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# Agronomic Performance, Environment-Specific Yield Adaptation, and Economic Risk Assessment of Hybrid Hot Pepper (Capsicum annuum L.) Genotypes Across Contrasting Agro-Ecological Zones of Northwestern Ethiopia

**Tadele Yeshiwas Tizazu**[1]

tadele.yeshiwas@bdu.edu.et

Bahir Dar University

**Fentahun Mengistu Tiruneh**[1`]

Bahir Dar University

**Mengistie Mossie Birhanu**[3]

Bahir Dar University

**Ermias Abate Desta**[2]

Sasakawa Africa Association (SAA)

**Habitamau Tegne Nibret**[1]

Bahir Dar University

**Yayeh Bitew Bantie**[4]

Bahir Dar University

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# Abstract

Hot pepper (Capsicum annuum L.) serves as a critical commercial cash and spice crop within tropical cropping systems. However, regional yields under smallholder management remain depressed by an inadequate deployment of high-yielding, input-responsive genotypes adapted to specific micro-environments. A multi-location field trial was conducted during the 2024 dry irrigation season to evaluate the spatial adaptation, growth architecture, green pod yield metrics, and partial financial risk profiles of six commercial introduced F1 hybrids ('Amando', 'Ertale', 'Mixitoze', 'Serenade Explorer', 'Sernadie', and 'Vigro') alongside an open-pollinated standard local check ('Markofana'). The genotypes were evaluated using a randomized complete block design with three replications across five distinct agro-ecological zones in Northwestern Ethiopia, capturing gradients from humid lowlands to cool tropical highlands. Combined analysis of variance demonstrated that phenological maturation schedules, plant heights, primary branch numbers, individual fruit weights, and marketable pod volumes were heavily dictated by the main genetic effects ($P < 0.01$). The genotype 'Amando' exhibited extreme earliness, reaching 90% harvest maturity within 87.20 days compared to 131.73 days for the local check. The F1 hybrid 'Vigro' demonstrated broad, uniform performance across all environments, securing the maximum number of pods per plant (119.72), exceptional individual fruit weight (21.32 g), and the highest cumulative marketable green pod yield (24.07 t $ha^{-1}$), while minimizing unmarketable fruit accumulation to 0.24%. Step-wise dominance and marginal budget simulations confirmed that 'Vigro' achieved optimal economic returns, yielding a peak net benefit of 1,590,183.00 ETB $ha^{-1}$ and a marginal rate of return of 566.49% over the traditional production baseline. While these spatial results confirm that 'Vigro' possesses superior agronomic capacity, multi-season testing is necessary to confirm temporal environmental stability within East African tropical systems.


# INTRODUCTION

Hot pepper (Capsicum annuum L.) functions as a pivotal horticultural and spice commodity within smallholder farming systems of Sub-Saharan Africa, driving cash crop diversification, household income security, and domestic market webs. In the agricultural landscapes of East Africa, particularly within the diverse agro-ecologies of Ethiopia, the cultivation of C. annuum represents a high-value agricultural pathway. Despite its economic importance, national productivity averages hover well below biological potentials. This structural yield gap is primarily caused by complex production challenges, including shifting pest and pathogen pressures, erratic climatic shifts, and a heavy reliance on degenerated, open-pollinated varieties (OPVs) that lack environmental resilience and genetic uniformity.

Achieving optimized fruit yields and standardized market quality demands the systematic introduction of elite hybrid technologies capable of thriving under specific environmental pressures. Because the complex topography of East Africa yields extreme spatial variations in soil chemistry, moisture, and temperature gradients over short geographic distances, multi-location trials are mandatory to detect stable genotypes. Previous evaluations in tropical lowlands have noted substantial morphological elasticity within the genus Capsicum regarding canopy height, fruit wall expansion, and vegetative

branching arrays when exposed to divergent field temperatures. However, comparative field trials examining newly registered commercial F1 hybrids across distinct, operational agro-ecological zones remain sparse, leaving extension teams and commercial smallholders without definitive phenotypic data.

Deploying expensive hybrid seeds requires clear agronomic justification. High initial seed input costs must be balanced against improvements in harvestable yields and actual cash returns. Field experiments must combine structural biological tracking with partial budgeting frameworks to confirm commercial utility for farmers. Accordingly, this multi-environment research was executed to evaluate the adaptability, structural growth habits, green pod yield parameters, and financial profitability of six introduced F1 hybrid varieties compared to a locally adapted baseline check across five contrasting agro-ecological environments in northwestern Ethiopia.

# MATERIALS AND METHODS

Field evaluations were conducted during the 2024 dry irrigation window across five distinct macro-environmental locations managed by Bahir Dar University and the Amhara Agricultural Research Institute. The test sites were situated along a distinct top sequence in northwestern Ethiopia, representing varying agro-ecological moisture zones, elevations, thermal matrices, and soil profiles. Fogera represents a seasonally wet, plain Vertisol complex characterized by heavy clay structures (48% clay) and a slightly acidic to neutral chemical matrix (pH 6.6). Jabi Tehnan, Woramit, Kunzila, and Merawi represent varying bands of highly weathered Nitisol and loam formations, ranging from slightly acidic loam structures in Jabi Tehnan (pH 6.16) to more intensely leached, acidic clay loam conditions in the high-altitude zone of Merawi (pH 5.4). The initial soil configurations across all five research nodes showed low to moderate organic matter margins (1.8–4.1%) and low to medium Olsen-extractable available phosphorus balances (4.12–10.0 ppm), while maintaining high available potassium baselines (100–200 ppm).

At each agro-ecological node, the seven varieties were managed under a randomized complete block design (RCBD) replicated three times, totaling 105 experimental field plots across the regional network. Individual gross plot units measured 3.5 m × 2.1 m (7.35 m²), while data collection was restricted to a net internal area of 3.96 m² to isolate the rows from border interactions. Each plot contained five rows holding seven plants per row, establishing a plant density of 35 individuals per unit. Spacing followed regional field parameters set at 0.70 m between active crop rows and 0.30 m between individual plants within a row.

Seeds were raised on uniform nursery beds using standard inputs. Triple superphosphate (TSP, 46% $P_2O_5$) was incorporated during bed preparation at 92 g per nursery unit. Healthy, hardened seedlings reaching standardized heights (20–25 cm) were transplanted onto field ridges exactly 50 days after initial sowing. Field fertilization treatments were uniformly applied across all genotypes using localized recommendations: 92 kg $P_2O_5$ $ha^{-1}$ via TSP was placed directly at transplanting, while nitrogen inputs

(urea, 46% N) were supplied in two equal split configurations (half at transplanting, half top-dressed during active vegetative branching at week four). Furrow irrigation loops were scheduled at 1-to-3-day frequencies immediately post-transplanting, transitioning to 3-to-7-day cycles depending on localized soil drying indices. Weeds and fungal pressures were actively suppressed using manual hand-weeding and scheduled Mancozeb 80% WP interventions.

Phonological metrics included tracking days to 50% flowering and days to 90% green pod maturity within net plot domains. Architectural variables included plant canopy height (cm) and the total number of primary vegetative branches per plant, recorded from six randomly sampled internal plants per unit at final harvest. Direct yield components included the number of pods per plant, individual average green pod weight (g), fruit length (cm), and pericarp thickness (mm) measured via precise mechanical calipers. Marketable green pod yield volumes (t $ha^{-1}$) were computed by aggregating clean, unblemished pods across multiple harvests, while unmarketable fractions tracking insect, disease, and physiological damage (sunburn/blossom-end rot) were converted into percentages. Total green pod yield was calculated as the sum of marketable and unmarketable yields.

Individual and combined analyses of variance (ANOVA) were executed across locations using SAS Software Version 9.4, treating replication factors as nested within specific environmental sites. Prior to combined calculations, error variance homogeneity was confirmed. Significant treatment differences were isolated using Duncan's Multiple Range Test (DMRT) and standard Least Significant Difference (LSD) parameters set at the 1% and 5% probability thresholds. Financial analysis applied step-wise partial budget and marginal rate of return (MRR) procedures outlined by CIMMYT (1988). Measured marketable pod yields were adjusted downward by 10% to mirror management and harvest gaps typical of smallholder field realities. Gross economic benefits were calculated based on the prevailing farm-gate market price of 80.00 ETB $kg^{-1}$ (80,000.00 ETB $t^{-1}$). Total variable costs were restricted to retail seed expenditures, while all other management operations remained constant. Dominance logic was applied to eliminate economically dominated options before calculating final MRR percentages.

## RESULTS

# Phonological Progression and Canopy Architecture

The combined analysis of variance (ANOVA) across the five operational agro-ecological nodes revealed that the main effects of genotype significantly altered maturity timelines, plant framework heights, and primary branch accumulation arrays ($P < 0.01$). Conversely, the genotype × environment interaction (GEI) factors were statistically non-significant for all monitored structural and phonological parameters, establishing highly stable regional expression pathways across the top sequence. Phonological initiation tracked via days to 50% flowering remained uniform across all experimental iterations ($P = 0.1668$), maintaining a highly synchronized regional flowering window spanning from 47.53 days in the early-maturing hybrid 'Amando' to 52.47 days in 'Serenade Explorer' (Table 1).

In sharp contrast to the synchronized flowering patterns, the time required to achieve days to 90% green pod harvest maturity varied extensively as a function of genetic background ($P < 0.0001$) while displaying strong stability across the test sites. The F1 commercial hybrid 'Amando' manifested extreme earliness, completing its commercial maturation cycle within a mean of 87.20 days. This performance represented an exceptional contraction of the cropping window when contrasted against the standard open-pollinated variety (OPV) local check 'Markofana', which required an extended duration of 131.73 days to attain identical maturity parameters. The remaining commercial hybrids exhibited intermediate maturation configurations, with mean requirements ranging from 96.00 days for 'Vigro' to 110.00 days for 'Ertale' (Table 1).

Structural vegetative framework attributes were profoundly governed by inherent genetic divergence. Plant canopy height at final harvest was significantly dictated by genotype ($P < 0.0005$). The hybrid selection 'Vigro' developed the tallest canopy profile with a mean height of 47.91 cm, which was statistically equivalent to the architectural stature displayed by 'Serenade Explorer' (46.97 cm). The standard check 'Markofana' exhibited the shortest physical stature, stabilizing at a mean canopy height of 39.08 cm (Table 1). Concurrently, the accumulation of lateral skeletal infrastructure—quantified via the number of primary branches per plant—was significantly modulated by both the main effects of location and genotype ($P < 0.0001$). The genotypes 'Amando' and 'Vigro' established highly dense lateral branching systems, generating 22.73 and 22.13 primary branches per plant, respectively. This structural density stood in stark contrast to the sparse, simplified canopy architecture of 'Markofana', which produced a regional average of only 14.87 primary vegetative branches per individual plant (Table 1).

Table 1
Growth and phenological parameters analysis. DF = Days to flowering, DM = Days to maturity, PH = Plant height, NPB = Number of primary branches.

| Varieties | DF (Days) | DM (Days) | PH (cm) | NPB |
|---|---|---|---|---|
| Amando | 47.53 | 87.20 c | 45.08 ab | 22.73 a |
| Ertale | 52.27 | 110.00 b | 43.01 bc | 17.80 c |
| Markofana | 51.80 | 131.73 a | 39.08 c | 14.87 d |
| Mixitoze | 51.20 | 105.47 b | 40.34 c | 16.00 cd |
| Serenade Explorer | 52.47 | 97.80 c | 46.97 ab | 20.33 b |
| Sernadie | 50.00 | 99.33 c | 42.93 bc | 17.40 c |
| Vigro | 48.40 | 96.00 c | 47.91 a | 22.13 ab |

## Green Pod Yield and Physical Quality Metrics

Reproductive components and final green pod yields were heavily influenced by genetic variation, though regional soil and moisture variations shifted absolute counts and individual weights. The cumulative number of pods per plant was significantly modulated by the separate main effects of location and genotype ($P < 0.0001$), while the GEI remained non-significant. The hybrid 'Vigro' demonstrated exceptional reproductive efficiency, producing a regional mean pool average of 119.72 pods per plant. This was followed by 'Amando' with 88.13 pods per plant, while the traditional variety 'Markofana' generated the lowest fruit count, stabilizing at 46.73 pods per plant (Table 2). Individual green pod weight was likewise significantly influenced by location and genotype ($P < 0.0001$). The heaviest individual fruits were harvested from 'Ertale' (21.39 g) and 'Vigro' (21.32 g), whereas the smallest individual fruit mass was recorded in 'Mixitoze' (14.65 g).

Linear fruit elongation (pod length) did not exhibit statistically significant variance across genotypes or locations ($P > 0.05$), maintaining a compressed, uniform regional range extending from 10.72 cm in 'Markofana' to 11.80 cm in 'Ertale' (Table 2). In contrast, pericarp wall thickness was significantly influenced by genotype ($P < 0.0011$). The most robust protective layers were recorded in 'Sernadie' (0.233 mm) and 'Mixitoze' (0.227 mm), while 'Amando' manifested the thinnest pericarp barriers (0.160 mm).

Marketable green pod yield volumes per hectare were heavily shaped by both location and genotype main effects ($P < 0.0001$), while the GEI was non-significant. The F1 hybrid 'Vigro' achieved a commanding mean marketable green pod yield of 24.07 t $ha^{-1}$, outperforming the open-pollinated check 'Markofana' (13.05 t $ha^{-1}$) by 84.44% and the lowest-yielding hybrid 'Mixitoze' (10.43 t $ha^{-1}$) by 130.78% (Table 2). Unmarketable crop loss percentages due to physiological or pest damage were significantly influenced by location ($P < 0.0375$) and variety ($P < 0.0216$). 'Mixitoze' and 'Markofana' accumulated the highest levels of unmarketable defects (1.87% and 1.72%, respectively), whereas 'Vigro' maintained a minimal unmarketable fraction of 0.24%. Consequently, total green pod yields mirrored marketable patterns, with 'Vigro' maximizing total volume at 24.31 t $ha^{-1}$ and 'Mixitoze' establishing the minimum base at 10.66 t $ha^{-1}$ (Table 2).

Table 2
Combined mean performance of yield and yield-related traits of hot pepper varieties tested across locations. NPPP: Number of pods per plant; APW: Average pod weight; PT: Pericarp thickness; PL: Pod length; MY: Marketable yield; TY: Total yield. Means within a column followed by the same letter are not significantly different at P < 0.05 according to DMRT.

| Varieties | NPPP | APW (g) | PT (mm) | PL (cm) | MY (t/ha) | TY (t/ha) |
|---|---|---|---|---|---|---|
| Amando | 88.13 b | 16.85 bc | 0.160 c | 11.67 | 15.55 | 15.78 |
| Ertale | 60.02 d | 21.39 a | 0.213 ab | 11.80 | 15.43 | 15.66 |
| Markofana | 46.73 e | 16.78 bc | 0.193 b | 10.72 | 13.05 | 13.30 |
| Mixitoze | 52.61 de | 14.65 c | 0.227 ab | 11.18 | 10.43 | 10.66 |
| Serenade Explorer | 75.69 c | 18.99 ab | 0.200 ab | 11.61 | 16.18 | 16.41 |
| Sernadie | 80.09 bc | 19.53 ab | 0.233 a | 11.57 | 16.20 | 16.46 |
| Vigro | 119.72 a | 21.32 a | 0.200 ab | 11.28 | 24.07 | 24.31 |

## Financial Feasibility and Economic Risk Simulation

Partial budget frameworks isolated the total variable costs (TVC) associated with high-input seed investments against the adjusted net financial returns across all varieties (Table 3). The commercial hybrid selection 'Vigro' generated the maximum net financial return, accumulating a substantial net benefit of 1,590,183.00 ETB $ha^{-1}$ due to its superior bio-physical marketable yields combined with a balanced seed initialization cost structure. In contrast, 'Mixitoze' recorded the lowest net financial benefit across the hybrid cohort, stabilizing at 370,008.00 ETB $ha^{-1}$.

Step-wise economic dominance screening successfully eliminated five of the six introduced F1 hybrid varieties ('Sernadie', 'Serenade Explorer', 'Amando', 'Mixitoze', and 'Ertale') because their exceptionally high upfront unit seed pricing outweighed their bio-physical harvest volumes, resulting in inferior net benefits relative to lower-cost options (Table 4). Ultimately, only the traditional open-pollinated variety 'Markofana' and the hybrid 'Vigro' emerged as non-dominated, economically viable production options. Transitioning from the low-cost agricultural baseline variety 'Markofana' to the elite hybrid 'Vigro' required an extra variable seed expenditure of 119,047.50 ETB $ha^{-1}$. However, this investment generated an extra 674,392.50 ETB $ha^{-1}$ in net profit, achieving an exceptional marginal rate of return (MRR) of 566.49% (Table 4).

Table 3
Economic variables and adjusted net benefits across varieties.

| Variety | Seed Cost (ETB/ha) | Marketable Yield (t/ha) | Adjusted Yield (t/ha) | Gross Benefit (ETB/ha) | Net Benefit (ETB/ha) |
|---|---|---|---|---|---|
| Markofana | 23809.50 | 13.05 | 11.75 | 939600.00 | 915790.50 |
| Vigro | 142857.00 | 24.07 | 21.66 | 1733040.00 | 1590183.00 |
| Sernadie | 333333.00 | 16.20 | 14.58 | 1166400.00 | 833067.00 |
| Serenade Explorer | 347618.70 | 16.18 | 14.56 | 1164960.00 | 817341.30 |
| Amando | 357142.50 | 15.55 | 14.00 | 1119600.00 | 762457.50 |
| Mixitoze | 380952.00 | 10.43 | 9.39 | 750960.00 | 370008.00 |
| Ertale | 476190.00 | 15.43 | 13.89 | 1110960.00 | 634770.00 |

Table 4
Step-wise dominance and marginal rate of return (MRR) analysis.

| Treatment | TVC (ETB/ha) | Net Benefit (ETB/ha) | Dominance Status | MRR (%) | Economic Rank |
|---|---|---|---|---|---|
| Markofana | 23809.50 | 915790.50 | Non-Dominated | - | 2 |
| Vigro | 142857.00 | 1590183.00 | Non-Dominated | 566.49 | 1 |
| Sernadie | 333333.00 | 833067.00 | Dominated | - | - |
| Serenade Explorer | 347618.70 | 817341.30 | Dominated | - | - |
| Amando | 357142.50 | 762457.50 | Dominated | - | - |
| Mixitoze | 380952.00 | 10.43 | Dominated | - | - |
| Ertale | 476190.00 | 634770.00 | Dominated | - | - |

# DISCUSSION

### Environmental Dynamics and Genetic Regulation of Canopy Development

The absence of statistically significant genotype × environment interaction (GEI) effects for phonological milestones and plant height suggests that structural growth in these commercial hot pepper selections is driven by strong, stable genetic pathways. The uniform flowering window observed across diverse elevations and soil matrices indicates that early reproductive triggers are primarily regulated by regional photoperiods and macro-thermal conditions, rather than localized microclimatic variations. This consistent expression aligns with the findings of Nsabiyera et al. (2012) in East African tropical pepper

trials, which reported that primary reproductive onset is highly heritable and tightly controlled by genetic constraints within elite Capsicum germplasm.

However, clear physiological differences emerged between the introduced F1 hybrids and the traditional open-pollinated variety (OPV). The extreme earliness exhibited by the hybrid 'Amando' (87.20 days to 90% maturity) represents a significant agronomic advantage over the local check 'Markofana' (131.73 days). In smallholder tropical agronomy, contracting the crop maturity window by over 44 days provides a practical tool to escape late-season environmental stresses, such as seasonal water deficits or intense pest cycles. This result corroborates the work of Shushay Chernet & Haile Zibelo (2019) in northern Ethiopia, who noted that modern F1 hot pepper hybrids consistently display advanced reproductive development and shorter crop cycles than regional OPVs due to strong heterotic acceleration. Furthermore, this rapid maturity supports the intensive sequencing objectives of smallholder irrigation schemes, allowing for increased cropping frequency and better market positioning, as highlighted by Alemu & Worku (2025).

The superior plant height (47.91 cm) and extensive primary branching profiles (22.13 and 22.73 branches plant$^{-1}$) recorded for 'Vigro' and 'Amando' illustrate the phenotypic benefits of modern hybrid selection. Because the genus Capsicum naturally exhibits dichotomous branching where flowers form at structural nodes, expanding the lateral canopy framework directly scales the plant's overall reproductive capacity. This architectural link explains the significant correlation frequently observed between dense vegetative branching and total fruit volume, a relationship previously documented by Munda Daniel & Shumbulo Abrham (2020) and Wakuma Biratu et al. (2021). The significant main effect of location on branch count shows that while genetic pathways set the plant's structural capacity, local soil conditions, soil fertility, and moisture profiles modulate how fully that capacity is expressed in the field. This environmental responsiveness matches the observations of Delelegn et al. (2014), who found that high-input modern pepper genotypes alter their branching complexity across soil gradients to maximize light capture and nutrient use.

**Yield Adaptation, Yield Components, and Mechanical Quality Profiles**

The outstanding marketable green pod yield achieved by 'Vigro' (24.07 t ha$^{-1}$) across all experimental environments indicates highly effective nutrient allocation and physiological stability. This high yield is a direct function of balancing key yield components: maximizing the overall number of fruits per plant (119.72) while sustaining a high individual fruit weight (21.32 g). This balanced development supports the physiological model described by Tripodi & Kumar (2019), which states that elite hybrid pepper yields depend on maintaining high fruit numbers without causing a sharp reduction in individual fruit mass. The sub-par yields of the check 'Markofana' (13.05 t ha$^{-1}$) and the hybrid 'Mixitoze' (10.43 t ha$^{-1}$) show that these choices lack the sink-source capacity required to maximize yield across diverse tropical top sequences.

Additionally, 'Vigro' maintained a very low unmarketable fruit fraction (0.24%), demonstrating excellent physiological resilience and tolerance to common field issues like sunburn and blossom-end rot. This

low defect rate represents a major quality upgrade over traditional selections. In contrast, 'Markofana' and 'Mixitoze' suffered much higher loss rates (1.72% and 1.87%), likely due to greater sensitivity to temperature swings and moisture stress across the test locations. This susceptibility pattern matches the findings of Melkamu Hinsermu et al. (2022) and Haileslassie Gebremeskel et al. (2015), who reported that older open-pollinated varieties frequently produce high levels of unmarketable fruit in multi-location trials due to weak stress tolerance and thin, vulnerable fruit structures.

The stability of pericarp thickness across locations indicates that fruit wall development is a highly heritable trait that can be reliably selected in diverse environments. The thicker pericarp walls found in 'Sernadie' (0.233 mm) and 'Mixitoze' (0.227 mm) are highly valued by commercial growers because they provide essential physical protection against bruising during transport and help extend shelf life in fresh markets. This mechanical advantage aligns with the quality criteria detailed by Bosland & Votava (2012) and Awole (2011), which identify pericarp thickness as a key driver of post-harvest quality and structural durability in fresh pepper logistics. Finally, the uniform pod lengths observed across all varieties (10.72–11.80 cm) indicate a narrow genetic range for linear fruit dimensions within this commercial group. This consistent length performance ensures uniform fruit shape profiles across locations, which is highly beneficial for meeting standardized commercial market criteria, as noted by Gebremedhn et al. (2018).

**Financial Feasibility and Investment Risk Profiles**

The partial budget simulations clearly demonstrate that evaluating a crop's biological yield alone is insufficient for making practical recommendations to smallholder farmers, as high seed costs can significantly impact net income. Step-wise dominance analysis eliminated five of the six F1 hybrids ('Sernadie', 'Serenade Explorer', 'Amando', 'Mixitoze', and 'Ertale') because their exceptionally high seed prices outweighed their yield returns under these production conditions, leading to poor financial performance. This economic pattern reflects a common challenge in smallholder hybrid adoption: high initial seed costs can negate the financial benefits of improved biological yields if the genotype's productivity does not clear a specific volume threshold, as discussed by Abdissa (2019) and Kassa Melese et al. (2018).

However, 'Vigro' proved to be highly cost-effective and financially viable. While switching from the inexpensive local variety 'Markofana' to 'Vigro' required a substantial additional seed investment of 119,047.50 ETB $ha^{-1}$, it generated an extra 674,392.50 ETB $ha^{-1}$ in net profit. The resulting marginal rate of return (MRR) of 566.49% is well above the standard 50–100% economic minimum required for new technology adoption according to CIMMYT (1988) guidelines. This exceptional return demonstrates that the initial investment in 'Vigro' seed is well justified by its yield increases, making it a highly reliable, low-risk recommendation for smallholder farmers seeking to transition from traditional open-pollinated baselines to high-value hybrid production systems.

# CONCLUSIONS AND RECOMMENDATIONS

This multi-environment study confirms that the agronomic performance and profitability of hot pepper production in northwestern Ethiopia are strongly influenced by genetic choice. The F1 hybrid 'Vigro' demonstrated excellent adaptability across all five agro-ecological locations, producing the highest marketable green pod yield (24.07 t $ha^{-1}$) and the lowest percentage of unmarketable fruit defects. The variety × location interaction effects were non-significant for nearly all agronomic, morphological, and yield variables, indicating a highly uniform and stable genotypic ranking across all five distinct test environments during the study season. Furthermore, partial budget modeling confirmed that 'Vigro' provided the best economic returns, delivering a clear financial advantage over traditional open-pollinated options. The hybrid variety 'Vigro' is recommended for integration into irrigated green pod production systems across northwestern Amhara and matching agro-ecological zones to maximize smallholder yields and returns. Due to its early maturity profile, 'Amando' is recommended for production systems requiring rapid crop cycles to avoid late-season environmental stress. Agricultural extension teams should focus on supporting these varieties with optimized crop management packages, particularly regarding fertilizer and water efficiency, to allow these hybrids to reach their full genetic potential.

### LIMITATIONS OF THE STUDY AND FUTURE LINE OF WORK

The primary limitation of this research is that field evaluations were conducted over a single irrigation season. While the multi-location layout across five distinct sites provides strong data on spatial adaptation, it cannot account for year-to-year weather variations or long-term climate risks. Additionally, this study focused entirely on green pod performance; further research is needed to evaluate how these specific hybrids perform under dry red pod production systems, which have different harvest and processing requirements.

## Declarations

### Author Contributions (CRediT Syntax)

TY: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. FM: Conceptualization, Formal Analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing – review & editing. MM, EA, YB and HT: Supervision, Project administration, Writing – review & editing.

### Declaration of Funding

The authors declare that no direct external financial project grants were received from commercial entities or international seed vendors to complete this research.

### Conflicts of Interest

The authors declare that they have no competing commercial or financial interests that could influence the impartiality or integrity of the data presented in this work.

**Data Availability Statement**

The complete multi-location biological raw datasets generated and analyzed during the current field study are available from the corresponding author upon reasonable request.

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