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Optimizing Agronomic Management of Wheat Varieties UP 2338, PBW 343, and VL 804 for Sustainable Productivity and Food Security in Sikkim's Diverse Agro-Climatic Conditions

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Abstract
Wheat productivity in Sikkim remains below the national average due to fragmented landholdings, soil acidity, erratic rainfall, and limited adoption of scientific agronomic practices. This study evaluated three widely cultivated wheat varieties—**UP 2338**, **PBW 343**, and **VL 804**—under optimized and farmer-managed agronomic practices across Sikkim's mid- and high-hill agro-climatic zones. A two-year field experiment using a Randomized Complete Block Design (RCBD) assessed growth dynamics, yield attributes, grain quality, soil health parameters, and economic returns. Optimized management significantly enhanced grain yield (18–27%), improved protein content (0.6–1.1%), and increased benefit–cost ratio (1.48 to 2.12). Among varieties, VL 804 performed best in high elevations, while PBW 343 showed superior performance in mid-hills under improved nutrient scheduling. Results provide region-specific, evidence-based recommendations for sustainable wheat production in Sikkim.

Keywords: Wheat varietal evaluation, Agro-climatic adaptation, Integrated nutrient, management, Soil acidity correction, Sustainable hill agriculture, Grain quality optimization, Climate-resilient wheat production

1. Introduction

Wheat Production Scenario in Sikkim: Constraints and Strategic Interventions

Sikkim's wheat cultivation is geographically restricted to winter-grown patches within terrace-based mid- and high-hill ecosystems (1,200–2,200 m above mean sea level). These agro-ecological zones experience cool and favorable winter temperatures ranging between 8–22°C, which are physiologically suitable for tillering, anthesis, and grain filling. However, despite this climatic advantage, the average productivity (2.2–2.8 t ha^{-1}) remains substantially below the national average (~3.5 t ha^{-1}) as documented by the Indian Council of Agricultural Research and the Food and Agriculture Organization.

This yield gap is primarily attributable to a combination of edaphic, agronomic, and management constraints rather than temperature limitations alone.

Soil Acidity (pH 4.8–5.5) : A major limiting factor in Sikkim's hill agriculture is acidic soil reaction. Continuous high rainfall results in base leaching and accumulation of exchangeable aluminum (Al^{3+}), which leads to – a) Aluminum toxicity inhibiting root elongation, b) Reduced phosphorus availability due to fixation, c) Decreased microbial biomass and nutrient mineralization, d) Poor nutrient uptake efficiency. At pH below 5.5, phosphorus becomes less available, and nitrogen use efficiency declines. Root proliferation is restricted, resulting in weak anchorage and lower tiller survival. Liming or integrated soil amendment strategies remain underutilized in the region.

Nutrient Deficiencies (Nitrogen and Phosphorus) : Nitrogen (N) and phosphorus (P) are the most limiting macronutrients in Sikkim's wheat systems – a) Nitrogen deficiency reduces chlorophyll content, tillering capacity, and grain protein concentration, b) Phosphorus deficiency restricts early root development and spike initiation.

Heavy rainfall further aggravates nutrient losses through leaching and runoff from sloped terraces. Farmers traditionally apply low fertilizer doses due to cost and accessibility constraints, resulting in suboptimal crop nutrition.

Rainfed Dependence : Wheat cultivation in Sikkim is predominantly rainfed. The absence of assured irrigation infrastructure exposes crops to – a) Uneven soil moisture distribution, b) Moisture deficit during critical growth stages (booting and grain filling), c) Reduced grain weight under intermittent drought

Rainfall variability linked to climate change increases production instability, particularly in high-altitude rain-shadow pockets.

Terminal Moisture Stress : Even when early-season moisture is adequate, terminal moisture stress often occurs during grain filling due to declining winter precipitation and rising pre-summer temperatures. This leads to a) Accelerated leaf senescence, b) Reduced photosynthate translocation, c) Shrinkage in 1000-grain weight, d) Yield reduction of 10–25% depending on stress intensity

Shortened grain-filling duration directly affects final productivity and grain quality parameters.

Traditional Cultivation Practices : Wheat cultivation largely follows conventional method i.e. a) Broadcasting instead of line sowing, b) Limited seed treatment, c) Absence of raised-bed or ridge planting, d) Minimal soil testing-based fertilizer application

These practices contribute to uneven plant population, poor nutrient synchronization, and inefficient resource use.

Strategic Pathway to Bridge the Yield Gap : Closing the yield gap in Sikkim requires a multi-dimensional strategy integrating genotype × management × environment interactions

A. Varietal Adaptability - Selection of genotypes with – a) Acid soil tolerance, b) Efficient nutrient uptake, c) Strong root architecture, d) Terminal stress resilience, e) Early vigor and cold tolerance. Hill-adapted varieties must combine yield stability with disease resistance under humid conditions.

B. Soil Acidity Correction – a) Application of agricultural lime or dolomite to raise pH toward 6.0–6.5, b) Integrated nutrient management combining organic manure and balanced fertilizers, c) Promotion of soil testing-based nutrient recommendations

C. Precision Nutrient Management – a) Split nitrogen application (basal + CRI + boot stage), b) Phosphorus placement near root zone, c) Inclusion of biofertilizers to improve nutrient use efficiency

D. Moisture Conservation and Agronomic Innovation – a) Raised-bed planting for improved drainage and aeration, b) Mulching to reduce moisture loss, c) Optimized sowing time to escape terminal stress, d) Line sowing for uniform crop stand

2. Literature Review

Wheat Productivity Constraints in Himalayan Hill Ecosystems : Wheat productivity in Eastern and Northeastern Himalayan regions remains lower than the national average due to edaphic and climatic limitations. National productivity averages ~3.5 t ha^{-1}, whereas hill regions report 2.2–2.8 t ha^{-1} **(Indian Council of Agricultural Research, 2020; Food and Agriculture Organization, 2021)**. Major constraints include – 1. Strong soil acidity (pH 4.8–5.5) leading to Al^{3+} toxicity and phosphorus fixation **(Yadav & Gupta, 2015),** 2. Nutrient leaching under high rainfall regimes (1,800–2,500 mm annually), 3. Fragmented terraced landholdings reducing mechanization efficiency **(Government of Sikkim, 2022)**., 4. Terminal moisture stress and delayed sowing effects under changing climatic patterns **(IMD, 2021).**

Hill agriculture requires location-specific agronomic refinement rather than plains-based generalization.

Soil Acidity and Liming in Eastern Himalayas

Acid soils dominate Sikkim's wheat fields. According to 1. **Yadav & Gupta (2015)**, phosphorus availability declines by 30–50% below pH 5.5 due to fixation by Fe and Al oxides. Liming corrects soil reaction and improves nutrient bioavailability, 2. **Brady & Weil (2016)** explain that liming – a) Neutralizes exchangeable acidity, b) Enhances microbial activity, c) Improves root proliferation, 3. Empirical hill studies report yield improvements of 0.3–0.5 t ha^{-1} following lime application **(ICAR, 2020).**

Integrated Nutrient Management and Nitrogen Scheduling : Nitrogen is the most yield-determining nutrient in wheat. However, basal-only application reduces Nitrogen Use Efficiency (NUE) due to leaching and volatilization **(Singh et al., 2018).**

Split application (basal + CRI + booting) – a) Synchronizes N supply with crop demand, b) Enhances tiller survival at CRI stage, c) Improves grain protein synthesis during booting.

Studies in hill conditions reported 15–25% yield enhancement and 0.6–1.2% protein increment under split N scheduling **(Singh et al., 2018; ICAR-IIWBR, 2022).**

Varietal Adaptation and Agro-Climatic Suitability

Varietal selection plays a critical role in stress-prone ecosystems i.e. 1. **PBW 343**: High yielding, strong gluten wheat, responsive to fertilizer **(ICAR-IIWBR, 2022)**, 2. **UP 2338**: Moderately adaptable, stable performance across mid-hills, 3. **VL 804**: Developed for hill conditions; better cold tolerance and tillering under low temperature regimes.

Cold-tolerant genotypes perform better above 1,600 m altitude where vegetative growth period extends under cool temperatures **(IMD, 2021).**

Sowing Time and Climate Synchronization : Timely sowing ensures optimal Growing Degree Days (GDD). Delayed sowing reduces grain filling duration and 1000-grain weight (ICAR, 2020). Hill experiments show 12–18% yield decline with December sowing due to shortened maturity period and exposure to higher terminal temperatures.

Line Sowing vs Broadcasting : 1. Uniform plant geometry improves light interception and reduces weed competition (Gomez & Gomez, 1984), 2. Hill-based experiments indicate 12–18% yield advantage under line sowing due to better plant population maintenance.

Integrated Pest Management (IPM) : Leaf rust and spot blotch remain significant constraints in humid hill regions (Sharma & Duveiller, 2007). IPM strategies reduce yield loss from 10–12% to below 5%.

Soil Organic Carbon and Sustainability : Hill soils show relatively high organic carbon (0.9–1.4%), enhancing moisture retention and resilience (Brady & Weil, 2016). However, nitrogen mineralization remains moderate under cool conditions, necessitating balanced fertilization.

Economic Viability of Optimized Packages : Adoption of scientifically recommended packages improves Benefit–Cost ratio from ~1.5 to above 2.0 (ICAR-IIWBR, 2022). Economic sustainability is essential for hill smallholders where farm income stability determines adoption.

Materials and Methods

Agro-Ecological Characterization of Experimental Sites in East and South Sikkim

The field trials were conducted across representative mid- and high-hill agro-ecological zones of **Sikkim**, specifically in East and South districts. These locations were selected to capture the altitudinal gradient, soil variability, and climatic heterogeneity that influence wheat performance in Himalayan ecosystems. A detailed characterization of each parameter is presented below.

Altitude (1,200–2,100 m above mean sea level) : Altitude strongly governs temperature regime, radiation interception, crop phenology, and biomass accumulation.

Agro-Climatic Zonation Table No. 1

Altitude Range	Agro-Climatic Zone	Dominant Features
1,200–1,500 m	Mid-hill subtropical	Mild winters, longer growing season
1,500–1,800 m	Transition zone	Moderate cold stress
1,800–2,100 m	High-hill temperate	Cooler winters, slower growth

Impact on Wheat Growth – a) Growing Degree Days (GDD) ranged from 1,620 to 1,780°C days, b) Higher altitudes prolonged vegetative phase by 5–7 days, c) Grain filling duration extended by 4–6 days above 1,800 m.

At elevations above 1,900 m – a) Plant height reduced by 6–9%, b) however, grain weight increased slightly due to extended cool grain-filling conditions. This altitudinal diversity allowed assessment of varietal adaptability under temperature gradients typical of Himalayan wheat systems.

2. Soil pH (4.8–5.6)

Soils in the study area are moderately to strongly acidic, characteristic of high rainfall Himalayan regions.

Soil Reaction Profile – **Table No. 2**

pH Range	Acidity Class	Agronomic Implication
4.8–5.0	Strongly acidic	Aluminum toxicity risk
5.1–5.6	Moderately acidic	P fixation, reduced nutrient availability

Measured Soil Chemistry – i.e. a) Exchangeable Al: 0.45–0.72 cmol kg^{-1}, b) Available P: 14–20 kg ha^{-1}, c) Base saturation: 38–46%

Acidic conditions resulted in – a) 25–35% reduction in phosphorus availability, b) Suppressed root elongation under untreated plots, c) Reduced microbial mineralization efficiency.

Liming interventions increased pH by 0.5–0.8 units and improved available phosphorus by 30–42%, confirming acidity as a major production constraint.

Organic Carbon (0.9–1.4%) : The soils showed relatively high organic carbon compared to alluvial plains due to forest-derived residues and low decomposition rates in cooler climates.

Soil Organic Matter Dynamics – Table No. 3

OC (%)	Soil Fertility Status
<0.75	Medium

OC (%)	Soil Fertility Status
0.75–1.0	High
>1.0	Very High

Average measured organic carbon: **1.15%**

Implications are a)Enhanced moisture retention (field capacity 38–44%), b) Improved soil aggregation and porosity, c) Moderate nitrogen mineralization rate (~45–65 kg N ha^{-1} season^{-1}). However, despite high OC, available nitrogen was only 250–290 kg ha^{-1}, indicating limited mineralization during cooler winters. Thus, balanced fertilization remained essential despite relatively good organic matter status.

Annual Rainfall (1,800–2,500 mm) : The region experiences high monsoonal rainfall concentrated between June and September.

Rainfall Distribution Pattern – Table No. 4

Season	Rainfall Contribution
Monsoon (Jun–Sep)	75–80%
Winter (Dec–Feb)	5–8%
Pre-monsoon	10–12%

Wheat is grown in rabi season under residual soil moisture and occasional winter showers (~80–120 mm).

Agronomic Implications are a) High monsoon rainfall leads to nutrient leaching, b) Elevated risk of soil erosion on slopes, c) Residual moisture supports early crop establishment. However, inadequate winter rainfall sometimes causes terminal moisture stress at grain filling, reducing yield by 8–12% in rainfed fields.

Winter Temperature (8–22°C) : Winter temperatures are favorable for wheat growth but vary across elevation.

Temperature Regime – Table No. 5

Stage	Mean Temp (°C)
Germination	14–18
Tillering	10–15
Grain Filling	16–22

Minimum temperatures occasionally dropped to 5–6°C at higher altitudes but remained above frost threshold.

Physiological Impact are a) Cool temperatures improved grain filling efficiency, b) Extended grain filling by 4–8 days compared to plains, c) Reduced heat stress incidence. However, delayed sowing exposed crops to temperatures above 24°C during grain filling, shortening maturity by 5–6 days and reducing 1000-grain weight by 8–10%.

Soil Texture (Sandy Loam to Clay Loam)

Textural Distribution – Table No. 6

Texture	Percentage of Sites
Sandy Loam	40%
Loam	35%
Clay Loam	25%

Physical Properties are – a) Bulk Density: 1.22–1.35 g cm^{-3}, b) Field Capacity: 38–44%, c) Permanent Wilting Point: 17–20%, d) Available Water Capacity: 18–22%. Clay loam soils showed higher nutrient retention but slower drainage. Sandy loam soils allowed better root proliferation but required careful nutrient management due to leaching risk.

Integrated Agro-Ecological Interpretation : The experimental region represents as a) High rainfall, b) Acidic soil, c) Organic matter-rich, d) Temperature-moderated Himalayan agro-ecosystem. The production constraints identified as 1. Soil acidity and phosphorus fixation, 2. Nutrient leaching under high rainfall, 3. Terminal moisture variability, 4. Slope-induced soil erosion and advantages are 1. Favorable cool winter temperatures, 2. High organic carbon status, 3. Adequate residual soil moisture, 4. Low heat stress incidence

Experimental Design : A scientifically robust experimental framework was adopted to ensure precision, reproducibility, and statistical validity under Sikkim's heterogeneous hill conditions.

Randomized Complete Block Design (RCBD) : The study was laid out in a **Randomized Complete Block Design (RCBD)** to minimize variability arising from slope gradient, soil heterogeneity, and microclimatic differences. Rationale for RCBD are Hill agriculture exhibits spatial variability in a) Soil fertility, b) Moisture retention, c) Slope position. Blocking controls environmental variability within each replication.

Statistical Model

$$Y_{ij} = \mu + t_i + r_j + \epsilon_{ij}$$

Where Y_{ij}= observation from ith treatment in jth replication, μ= overall mean, t_i= treatment , effect, r_j= replication effect, ϵ_{ij}= experimental error

Precision Indicators are a) Coefficient of Variation (CV%): 4.8–7.5%, b) Standard Error of Mean (SEm): ±0.08–0.12 t ha^{-1}, c) Critical Difference (CD at 5%): 0.22–0.30 t ha^{-1}. RCBD ensured improved experimental accuracy under variable hill terrain.

Replications: Three replications were maintained to a) Increase reliability of results, b) Reduce experimental error, c) Enable valid statistical comparisons

Statistical Adequacy : With 2 treatments × 3 replications × 3 varieties: a) Total experimental units = 18 plots per season, b) Error degrees of freedom sufficient for ANOVA validity. Replication reduced site-specific bias and improved treatment comparison robustness.

Duration: Two Rabi Seasons - The experiment was conducted for **two consecutive rabi seasons** to capture – a) Seasonal climatic variability, b) Inter-annual rainfall fluctuations, c) Temperature variation effects

Seasonal Variation Observed – Table No. 7

Parameter	**Season I**	**Season II**
Mean Temp (°C)	15.8	16.4
Winter Rainfall (mm)	110	85
Relative Humidity (%)	72	68

Yield variation between years ranged from 4–8%, indicating moderate seasonal stability. Multi-season evaluation enhances reliability and supports climate-resilient recommendations.

Plot Size: 4 m × 5 m (20 m² Gross Plot Area) : Gross plot area was standardized at 20 m² to a) Allow uniform crop management, b) Minimize border effects, c) Enable realistic agronomic practices

Row Configuration- a) Row spacing: 20 cm, b) **Number of rows per plot**: 20 , c) **Plant population:** 4.5–5.0 lakh plants ha^{-1}. The chosen plot size balances statistical precision and practical field manageability.

Net Harvest Area: 12 m² - Border rows and 0.5 m margins were excluded to eliminate edge effects. Reasons for Net Plot Harvesting are a) Avoid nutrient and moisture edge bias, b) Improve yield accuracy, c) Ensure uniform sampling

Harvested area: central 12 m² - Converted to yield (t ha^{-1}) using standard extrapolation. Harvest index ranged from 0.42–0.46 under optimized management.

Treatment :

T$_1$: Optimized Agronomic Package : Designed based on soil test recommendations and hill-specific agronomic research. Components are a) 120:60:40 kg N:P_2O_5:K_2O ha^{-1}, b) Split nitrogen (Basal + CRI + Booting), c) Lime @ 1.5 t ha^{-1}, d) Line sowing, e) Timely sowing (15–30 November), f) Integrated Pest Management

Expected Scientific Advantages – a) 20–25% higher Nitrogen Use Efficiency, b) Improved phosphorus availability by 30–40%, c) Enhanced tiller production, d) Reduced lodging

T$_2$: Farmer Practice: Represents prevailing traditional cultivation methods. Characteristics are a) 80 kg N ha^{-1} (basal only), b) No liming, c) Broadcasting, d) Delayed sowing, e) Minimal pest management and observed constraints are a) Nitrogen loss up to 30–40%, b) Reduced tiller survival, c) 12–18% yield reduction

Comparative Yield Performance Table No. 8

Treatment	Grain Yield (t ha^{-1})	Protein (%)	B:C Ratio
T$_1$ Optimized	3.68	12.6	2.05
T$_2$ Farmer Practice	2.94	11.7	1.52

Yield improvement under optimized treatment: **~25%**

Agronomic Management Practices : Optimized Package – 1. Nutrient Management: 120:60:40 kg N:P_2O_5:K_2O ha^{-1} and Soil analysis showed – a) Available N: 250–290 kg ha^{-1} (medium), b) Available P: 14–20 kg ha^{-1} (low due to fixation), c) Available K: 180–240 kg ha^{-1} (medium). Thus, a balanced fertilization strategy was necessary.

Applications are a) Nitrogen (120 kg ha^{-1}) as urea, b) Phosphorus (60 kg P_2O_5 ha^{-1}) as SSP/DAP, c) Potassium (40 kg K_2O ha^{-1}) as MOP

Impact on Growth and Yield – Table No.9

Parameter	Farmer Practice	Optimized
Effective tillers (m^{-2})	360	410
Spike length (cm)	9.8	11.2
Grain yield (t ha^{-1})	2.94	3.68
Nitrogen Use Efficiency (kg grain/kg N)	36.7	42.5

Balanced fertilization improved yield by ~25% and enhanced protein content by 0.8–1.1%.

Split Nitrogen Application (Basal + CRI + Booting) : Schedule – a) 50% Basal at sowing, b) 25% at Crown Root Initiation (CRI, 20–25 DAS), c) 25% at Booting stage (55–60 DAS) and Scientific

Justification are a) CRI stage determines tiller survival, b) Booting stage influences grain protein synthesis. Observed Benefits are a) Tiller survival improved by 12–15%., b) Grain protein increased from 11.7% to 12.6%., c) Reduced N losses (leaching/volatilization) by 18–22%. Split application improved Nitrogen Recovery Efficiency from 32% to 45%.

Lime Application @ 1.5 t ha⁻¹ : Soil Constraint - **Baseline soil pH:** 4.8–5.2, **Exchangeable aluminum**: 0.45–0.72 cmol kg⁻¹

Effects of Liming – Table No. 10

Parameter	**Before Liming**	**After Liming**
Soil pH	5.0	5.6
Available P (kg ha⁻¹)	15	23
Root length (cm)	14.8	19.2

Liming are a) Reduced aluminum toxicity, b) Improved phosphorus availability by 35–40%, c) Increased microbial activity. Yield increase attributable to liming alone: 0.35–0.48 t ha⁻¹.

Line Sowing (20 cm Spacing) : Advantages Over Broadcasting – a) Uniform plant distribution, b) Improved aeration, c) Better light interception, d) Ease of interculture operations

Field Observations – Table No. 11

Parameter	**Broadcasting**	**Line Sowing**
Plant population (lakh ha⁻¹)	3.8	4.8
Weed density (m⁻²)	72	45
Yield (t ha⁻¹)	3.05	3.68

Line sowing improved yield by 15–18% compared to broadcasting.

Seed Rate: 100 kg ha⁻¹ - Optimized seed rate ensured – a) Target plant population: 4.5–5.0 lakh plants ha⁻¹, b) Reduced intra-plant competition, c) Improved tiller formation

Higher seed rates (>120 kg ha⁻¹) caused excessive competition and reduced spike size. **Lower rates** (<80 kg ha⁻¹) reduced canopy coverage and yield.

Timely Sowing (15–30 November) : Climatic Considerations are a) **Optimal germination temperature**: 14–18°C, b) **Avoids terminal heat** (>24°C) during grain filling

Yield Impact – Table No. 12

Sowing Date	**Grain Yield (t ha⁻¹)**
20 Nov	3.85
5 Dec	3.42
15 Dec	3.05

Delayed sowing reduced grain filling duration by 5–7 days and decreased 1000-grain weight by 8–10%. Timely sowing improved yield by 12–18%.

Integrated Pest Management (IPM) : Major Observed Pests/Diseases are a) Aphids, b) Leaf rust, c) Spot blotch

IPM Components are Resistant varieties – a) Seed treatment (fungicide @ 2 g kg⁻¹ seed), b) Need-based insecticide spray, c) Field monitoring

Results- Table No. 13

Parameter	**Farmer Practice**	**IPM**
Pest incidence (%)	18	9
Yield loss (%)	12	5

IPM reduced pest incidence by ~50% and increased net returns by ₹4,000–6,000 ha^{-1}.

Integrated Effect of Optimized Package – Table No. 13

Parameter	**Farmer Practice**	**Optimized Package**
Grain Yield (t ha^{-1})	2.94	3.68
Protein (%)	11.7	12.6
Net Return (₹ ha^{-1})	46,200	61,800
B:C Ratio	1.52	2.05

Overall yield improvement: ~25%, Income enhancement: ₹15,000–20,000 ha^{-1}

Farmer Practice : 1. Nitrogen Application: 80 kg N ha^{-1} (Basal Only) and applications are a) Entire nitrogen dose applied at sowing, b) No top dressing at CRI or booting stages, c) No balanced P and K application in most cases.

Scientific Implications are 1. Basal-only nitrogen leads to – a) Higher leaching losses under residual soil moisture, b) Poor synchronization with crop demand., 2. Nitrogen availability declines during CRI stage (20–25 DAS), affecting tiller survival.

Field Observations – Table No. 14

Parameter	**Farmer Practice**	**Optimized**
Effective tillers (m^{-2})	360	410
Nitrogen Recovery Efficiency (%)	30–32	42–45
Grain Protein (%)	11.7	12.6

Nitrogen losses through leaching and volatilization were estimated at 25–35% due to high rainfall-induced soil porosity. Yield reduction attributable to suboptimal N management: **0.55–0.75 t ha^{-1}**.

No Liming Under Acidic Soils : Soil Condition is a) Soil pH: 4.8–5.2, b) **Exchangeable Al:** 0.45–0.72 cmol kg^{-1} and Consequences are a) Aluminum toxicity restricts root elongation, b) Phosphorus fixation increases under low pH, c) Reduced microbial activity and nutrient mineralization.

Measured Effects – Table No.15

Parameter	**Without Liming**	**With Liming**
Root length (cm)	14.8	19.2
Available P (kg ha^{-1})	15	23
Grain Yield (t ha^{-1})	2.94	3.68

Absence of liming reduced phosphorus availability by approximately 30–40% and suppressed root biomass by 15–18%. Yield loss due to acidity stress: **0.35–0.48 t ha^{-1}**.

Broadcasting Method : Characteristics are a) Seed scattered manually, b) Irregular plant spacing, c) Uneven plant density.

Plant Population Effects – Table No. 16

Parameter	Broadcasting	Line Sowing
Plant population (lakh ha^{-1})	3.8	4.8
Weed density (m^{-2})	72	45
Yield (t ha^{-1})	3.05	3.68

Broadcasting resulted in a) Uneven germination, b) Higher intra-plant competition, c) Increased weed infestation, d) Lower light interception efficiency. Yield penalty due to broadcasting: **12–18%**.

Delayed Sowing (Early December) : Climatic Exposure are a) Higher temperature during grain filling (22–25°C), b) Shortened grain filling period (reduced by 5–7 days).

Observed Impact – Table No. 17

Sowing Date	Grain Yield (t ha^{-1})	1000-Grain Weight (g)
20 Nov	3.85	44
5 Dec	3.42	41
15 Dec	3.05	39

Delayed sowing caused by a) 12–18% yield reduction, b) Reduced test weight, c) Increased exposure to terminal moisture stress. Growing Degree Days (GDD) reduced by 80–110°C days compared to timely sowing.

Minimal Pest Monitoring : Common Issues Observed are a) Aphid infestation, b) Leaf rust and spot blotch, c) Occasional stem borer incidence.

Field Data – Table No. 18

Parameter	Farmer Practice	IPM
Pest incidence (%)	18	9
Yield loss (%)	12	5

Lack of systematic monitoring resulted in a) Delayed control measures, b) 8–12% yield losses, c) Reduced grain quality.

Integrated Impact of Farmer Practice – Table No. 19

Parameter	Value
Grain Yield (t ha^{-1})	2.94
Protein (%)	11.7
Net Return (₹ ha^{-1})	46,200
B:C Ratio	1.52

Total yield gap compared to optimized package: **~25%**.

Results and Discussion

Growth Performance – Table No. 20

Variety	Plant Height (cm)	Tillers m^{-2}	Leaf Area Index
UP 2338	92	365	3.8

Variety	Plant Height (cm)	Tillers m⁻²	Leaf Area Index
PBW 343	98	390	4.2
VL 804	88	402	4.4

VL 804 produced significantly higher effective tillers in high-altitude locations due to better cold tolerance. Optimized management increased tiller density by 14–19% over farmer practice.

Yield Attributes – Table No. 21

Variety	1000-Grain Weight (g)	Grain Yield (t ha⁻¹) Optimized	Farmer Practice
UP 2338	41	3.45	2.82
PBW 343	44	3.82	3.05
VL 804	42	3.76	2.95

Yield improvement under optimized management ranged from 18–27%. PBW 343 performed best in mid-altitude terraces due to strong grain filling capacity.

Grain Quality – Table No. 22

Variety	Protein (%)	Wet Gluten (%)	Test Weight (kg hl⁻¹)
UP 2338	11.9	24.8	74
PBW 343	12.8	29.5	77
VL 804	12.3	26.4	75

Split nitrogen application significantly improved protein content by 0.6–1.1%. PBW 343 showed superior bread-making potential due to higher gluten strength.

Soil Health Improvements – Table No. 23

Parameter	Before Trial	After Optimized
Soil pH	5.0	5.6
Available P (kg ha⁻¹)	15	24
Available N (kg ha⁻¹)	260	305

Liming improved phosphorus availability by 35–40% and enhanced root biomass.

Pest and Disease Incidence : Rust incidence was lowest in VL 804 (8%) compared to PBW 343 (14%). IPM reduced pest damage by 22% over farmer practice.

Economic Analysis – Table No. 24

Variety	Net Return (₹ ha⁻¹)	B:C Ratio
UP 2338	52,400	1.89
PBW 343	61,200	2.12
VL 804	58,750	2.05

Optimized management increased net income by ₹15,000–20,000 ha⁻¹.

Climate Resilience Assessment : These are a) VL 804 showed better tolerance to low temperature stress, b) PBW 343 demonstrated superior yield stability under moderate moisture stress, c) UP 2338 performed moderately across environments. Growing Degree Days (GDD) accumulation was optimal under timely sowing (1,650–1,780°C days). Delayed sowing reduced yield by 12–18% due to shortened grain filling.

Sustainability Implications : Optimized practices resulted in – a) 18–27% higher productivity, b) Improved nutrient-use efficiency (NUE increased by 22%), c) Reduced yield variability, d) Improved grain quality for market segmentation. Adoption of lime-based nutrient correction and split N scheduling is critical for Sikkim's acidic soils.

Region-Specific Recommendations : Mid-Hill (1,200–1,600 m) – a) PBW 343 with 120:60:40 NPK, b) Lime application mandatory, c) Timely sowing before 30 November
High-Hill (1,600–2,100 m), d) VL 804 recommended, e) Slightly higher seed rate (110 kg ha^{-1}), f) Cold-tolerant management strategy

Discussion

1. Yield Enhancement under Optimized Management : The optimized package increased grain yield from 2.94 to 3.68 t ha^{-1} (~25% improvement). Primary drivers are a) Balanced NPK improved tiller density (360 → 410 m^{-2}), b) Liming increased available P by 35–40%, stimulating root biomass, c) Split N raised NUE from 32% to 45%. This aligns with hill-based nitrogen management studies (Singh et al., 2018). Yield gain was not merely input-driven but efficiency-driven.

Varietal Performance Across Elevations – Table No. 25

Variety	Optimized Yield (t ha^{-1})	Key Strength
PBW 343	3.82	High grain filling efficiency
VL 804	3.76	Cold tolerance, higher tillers
UP 2338	3.45	Stable adaptability

PBW 343 showed superior sink capacity (44 g test weight) in mid-hills. VL 804 produced highest tiller density (402 m^{-2}) in high elevations, confirming cold adaptability. This indicates genotype × environment interaction optimized through management.

Grain Quality Improvements ; Protein increased from 11.7% to 12.6% under split nitrogen. PBW 343 achieved 12.8% protein and 29.5% wet gluten — suitable for bread markets. Higher protein reflects improved nitrogen partitioning rather than yield-protein trade-off.

Soil Health Restoration : a) Soil pH improved from 5.0 to 5.6., b) Available P increased from 15 to 24 kg ha^{-1}, c) Root length increased from 14.8 to 19.2 cm. This demonstrates that soil correction alone contributed 0.35–0.48 t ha^{-1} yield gain.

Climate Resilience : VL 804 performed better above 1,600 m due to extended grain filling under cool conditions. Timely sowing optimized GDD (1,650–1,780°C days). Delayed sowing reduced yield by 12–18% due to shortened grain filling. Thus, climate synchronization was critical for yield stabilization.

Economic Strengthening : a) Net return increased from ₹46,200 to ₹61,800 ha^{-1}., b) B:C ratio improved from 1.52 to 2.05., c) Economic gain (~₹15,000–20,000 ha^{-1}) makes the optimized package financially viable for smallholders.

Conclusion

This study systematically demonstrates that wheat productivity in Sikkim's diverse agro-climatic zones is constrained primarily by soil acidity, nutrient imbalance, suboptimal sowing time, and traditional management practices. Key integrated findings:

1. **Liming is foundational** — Correcting soil acidity increased phosphorus availability by 35–40% and contributed significantly to yield enhancement.

2. **Split nitrogen scheduling improved NUE by 22%**, increasing both yield and protein content.
3. **PBW 343 is best suited for mid-hill terraces**, providing highest economic return and grain quality.
4. **VL 804 is ideal for high-hill conditions**, demonstrating superior tiller production and cold tolerance.
5. **Timely sowing and line planting reduced yield variability by 12–18%.**
6. Optimized management improved yield by 18–27%, increased B:C ratio to above 2.0, and enhanced grain quality for market segmentation.
7. Soil health improvement ensures long-term sustainability and climate resilience.

Therefore, integrating varietal selection with precision nutrient management, liming, and climate-synchronized agronomy provides a replicable model for sustainable wheat intensification in Himalayan ecosystems.

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