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TRANSFORMING POTATO RESEARCH FROM GLOBAL GERMPLASM DIVERSITY TO SUSTAINABLE ZERO-TILLAGE AND SEED TECHNOLOGIES FOR CLIMATE-RESILIENT FARMING: A REVIEW

Arunima Goswami^{1*}, Purba Mishra¹, Digambar Sarma² and Bratati Das³¹Department of Agronomy, Odisha University of Agriculture and Technology, Bhubaneswar-751003, India.²Department of Agronomy, Biswanath College of Agriculture, Assam Agricultural University, Biswanath Chariali - 784176, Assam, India.³Department of Agronomy, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, Uttar Pradesh – 221005.*Corresponding author E-mail: arunima.rs23@ouat.ac.in

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ABSTRACT

Potato (*Solanum tuberosum*) serves as a foundational crop for global food security, ranking as a premier non-cereal food commodity. Originating in the Andean region, potato germplasm exhibits vast morphological and genetic diversity, which forms the baseline for contemporary breeding initiatives. This review synthesises global and domestic potato production dynamics, multi-tier classification frameworks (by texture, shape and culinary utility) and critical nutritional matrices. Special emphasis is placed on the Indian potato research network, analysing the performance, processing capabilities and storage properties of elite indigenous cultivars. Furthermore, we assess the mathematical evaluation of climate change adaptation via the Varietal Resilience Indicator (VRI) and detail advanced agronomic methodologies, such as True Potato Seed (TPS) technology and sustainable zero-tillage straw-mulching cultivation systems. Ultimately, this comprehensive synthesis identifies critical production bottlenecks and outlines collaborative strategic interventions required to optimize potato supply chains under escalating climatic variables.

Key words: Potato (*Solanum tuberosum*), Germplasm diversity, Sustainable zero-tillage, Climate-resilient farming

Introduction and Global Production Dynamics

The cultivated potato (*Solanum tuberosum*) represents one of the most critical caloric and nutritional resources globally. Historically domesticated approximately 7,000–10,000 years ago from the wild progenitor species *Solanum brevicaule* in the geographic corridor encompassing southern Peru and northwestern Bolivia, the crop has expanded into nearly every major agricultural system (Spooner *et al.*, 2005). While potatoes have an optimal growth range of 5°C to 30°C, temperatures exceeding these thresholds—coupled with soil moisture stress—significantly reduce yield. Furthermore, emerging research suggests that adaptive strategies, such as adjusting planting windows and selecting heat-tolerant varieties, can lead to global yield

increases of 9–20% under future climate scenarios (Hubab *et al.*, 2025; Jennings *et al.*, 2020). The International Potato Center (CIP) in Lima, Peru, established in 1971, serves as the ultimate repository for this global heritage, preserving an extensive germplasm collection of 4,870 distinct types, predominantly consisting of traditional landrace cultivars.

On a global scale, potato production reached approximately 359.1 million tonnes in 2020. According to international database metrics supplied by FAOSTAT in 2022, geographic production hierarchies are firmly dominated by Asian agricultural economies. China maintains the top global rank with an annual output of 78.2 million tonnes. India holds the second position globally in terms of absolute production volumes, accounting for 51.3 million tonnes, while ranking third in total cultivated

land area behind China and Russia. The remaining major global producers include Russia (22.5 mt), Ukraine (19.6 mt) and the United States (18.8 mt), supplemented by significant agronomic outputs from Bangladesh, Germany, France and Poland.

Within the Indian domestic agricultural sector, potato functions primarily as a temperate crop cultivated under subtropical conditions. It is colloquially termed the “poor man’s friend” due to its affordable caloric density. The spatial distribution of potato cultivation across India is highly concentrated in specialized agro-ecological zones. The leading domestic producer is Uttar Pradesh, showcasing the highest acreage (6.07 lakh hectares), total production (13.85 million tonnes) and a leading regional productivity average of 22.81 t/ha (Directorate of Economics and Statistics, 2017). Other crucial potato-producing states include West Bengal, Bihar, Gujarat, Madhya Pradesh, Punjab, Assam, Haryana, Maharashtra, Jharkhand and Chhattisgarh.

At the regional level, total national acreage expanded from 20.51 lakh hectares in 2018 to 22.47 lakh hectares by 2019. In the northeastern state of Assam, annual production averages roughly 1.1 million tonnes. Cultivation within Assam is geographically distributed across the districts of Barpeta, Bongaigaon, Dhubri, Nalbari, Biswanath, Sonitpur, Lakhimpur and Nagaon.

Institutional Research Frameworks

To sustain genetic advancements and solve localized agronomic challenges, a robust institutional framework has been erected both internationally and domestically. In India, organized public research began with the establishment of the Central Potato Research Institute (CPRI) in 1956 at Shimla, Himachal Pradesh. The national research matrix operates via the All India Coordinated Research Project (AICRP) on Potato, initiated during the 1970–71 period, which features 25 centers located in distinct agro-climatic regions. This institutional layout includes:

- Seven regional Central Potato Research Stations managed directly under CPRI, located at Patna (est. 1949), Shimla (est. 1956), Jalandhar (est. 1957), Ooty (est. 1957), Shillong (est. 1959), Modipuram (est. 1977) and Gwalior (est. 1978).
- Seventeen centers integrated within various State Agricultural Universities (SAUs), including the dedicated AICRP center at Assam Agricultural University in Jorhat.
- A solitary voluntary cooperative testing center situated at Ranichauri in Uttarakhand.

Typology, Morphological Classification and Pigmentation Chemistry

Textural Typologies

Potatoes are categorized into three major archetypes based on their structural behaviour during thermal processing and their specific starch-to-moisture ratios:

1. Starchy Potatoes: These cultivars contain elevated starch concentrations ranging from 20% to 22% alongside lower base moisture levels. Thermally, they manifest a fluffy, light internal texture ideal for baking, boiling and deep frying. However, because they disintegrate readily under prolonged heat, they are unsuited for complex layered applications like casseroles, salads, or gratins. Classic examples include Russet and King Edward.

2. Waxy Potatoes: Defined by reduced internal starch allocations (16% to 18%) and high moisture content, these tubers possess a creamy internal flesh and exceptionally thin periderm layers that eliminate the requirement for mechanical peeling. Waxy tubers retain structural cohesion post-cooking, rendering them the ideal selection for boiling, roasting and cold salad mixtures. Representatives include New Potato, French Fingerling and Russian Banana.

3. All-Purpose Potatoes: Exhibiting intermediate starch and moisture metrics, these tubers present a flexible middle ground. They provide a fluffy consistency when roasted or mashed, yet retain sufficient structural cell cohesion during simmering, pan-frying, or stewing. Prominent cultivars include Yukon Gold, Red Gold, Purple Majesty and Kennebec.

Morphological and Colour Classifications

Beyond texture, commercial international trade utilizes a six-tier framework defined by tuber geometry and periderm/cortex pigmentation:

- **Russet:** Characterized by an oblong, elliptical geometry, rough brown skin, numerous shallow eyes and white cortical tissue. They reach average dimensions of 4–6 inches in length and 2 inches in diameter, making them preferred for baking, mashing and commercial French fry production. Elite varieties include Russet Burbank, Russet Arcadia and Russet Butte.
- **White Potatoes:** Typically, medium-sized, round-to-oval tubers with light tan skins and creamy or waxy white flesh. Primarily grown in the Northeastern United States, notable varieties include Kennebec, Superior and Atlantic.

Table 1: Comparative Proximate Nutritional Matrix of Standard Potato Typologies (Per 138g Serving).

Potato Archetype	Geometrical Shape	Baseline Calories	Total Dietary Fiber (g)	Total Crude Fat (g)	Total Crude Protein (g)
Russet	Oblong shaped	134	3	0	4
Red Potatoes	Spherical, Round	123	2.5	0	3
White Potatoes	Oval to Round	130	3.0	0	3

Source: Adapted from experimental evaluations compiled by Katherine A. Beals (2019)

- **Fingerlings:** Distinctive thumb-sized geometries extending up to 3 inches in length and 1 inch in width. They possess narrow profiles, rich buttery textures and are represented by Ruby Crescent, Russian Banana, Long White and Purple Peruvian.
- **Yellow Potatoes:** Round to slightly oblong tubers with fine, yellowish-light brown skins and a distinct golden, moist interior flesh. Highly favoured for grilling, roasting and mashing, they are represented by Yukon Gold, Yellow Finn, German Butterball, Carola, Nicola and Alby's Gold.
- **Red Potatoes:** Frequently designated as “new potatoes,” these tubers feature round profiles with thin pink to deep reddish-brown skin covers and crisp, white internal flesh. Dominating the Northwestern United States market, primary varieties include Red Norland and Red Pontiac.
- **Purple/Blue Potatoes:** Deep grayish-blue or dark purple skin surfaces paired with deep indigo or inky blue internal flesh tissues. These cultivars are direct descendants of ancient native Peruvian landraces and include varieties like All Blue, Purple Peruvian, Purple Viking and Purple Majesty.

Biochemical Basis of Tuber Pigmentation

Tuber color profiles are governed by distinct classes of secondary metabolites bred specifically into the skin or flesh (Hirsch *et al.*, 2013). The golden or yellow hues seen in varieties like Yukon Gold are produced by accumulated fat-soluble carotenoid compounds. Conversely, red, blue and deep purple pigmentations are synthesized through water-soluble polyphenolic compounds, specifically from the anthocyanin biochemical pathways.

While anthocyanins mainly responsible for red or blue pigmentation enhance visual consumer appeal, they do not carry primary nutritional significance in standard dietary tables. Cultivars containing deeply colored flesh are common among native Andean potatoes, but remain relatively rare in modern commercial markets. Their

limited commercial adoption is driven by a distinct biological yield penalty; these colored native selections exhibit lower average harvest outputs compared to improved modern varieties (Mattoo *et al.*, 2022).

Nutritional Profile and Functional Food Value

Biochemically, the standard raw potato consists of approximately 79% elemental water, 17% total carbohydrates (of which 88% exists as complex starches) and minimal lipid fractions. Tuber tissue is rich in vitamin B Rs. 6 Rs. (providing 23% of the Daily Value) and vitamin C (providing 24% of the Daily Value), alongside essential mineral ions like sodium and potassium. From a dietary perspective, potatoes generally exhibit an elevated Glycemic Index (GI), leading to their frequent restriction or omission from low-GI regimens.

However, this metric is highly dynamic. The real-world glycemic impact varies considerably depending on specific genetic cultivar selections, environmental growing parameters, storage conditions and culinary preparation pathways. Notably, the thermal cooling of pre-cooked or reheated potato matrix systems minimizes the blood-glucose response due to retrogradation, which converts digestible starches into resistant starch complexes that function as dietary fibres (Fernandes *et al.*, 2005).

The consumption of these nutrient matrices directly enhances human health by supporting bone structure, cardiovascular function, neuro-cognitive pathways and immune defence mechanisms. Additionally, their high fiber and resistant starch concentrations provide distinct

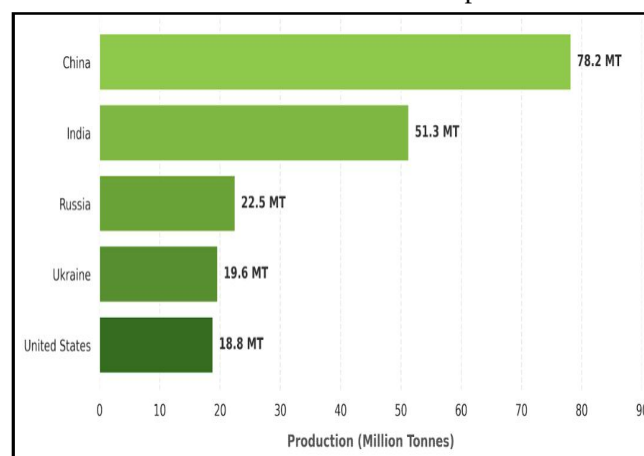
**Fig. 1:** Global Potato Production Matrix (2020).

Table 2: Detailed Micronutrient and Mineral Apportionment Profiles.

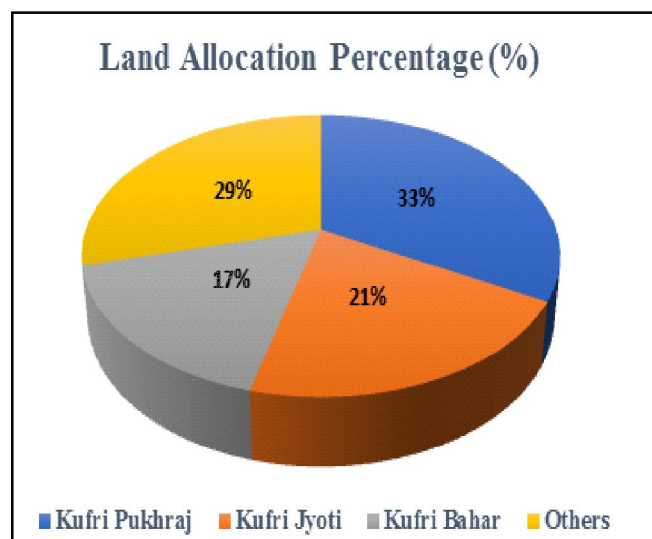
Tuber Selection	Russet	Red Potatoes	White Potatoes
Vit. C (mg)	11.5	17	17
Vit. B1 (mg)	0.1	0.1	0.07
Vit. B2 (mg)	0.07	0.07	0.06
Vit. B3 (mg)	1.9	2.2	2.1
Vit. B6 (mg)	0.5	0.3	0.3
Folate (ig)	36	37	52
K+ (mg)	759	752	751
Ca (mg)	25	12	14
Mg (mg)	41	39	37
Fe (mg)	1.5	1	0.9
Zn (mg)	0.48	0.55	0.48

Source: Adapted from experimental evaluations compiled by Katherine A. Beals (2019)

oncological protection, improve lower gastrointestinal transit and enhance metabolic satiety. Recent studies confirm that potatoes are excellent sources of essential minerals (potassium, magnesium, phosphorus) and high-quality protein. Genetic characteristics of different cultivars, such as those with red or purple flesh, have been shown to accumulate significantly higher levels of iron and zinc compared to light-fleshed varieties, offering pathways for biofortification (Landi (n.d.); Zarzecka *et al.*, 2024).

Beyond direct human nutrition, potato components are widely utilized across various industrial sectors:

- **Industrial Fermentation:** Used as a carbohydrate substrate for distilling premium alcoholic spirits like vodka.
- **Livestock Production:** Utilized as a high-energy fodder component for livestock herds.

**Fig. 2:** Total land allocation across six major states (2015).

- **Microbiology and Laboratory Diagnostics:** Formulated into Potato Dextrose Agar (PDA) media to culture fungal specimens.
- **Consumer Novelties:** Used in specialized novelty services, such as “Potato Parcels,” where custom personalized messages or decorative stickers are applied directly onto raw premium tubers for transport.

Agronomic Performance of Indigenous Indian Varieties

Nutritional Attributes and Dry Matter Components

Indian potato breeding efforts have successfully developed specific varieties customized for unique regional agro-ecological zones. These elite public lines are distinguished by clear variations in total starch concentration, crude protein synthesis and processing capability.

Processing Suitability Evaluation

For commercial processing into chips or French fries, varieties must maintain total dry matter allocations above 20% while restricting accumulating reducing sugars below 0.1% to prevent Maillard browning and bitter flavors during frying.

Storage Longevity Under Ambient Conditions

Post-harvest physiological weight loss and rotting are critical bottlenecks in ambient, non-refrigerated supply chains. Ambient tracking trials highlight crucial structural mass performance variables across varieties:

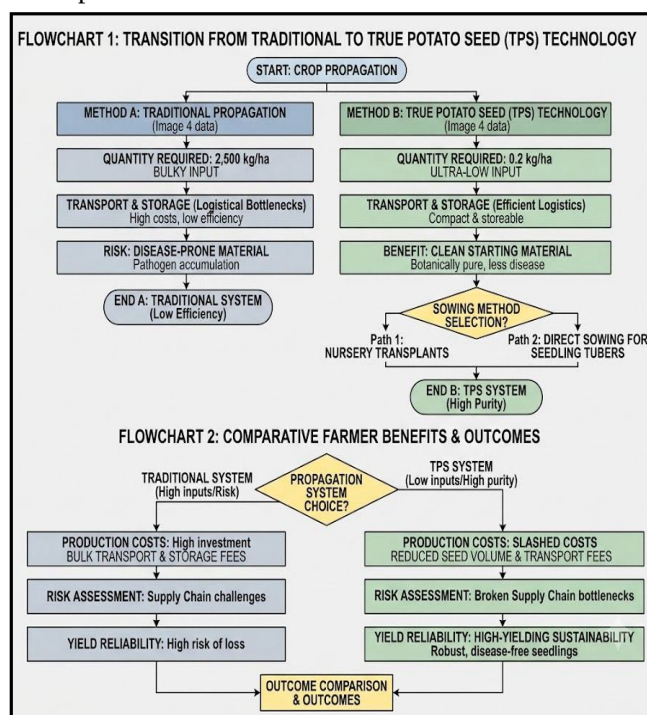
**Fig. 3:** Potato revolution from bulky tubers to tiny seeds.

Table 3: Biochemical Profiling of Prominent Indigenous Varieties.

S. No.	Cultivar Denomination	Total Organic Starch (%)	Crude Total Protein (%)	Total Mineral Ash (%)
1	Kufri Chipsona-1	18.50	5.20	1.12
2	Kufri Chandramukhi	18.10	4.50	2.09
3	Atlantic	15.90	2.90	1.12
4	Lady Rosetta	16.00	1.81	0.70
5	Kufri Chipsona-3	15.20	2.80	0.70
6	Kufri Lauvkar	14.20	2.00	0.98
7	Kufri Badshah	13.20	1.40	0.98
8	Kufri Jyoti	12.80	1.82	0.95
9	Kufri Khyati	12.80	1.61	1.08
10	Kufri Pushkar	12.31	1.34	0.98
11	Kufri Pukhraj	12.00	3.53	1.73

Source: Evaluated data tracks from Kaur *et al.*, (2014)

- **Kufri Pushkar:** Demonstrates premium ambient storability with a minimal physiological weight loss of 7.5%, an ultra-low rottage rate of 0.2% by count and 0.1% by weight, leading to the lowest net total weight loss metric of 7.7%.
- **Kufri Surya:** Highly stable heat-tolerant line showcasing a net weight loss of 8.3%, losing 8.0% via physiological mass reduction and restricting rottage to 0.2%.
- **Kufri Jyoti:** Exhibits standard ambient performance, losing 8.6% of mass physiologically, with 0.7% count rottage and 0.7% weight rottage, culminating in a 9.5% total weight loss.
- **Kufri Pukhraj:** Shows moderate ambient tracking stability, presenting a total weight loss of 11.2%, driven by a physiological weight loss baseline of 10.7% and a low rottage loss profile of 0.1% by weight.
- **Kufri Jeevan:** Features poor ambient storability, with a severe physiological weight loss of 17.5%, 2.1% rottage by count and a highest total cumulative weight loss of 20.6%.

(Multi-year ambient crop data compiled from Gupta *et al.*, 2015 trials)

Recent trials confirm that ZT with paddy straw mulching increases tuber yields, improves soil organic carbon, and facilitates early crop establishment compared to conventional tillage. This approach also promotes sustainable intensification by saving labor and reducing irrigation water usage in coastal and resource-constrained regions (Barua (n.d.); Sarangi *et al.*, 2024).

Climate Change Vulnerability and Varietal Resilience Quantification

The Mathematical Construct of the Varietal Resilience Indicator (VRI)

Escalating climate variability introduces severe risks to potato crop cycles via thermal spikes, droughts and increased fungal late blight (*Phytophthora infestans*) epidemics. To quantify how effectively a state adapts to climate change through its choice of cultivars, researchers utilize the Varietal Resilience Indicator (Pradel *et al.*, 2019). The VRI mathematically weights the total land area allocated to a specific cultivar against its verified tolerance score for explicit target stressors:

$$\text{Varietal Resilience}_{ts} = S (\text{Area}_{is} / \text{Tot Area}_s) \times \text{Level}_{tis}$$

Where,

Varietal Resilience is the varietal resilience indicator of trait 't' (i.e. maturity, heat, drought, and late blight) in State 's' in a particular year.

Area is the area in hectares cultivated by variety 'i' in State 's' in a particular year.

To 't' Area is the total area in hectares cultivated by potatoes in State 's' in a particular year.

Level of trait 't' of variety 'i' in State 's' in a particular year refers to the categories assigned to measure trait variances.

For the Maturity Trait, index scoring utilizes a 4-tier model:

- **0:** Late-maturing selections requiring 110–120 days.
- **1:** Medium-late lines requiring 100–110 days.
- **2:** Medium lines requiring 90–100 days.
- **3:** Early-maturing varieties requiring 70–90 days.

For environmental stress traits (Heat, Drought and Late Blight Resistance), the score matches verified survival parameters:

Table 4: Processing Quality Attributes of Elite Varieties.

S. No.	Cultivar Denomination	Total Dry Matter (%)	Reducing Sugars (%)	Total Sugars (%)
1	Kufri Chipsona-1	24.31	0.06	0.12
2	Kufri Chandramukhi	24.30	0.18	0.30
3	Atlantic	23.90	0.07	0.12
4	Lady Rosetta	24.00	0.06	0.14
5	Kufri Chipsona-3	22.30	0.18	0.32
6	Kufri Lauvkar	21.10	0.22	0.32
7	Kufri Badshah	18.30	0.38	0.46
8	Kufri Jyoti	18.20	0.38	0.41
9	Kufri Khyati	14.30	0.30	0.50
10	Kufri Pushkar	14.06	0.30	0.40
11	Kufri Pukhraj	15.31	0.54	0.77

Source: Evaluated data tracks from Kaur *et al.*, (2014)

- **0:** Sensitive lines displaying resistance survival indices below 50%.
- **1:** Low-tolerance selections showing survival between 50% and 70%.
- **2:** Medium-tolerance variants showing survival between 70% and 90%.
- **3:** High-tolerance cultivars showcasing survival rates between 90% and 100%.

The Varietal Resilience Indicator is ranged between 0 and 1. Values closer to zero (0) are interpreted as lower adoption rates of high resistant and tolerant, and early-maturing varieties on a state-wide level i.e. sensitive or late-maturing varieties are likely to dominate. In these cases, climatic resilience provided by varieties is low. In contrast, values closer to 1 represent higher varietal resilience on a state-wide level

Cultivar Attribute Classification Matrix

Using this framework, the core climatic and disease tolerance characteristics of primary Indian cultivars are classified below:

State Adoption Distributions

Based on 2015 tracking metrics across six major states representing 75% of the total Indian potato area,

Kufri Pukhraj is the most widely adopted variety, covering 521,375 hectares (33% of the total area) due to its high yield performance and early maturity. This is followed by Kufri Jyoti at 325,665 hectares (21%) and Kufri Bahar at 272,642 hectares (17%).

- **Uttar Pradesh:** Principally relies on Kufri Bahar, which occupies 271,328 hectares (45% of state acreage), followed by Kufri Pukhraj at 28%.
- **Bihar:** Cultivates Kufri Pukhraj across 121,464 hectares (39%), but maintains a high allocation (22%) for the traditional landrace Bhura Aloo due to its superior palatability and premium market price, despite its vulnerability to late blight.
- **Gujarat:** Demonstrates the highest calculated climate resilience profile under the VRI framework. This is driven by an 85% state-wide adoption rate for the early-maturing, drought-tolerant variety Kufri Pukhraj.
- **West Bengal:** Centered around Kufri Jyoti, which covers 228,539 hectares (56% of total state area).
- **Punjab:** Extensively uses Kufri Pukhraj, which accounts for 64% of its regional production area.

Table 5: List of Varieties Released in India and Their Climate Change Related Attributes.

Cultivar Selection	Yield Potential (t/ha)	Maturity Category	Heat Tolerance Status	Drought Resilience	Late Blight Resistance
Kufri Pukhraj	35–40	Early	Sensitive	High	Medium
Kufri Jyoti	25–30	Medium	Sensitive	Medium	Medium
Kufri Bahar	30–35	Medium	Sensitive	Medium	Sensitive
Bhura Aloo	24	Late	Low	Sensitive	Sensitive
Kufri Chipsona	30–35	Medium	Sensitive	Medium	High
Kufri Sindhuri	30–35	Late	High	Medium	Sensitive
Kufri Chandramukhi	20–25	Early	Sensitive	High	Sensitive
Kufri Khyati	25–30	Early	Sensitive	High	High

Source: Adapted from Pradel *et al.*, (2019)

Table 6: Interactive Agronomic Performance Trends under Zero-Tillage Sowing Cycles.

Agronomic Treatment Metric	Tuber Yield (t/ha)	Operational Benefit-Cost (B:C) Ratio
Ridge Sowing (Traditional Tillage Control)	16.73	1.42
Zero Tillage + 9t/ha Paddy Straw Mulching (PSM)	14.94	1.84
Zero Tillage + Rs.9 t/ha PSM + Foliar Nutrient Spray	18.30	2.19
Zero Tillage + Rs.12 t/ha Paddy Straw Mulching	17.88	2.17
Zero Tillage + Rs.12 t/ha PSM + Foliar Nutrient Spray	20.71	2.44
Zero Tillage + Rs.15 t/ha Paddy Straw Mulching	18.08	2.17
Zero Tillage + Rs.15 t/ha PSM + Foliar Nutrient Spray	20.32	2.37

Source: Adapted from Sarangi *et al.*, (2018)

- **Karnataka:** Highly dependent on a single variety, with Kufri Jyoti occupying 38,993 hectares, representing 84% of its total cultivated land area.

(Varietal adoption statistics adapted from Pradel *et al.*, 2019 research evaluations)

Advanced Agronomic Interventions

True Potato Seed (TPS) Technology

To bypass the high costs, heavy transport logistics and disease transmission risks associated with traditional vegetative tuber propagation, CPRI founder director Dr. S. Ramanujan introduced True Potato Seed (TPS) technology. TPS utilizes the actual botanical seed developed in the berry of the plant as a result of fertilization.

This strategy reduces the required seeding material from 2.5 tonnes of bulky vegetative seed tubers down to just 200 grams of lightweight TPS per hectare. This drastic reduction eliminates regional transportation bottlenecks, slashes storage overheads and provides farmers with virus- and disease-free seedling material that produces high yields. TPS crop production systems have been successfully implemented across non-seed producing states, including Himachal Pradesh, Uttar Pradesh and Tripura, utilizing elite parent lines like HPS1/13, HPS II/63, TPS C-3 and 92-PT-27.

Sustainable Zero-Tillage Straw-Mulching Cultivation System

Another major breakthrough methodology is Zero-Tillage Potato Cultivation, which utilizes the residual soil moisture and abundant straw residue left behind in fields following rice harvests. Rather than utilizing intensive mechanized tillage to construct soil ridges, farmers place seed tubers directly onto the untilled ground surface and cover them with a thick layer of post-harvest rice straw. The crop's roots draw water directly from the residual soil moisture left after the rice harvest, entirely eliminating the need for operational irrigation machinery. This methodology has been extensively demonstrated across

Sonitpur and related districts under the Assam Agribusiness and Rural Transformation Project (APART).

Multi-year field trials conducted at the AICRPDA center in Biswanath Chariali highlight how planting schedules affect crop performance:

- **October Sowing:** Sowing crops during the mid-October window (specifically October 16) optimizes tuber development, yielding 8,520 kg/ha in early trials and 8,495 kg/ha in later evaluations, while achieving an optimal Benefit-Cost (B:C) ratio of 2.02.
- **Water Efficiency Optimization:** Relative water-use efficiency (RWUE) improves significantly as the planting date shifts toward mid-November, jumping to a peak of 343.0 kg/ha-mm.
- **Cultivar Divergences:** Improved lines like **Kufri Pukhraj** demonstrate stable genetic performance, yielding 8,800 kg/ha to 8,831 kg/ha, outperforming local small tuber cultivars (Guti Aloo) like the local red-eye (6,845 kg/ha) or white-eye lines (6,720 kg/ha).

(Agronomic tracking metrics adapted from AICRPDA Annual Reports)

These data confirm that combining Rs.12 t/ha paddy straw mulching with targeted foliar nutrient applications maximizes agronomic efficiency. This combination produces the highest tuber yield (Rs.20.71 t/ha) and an optimal B:C ratio of 2.44, significantly outperforming traditional, labor-intensive tillage methods.

Key Production Challenges and Strategic Solutions

Modern potato supply chains face interconnected production bottlenecks that require targeted interventions:

1. Production Gaps and Land Limitations:

- **Challenges:** Small, uneconomic landholdings limit the use of large-scale farm mechanization, resulting in lower regional yields compared to international benchmarks.

- **Strategic Interventions:** Expand the distribution of high-yielding, elite indigenous lines—especially Kufri Pukhraj—to maximize production potential across smallholder farming systems.
2. Rising Input Costs and Labor Shortages:
 - **Challenges:** Potato cultivation is highly capital-intensive and seasonal labor shortages increase production costs.
 - **Strategic Interventions:** Disseminate zero-tillage potato cultivation methods to lower input requirements, minimize land preparation costs and reduce seasonal labor dependencies.
 3. Resource and Input Mismanagement:
 - **Challenges:** Incorrect fertilizer dosing degrades soil health, increases input waste and lowers overall crop nutrient efficiency.
 - **Strategic Interventions:** Implement site-specific nutrient management (SSNM) and eco-friendly farming practices to balance soil ecosystems and optimize resource efficiency.
 4. Logistics and Infrastructure Deficiencies:
 - **Challenges:** Weak transport links and inefficient cold storage networks cause severe post-harvest volume losses and degrade nutritional quality.
 - **Strategic Interventions:** Expand regional cold chain logistics, add processing centers near production zones and diversify utilization into value-added products like instant potato flakes and starch.
 5. Climate Change and Biotic Stress:
 - **Challenges:** Climate change shifts weather patterns and intensifies disease pressures, such as late blight epidemics.
 - **Strategic Interventions:** Use wild germplasm pools to cross-breed multi-strain resistance into commercial lines, utilize the Varietal Resilience Indicator (VRI) to guide seed distribution and expand climate-resilient varieties across high-risk agro-ecological zones.

Conclusion

Potato remains a cornerstone of global food security, but its production networks face significant challenges from climate change, infrastructural gaps and high input costs. Addressing these issues requires a systematic approach. Breeders and policymakers must prioritize using wild germplasm pools to build genetic resilience, expanding low-input systems like zero-tillage cultivation

and scaling up resource-saving seed technologies like True Potato Seed (TPS). Optimizing state-level cultivar choices using diagnostic tools like the Varietal Resilience Indicator (VRI) will safeguard smallholder yields, build resilient agricultural supply chains and secure steady caloric production under changing global climates.

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