have shown tremendous potential to increase food production in cereals. Many improved varieties of major cereal crops have been released in Nepal during the past six decades, however, most of these varieties have not been adopted by growers for various reasons. Maize, rice, wheat, and vegetable crops have enormous potential to benefit from hybrid technology; thus, the immediate focus should be directed to utilizing hybrid technology for cereal and vegetable crops. The development of hybrid breeding technology will also enhance opportunities for small-scale seed entrepreneurship.

The government should prioritize potential areas for agriculture and agro-based industries and follow policy to support their growth and development. Nepal should learn from neighboring countries including India and China, which are highly engaged with new technology, hybrid breeding, proper Plant Variety Protection (PVP) laws, and private-sector entrepreneurship. It is high time to make and use PVP laws to encourage private sector investment. NARC, Agriculture and Forestry University (AFU), Tribhuvan University (TU), and other agricultural institutions should also need to be heavily involved in agriculture research and plant breeding activities as part of graduate students' training. During the initial phase of private sector strengthening, NARC, TU, and AFU can focus their research efforts on inbred line development and maintenance. Private companies should be charged a royalty for using public inbreeds and these funds can be used to fund cultivar breeding research. Hybrid seed production, marketing, and distribution should be left and encouraged for private companies.

The application of modern biotechnological tools in crop improvement is very important; however, low investment in agricultural research, particularly crop breeding, is detrimental. National programs should be equipped with well-funded labs and qualified scientists. Advancement in genetics and data sciences is developing very rapidly and we should be able to take advantage of the new technology including gene editing (Feng et al., 2013; Shalem, Sanjana, & Zhang, 2015) transgenic approaches (Sheridan, 2021; Swamy et al., 2021) and molecular markers to improve efficiency in breeding and agricultural production. NARC and the Ministry of Agriculture should seriously consider developing new laws to test and evaluate biotechnological products such as golden rice and drought-tolerant wheat as soon as possible. Investment in new technology is the key to long-term sustainability and food sufficiency.

The Consultative Group on International Agricultural Research (CGIAR) have played a definitive role in boosting the national crop production and productivity in Nepal. Elite lines/varieties generated by the IRRI, CIMMYT, and ICRISAT have been extensively tested under different agroecological zones. In addition, our national programs have used these lines to make crosses with our local germplasm in rice, maize, wheat and legumes. The CGIAR centers have been generously supporting our national programs for the last five decades. Such collaborations should be strengthened to ensure a continuous exchange of germplasms, visits, and exchange of scientists and on-the-job training of research workers.

Increasing crop productivity should remain a top priority of Nepal's agricultural research and extension services. To be self-sufficient in food production, the growth rate in crop yield must be ahead of the population growth rate. A focused breeding program should be initiated with crops of neglected and underutilized species (NUS). A strong government commitment to adequate infrastructure development, funding for high-quality agricultural research, training, and skills development and attractive employee compensation are important areas for improvement.

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Authors Contribution

Khusi R. Tiwari: Conceiving ideas; formulation of overarching research goals and aims; Development or design of methodology; Application of statistical, mathematical, computational, or other formal; Conducting a research and investigation process, specifically performing the experiments, or data/ evidence collection; Report initial draft/review/ final draft polishing;

Dilip R. Panthee: Conceiving ideas; formulation of overarching research goals and aims; Development or design of methodology; Application of statistical, mathematical, computational, or other formal; Conducting a research and investigation process, specifically performing the experiments, or data/

evidence collection; Provision of study materials, reagents, materials, instrumentation, computing resources; Report initial draft/review/ final draft polishing;

Bal K. Joshi: Conceiving ideas; formulation of overarching research goals and aims; Development or design of methodology; Provision of study materials, reagents, meterials, instrumentation, computing resources; Report initial draft/review/ final draft polishing;

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Conflict of Interest

The authors declared no conflict of interest.

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Dr. Dilip R Panthee is an Associate Professor and Tomato Breeder at the Department of Horticultural Science at North Carolina State University (NCSU). Dr. Panthee received his Ph.D. in Plant Breeding and Genetics from the University of Tennessee, Knoxville, TN, USA and MPhil in Plant Breeding and from The University of Birmingham and Reading, UK, in 1997. Dr. Panthee has released ten hybrid cultivars, 19 breeding lines of tomato, and three soybean breeding lines. He has published over 80 journal articles, 10 book chapters, more than 75 abstracts, and research reports. He has received ten various professional awards for his contribution to the scientific community.

Dr. Bal Krishna Joshi

Dr. Bal Krishna Joshi received PhD in Agricultural Science from Japan. Dr. Joshi has been working on agrobiodiversity conservation and utilization since last 25 years and have developed and identified 101 good practices and approaches. Dr. Joshi has significant scientific contribution on in the field of Plant Genetics and Breeding, Agrobiodiversity and related policy, Biotechnology, Statistics, Conservation Science, Geographical information system, and Climate smart plant breeding. Dr. Joshi has served as an Editor-in-Chief in Journal of Nepal Agricultural Research Council and Nepal Agriculture Research Journal. He has received 12 different awards including National Technology Award, and Science and Technology Youth Award. His major thrust is to make native agricultural genetic resources competent globally.

Dr. Kalidas Subedi

Dr. Kalidas Subedi is an agricultural scientist, currently working with the Government of Canada as Project Lead/Study Director. He has extensive knowledge and experience of agriculture research, technology transfer and project management, gained through working with different national and international research and development organizations. Dr. Subedi has earned his Ph.D. degree in crop physiology and plant nutrition and M.Sc. Degree in Tropical Agriculture Development from the University of Reading, UK. Dr. Subedi has published over 60 papers in leading international peer-reviewed journals, books and book chapters, and over 200 research papers, training manuals, and proceedings in different aspects of agriculture.