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Application of DSSAT Crop Simulation Model to Identify The Yield Variation of Tomato and Cabbage During Mid Centuries Due to Global Warming and to Compare With The Effectiveness of Super Absorbent Polymer (ZEBA) on Yield of Those Crops

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ABSTRACT

The increased danger of global warming and the observed loss of persistent precipitation regimes threaten severe challenges to global crop yields. The study in this work employed a two-fold approach, which involved the integration of crop simulation modeling and a controlled environmental experiment, to examine measures for the maintaining of productivity in two significant vegetable crops, cabbage and tomato. The CROPGRO model, which is integrated into the Decision Support System for Agrotechnology Transfer (DSSAT v4.5), was applied to forecast yield responses for the years 2040, 2050, and 2060. Concurrently, a field experiment under a polytunnel replicated the unfavorable temperature conditions projected for 2060 to test the efficacy of the super absorbent polymer, ZEBA. Simulations under the model indicated significant loss in yield: fresh weight of tomato fruit per plant will be reduced by 40% to 53% by mid-century, and head weight of cabbage will also decrease by approximately 40%. Critical temperature situations forecasted highs of up to 36°C by 2060. Significantly, the controlled test affirmed that ZEBA application successfully reversed such losses, raising tomato and cabbage yields by 65.7% and 37.9%, respectively, against baseline yields simulated for the year 2060. These findings provide valuable insights into adaptive strategies that may help sustain crop productivity under future climate change scenarios.

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INTRODUCTION

Today, the inherent variability of global climate and localized weather are the result of an interaction of environmental and anthropogenic factors. Of these factors, abiotic stresses in the nature of long-duration drought and extreme thermal stresses (temperature stress) are the principal challenges to sustainable crop production worldwide. The call for action on the crisis is most keenly felt in vulnerable countries; namely, Sri Lanka was placed among the top ten most affected countries by climate change and extreme weather events in the 2020 ranking (Eckstein et al., 2019).

Citing the Second National Communication of 2011, Sri Lanka is anticipated to see a spectacular temperature rise, 1.1–2.4 °C by 2100, depending on future global emission paths. Moreover, projections using the HadCM3 general circulation model (De Silva et al., 2007) indicate an anticipated reduction in the volume of rainfall, i.e., a decline of 9% to 17% during the critical maha cultivation season by 2050. The World Bank climate change knowledge portal (2020) also indicates in tandem a projected rise in the nation's mean annual temperature, which is to become more aggressive by around the year 2030 and perhaps even accelerate further towards the year 2050. Although drought intensity projections are in doubt for the near future (2030), the future in and around the year 2050 is forecast to be plagued by both higher frequencies and intensified frequencies of drought, leading to lower efficiency of crop growth caused by both greater thermal stress and higher levels of evapotranspiration.

With these profound climatic uncertainties, sound forecasting and estimation of future declines in crop yield due to dynamic climatic conditions are most crucial to farm planning. The Decision Support System for Agro-technology Transfer (DSSAT) is a proven, modular, and internationally established crop simulation model specifically suited to this purpose, offering an effective tool for simulating the growth and yield of over 30 diverse crops under specified soil and daily weather conditions. The global applicability of the DSSAT-CERES module, even to varying climates and soils, has been satisfactorily proven (Geng et al., 2017), demonstrating its capability to effectively simulate complex interactions between growth, biomass production, yield, and water use efficiency under varying environmental and management regimes. The field feasibility in selecting optimized agriculture practices has also been proven (Sarkar, 2009). Its applicability across the years is also evidenced by its ongoing use by foreign scientists for the past 15 years (Kelly et al., 2021) for different reasons like crop management, estimation of climate impact, sustainability assessment, and precision farming. As required by Dias (2016), DSSAT is a vital tool for making realistic projections about future yields in response to variable weather and for formulating suitable, fact-based adaptive measures to enhance productivity.

The necessity of setting up and applying several mitigation methods is utmost in order to counter the ill effects of extreme temperature and water stress on plant growth and final yield. Among them, application of Super Absorbent Polymers (SAPs) has been a recent, trendy technological intervention in several nations specifically designed to counter high-temperature- and water-limited yield loss. ZEBA, the SAP form utilized in the present study, is a natural polymer that possesses the specific hydrophilic characteristic of having the capacity to absorb high levels of water and subsequently release the absorbed moisture to plants when the environmental water is limited and cannot be fully exploited. Earlier field experiments supports this procedure: experiments with cabbage (Ananda et al., 2009) and tomato (Meena et al., 2011) have confirmed that SAP application causes significant improvement in biophysical traits, including increased yield, increased plant height and spread, and increased head initiation compared to control conditions. Besides, Li et al. (2019) proved that SAP-amended soil possesses an even more striking temperature adjustment role, which effectively alleviates thermal stress in crop roots and tissues, thus contributing to the facilitation of improved yields even under extreme thermal stress conditions.

As a measure of counteracting the vulnerability of such crops—cabbage (Brassica oleracea) and tomato (Solanum lycopersicum)—to future climate conditions, the present research embarked on two independent, complementary research goals:

To develop predictive forecasts of cabbage and tomato yield responses to future climate scenarios for 2040, 2050, and 2060 using DSSAT crop simulation system.

To experimentally evaluate the effectiveness of super absorbent polymer ZEBA as a soil conditioner to reduce yield loss when crops are exposed to high temperatures mimicking the worst-case scenario in the future (2060).

MATERIAL AND METHOD

DSSAT Modeling Framework and Data Collection

The DSSAT crop model, that is, the Decision Support System for Agrotechnology Transfer (DSSAT v4.5), employing the CROPGRO module accurately, was employed to forecast the future yield of tomato (variety "Thilina") and cabbage (variety "Exotic F1"). Yield simulation included anticipated variability in temperature and rainfall, forecast by the Global climate model under the high-emissions Representative Concentration Pathway (RCP 8.5) climate change scenario. The RCP 8.5 scenario was specifically selected for this study as it represents, the 'high-emission' or 'business-as-usual' pathway, providing a critical framework for climate-risk assessment in Sri Lankan agriculture. By utilizing the most extreme plausible climate trajectory, this research aims to 'stress-test' the vulnerability of tomato and cabbage production. This approach ensures that the evaluated adaptation strategy, the integration of the super absorbent polymer (ZEBA)is analyzed under maximum climatic pressure. Given that global emission trends have historically tracked closely with high-end scenarios, focusing on RCP 8.5 offers a robust baseline for developing resilient food security policies and a 'worst-case' preparedness plan for smallholder farmers in tropical regions.

Technical reports offered by the DSSAT software served as a source of reference for the collection of data, with several sets of data collected using sample analysis, observation, and available data sources.

Meteorological and Soil Input Data

Daily meteorological parameters were monitored continuously from planting to harvest. The recorded dataset included solar radiation, cumulative rainfall, and daily air temperature (minimum and maximum).

Soil samples were collected and analyzed across two distinct depth intervals: the surface layer (0–20 cm) and the subsurface layer (20–50 cm). To provide a comprehensive profile of the study site, the following parameters were evaluated for both depths:

Physical Properties: Soil class, texture, bulk density (g/cm^3), and particle size distribution (sand, silt, and clay percentages).

Chemical Properties: Soil pH, percentage of organic carbon, and Cation Exchange Capacity (CEC; $cmol_c/kg$).

Crop Management Information

Critical crop management information was obtained from continuous field experiments at The Open University of Sri Lanka.

Model Calibration and Verification

To obtain accurate and reliable model outputs, the DSSAT model (v4.5) was independently calibrated for tomato and cabbage. This was done using field data obtained from the research fields of the University with the use of the sensitivity analysis mode under the software. Additional validation of the model was a comparison with independent experimental data gained from trials conducted at the Open University. The results gained were in agreement with the simulated values, meaning that the model was suitable for regional prediction.

Integration of Climate Scenarios and Yield Prediction

The growth and yield parameters that were simulated for tomato and cabbage were projected for 2040, 2050, and 2060. For yield prediction, future climate data was prepared from the Global climate model under the RCP 8.5 climate scenario specially prepared for the Colombo region, and then integrated into the weather data file within the DSSAT system.Future climate projections for the Colombo region were derived from the CMIP5 multi-model ensemble under the RCP 8.5 pathway. To bridge the gap between coarse-scale GCM outputs and the site-specific daily requirements of the DSSAT v4.5 model, a statistical downscaling approach was employed. Monthly climate anomalies from the GCM were translated into daily weather sequences (maximum temperature, minimum temperature, and rainfall) using the MarkSim GCM stochastic weather generator. This process utilized a third-order Markov chain to simulate daily variability and ensured the generated. WTH files captured the local climatic nuances of the Colombo area. The year 2020 served as the baseline for calculating climate shifts, allowing for a consistent comparison of yield performance across the 2040, 2050, and 2060 horizons.

Controlled Environment Experiment

In addition to the model-based estimates, another field trial was conducted in a controlled polytunnel environment. This environment was carefully controlled under conditions which approximate 36 °C, the estimated peak temperature for the year 2060 under the climate change scenario RCP 8.5. The recommended application rate of ZEBA, a super absorbent polymer, was utilized in this experiment to determine the efficacy of SAPs in mitigating the adverse impact of extreme temperature on crop yield.

Statistical Analysis

The experiment was conducted under a Completely Randomized Design (CRD) with twenty-five replicates per crop to ensure statistical robustness. The data gathered on yield were quantified and thereafter analyzed through the Analysis of Variance (ANOVA) approach. Statistical significance was determined using a Revised Least Significant Difference (LSD) test to estimate treatment differences at a level of significance of $p<0.05$, following the suggested procedure outlined by Snedecor and Cochran (1989).

RESULTS AND DISCUSSION

Calibration and Validation of the Model

Tomato (Var. Thilina)

The CROPGRO model utilizes cultivar-specific parameters (CSPs) to accurately simulate the growth of the crop and the yield. The CSPs obtained through the calibration trials of the 'Thilina' variety of tomato are shown in Table 1, along with previously calibrated values for the commercial variety 'Florida 47' (Boote et al., 2012) for comparative purposes.

Table 1. Genetic coefficient of tomato (var. Thilina) calibrated in DSSAT (Decision Support System for Agricultural Transfer) against a previously calibrated FL 47 tomato cultivar.

Code	Description	Thilina	FL.47
EM.FL	Time between plant emergence and flower appearance (R1) (Photo thermal days)	24.90	24.4
FL.SH	Time between first floer and first pod (R3) (Photo thermal days)	2.70	2.20
SD.PM	Time between first seed (R5) and physiological maturity (R7)	45.01	45.20
SIZLF	Maximum size of full leaf (three leaflets) (cm^2)	300.0	300.0

Minor variations were observed between the two varieties. Specifically, the estimated thermal time from emergence to flowering (EM.FL) slightly in favor of 'Thilina' (24.90) over 'Florida 47' (24.40). Similarly, 'Thilina' took a shorter thermal time from first flower to first fruit (FL.SH) at 2.10, compared to 'Florida 47's 2.70. Apart from these parameters,estimated values for all other parameters were identical, which indicates comparable genetic growth characteristics.For the validation of the accuracy of the calibrated CSPs, the simulated outputs for physiological maturity, dry biomass production, and fruit yield were compared with corresponding field-measured values. Statistical measure d-stat (agreement index) was used to measure how close the model fit was, as shown in Table 2.

Table 2. Simulated and observed mean values for anthesis, maturity, fruit yield, and biomass production at physiological maturity and their respective statistical indices of tomato variety Thilina

Parameter RMSE	Simulated	Obseraved	d-sat
Days to anthesis	26	27	0.99
Days to physiological maturity	98	97	0.98
Dry biomass production (kg/ha)	5781	5419	0.95
Fruit yield (kg/ha)	3310	3234	0.97

A high correlation, with d-stat values ranging between 0.95 and 0.99, was identified between the simulated and observed values for every parameter examined. This successful correlation validates the 'Thilina' model calibration and its applicability in future yield estimation.

Cabbage (Var. Exotic-F1)

The CROPGRO model of cabbage that had initially been calibrated in a tropical Hawaiian setting (Hoogenboom et al., 2003) was then re-calibrated for the 'Exotic-F1' cultivar. The CSPs derived are compared with the earlier calibrated values for the 'Tastie' cultivar in Table 3.

Table 3. Genetic coefficient of cabbage (var. Exotic-F1) calibrated in DSSAT (Decision Support System for Agricultural Transfer) against a previously calibrated Testie cultivar.

Code	Description	Exotic-F1	Testie
FL.SH	Time between first flower and first pod (Photo thermal days)	6.0	5.0
FL.SD	Time between first flower and first seed (Photo thermal days	15	11
SD.PM	Time between first seed and physiological maturity	71	55

While the overall estimated CSP values for both varieties were comparable, there was some variation in specific growth stage durations. Time from flower to first pod (FL.SH) was slightly longer for 'Exotic-F1' (6.0 photothermal days) than 'Tastie' (5.0). Similarly, first flower to first seed (FL.SD) was 15 photothermal days in 'Exotic-F1' as opposed to 11 in 'Tastie', while first seed to physiological maturity (SD.PM) was 71 photothermal days in 'Exotic-F1' and 55 in 'Tastie'.Validation results for the 'Exotic-F1' cabbage variety, comparing simulated and observed yields, are presented in Table 4.

Table 4. Simulated and observed mean values for fresh weight of head, dry matter head yield and total above ground dry matter per plant and their respective statistical indices of cabbage variety Exotic-F1

Parameter RMSE	Simulated	Obseraved	d-sat
Fresh weight of head weight	327g	315g	0.97
Dry matter head yield	101g	97g	0.99
Total above ground dry matter	421g	407g	0.96

The high d-stat values ranging between 0.96 and 0.99 indicate an agreement in close proximity between the simulated values derived from the model calculations and field measurements of the growth and yield parameters, thereby establishing the model's dependability for future yield projection in cabbage.

Future Climate Projections and Scenario Setup

According to the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, the Representative Concentration Pathway (RCP) 8.5 scenario—the most emissions-intensive pathway—was employed for future climate prediction in the Colombo region. The predicted changes in key climatic factors for the simulation years (2040, 2050, and 2060) with respect to the base year (2020) are summarized in Table 5.

Table 5. Observed and forecasted weather data for Colombo area.

Parameter	2020	2040	2050	2060
Maximum temperature (^{0}C)	32	33.2	34.3	36.1
Minimum temperature (^{0}C)	26	28.1	29.2	30.4
Rainfall (mm)	1760.9	1700.1	1654.2	1501.7
Solar radiation	19.54	20.7	20.2	22.1

The forecasted weather data clearly shows a rising trend of air temperatures and decreased rainfall in the Colombo region. Peak temperatures will increase from 32 ^{0}C in 2020 to a maximum of 36.1 ^{0}C by the year 2060, with minimum temperatures increasing from 26 ^{0}C to 30.4 ^{0}C over the same period. Conversely, precipitation is predicted to decrease from 1760.9 mm to 1501.7 mm. All these changes form the climatic basis for the future yield estimates.

Future Yield Projection under RCP 8.5

Changes in Tomato Yield

Simulation outcomes of 'Thilina' tomato variety under the RCP 8.5 climate change scenario project an extreme decrease of overall yield components in the mid-century compared to the 2020 baseline. Numbers of fruits per plant along with the fresh fruit weight per plant are expected to decrease.

The reduction in the number of new fruits per plant that is forecasted is estimated to be roughly 42% within this period (Figure 1). This reduction is primarily brought about by the synergistic effect of higher temperature and lower rainfall, which negatively impacts reproductive success, particularly flower and fruit set. Gao(2026) utilized DSSAT-CROPGRO to project that tomato productivity in South Asia could decline by approximately 26.24% under the RCP 8.5 scenario by the end of the century due to escalating heat stress.

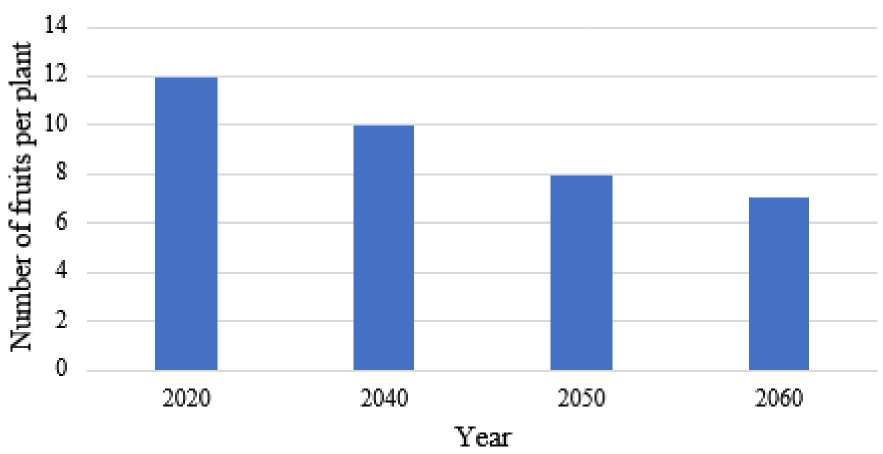


Figure 1.Variation of number of fruits of tomato per plant in simulated years

Moreover, the highest commercial productivity metric, i.e., fresh weight of fruits per plant, is projected to decline by approximately 40% to 53% in 2050 and 2060 years, respectively, from the 2020 level (which can be seen from Figure 2: Variation of fresh weight of fruits of tomato per plant in simulated years).

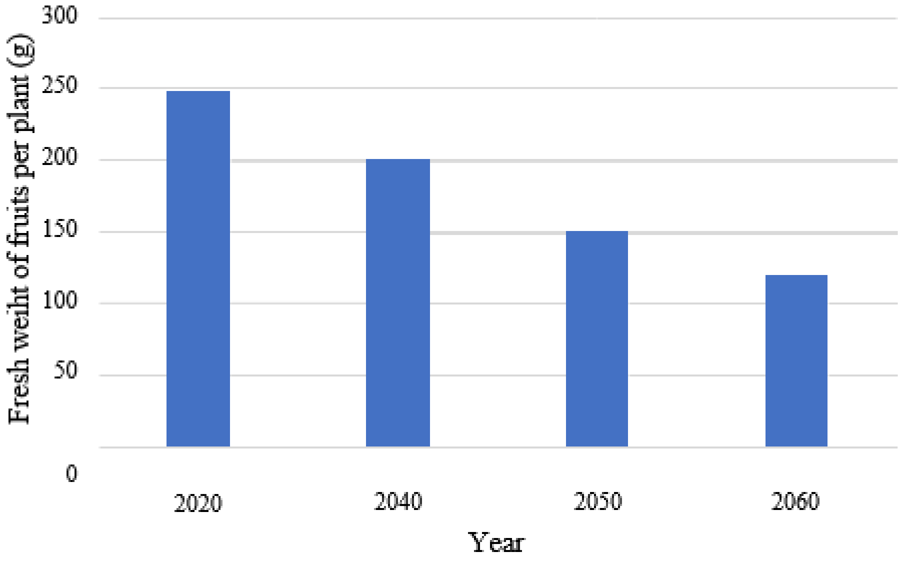


Figure 2. Variation of fresh weight of fruits of tomato per plant in simulated years

Changes in Cabbage Yield

The simulation outcomes for the 'Exotic-F1' cabbage crop also indicate a drastic yield decrease under the future climatic scenario (RCP 8.5). Specifically, the fresh weight of the cabbage heads will decrease by about 40% during the mid-century timeframe, an effect directly generated by the increased temperature and the projected reduction in effective rainfall.The simulated outcomes for head weight of cabbage are pictorially presented in Figure 3: Variation of fresh weight of heads of cabbage in simulated years.

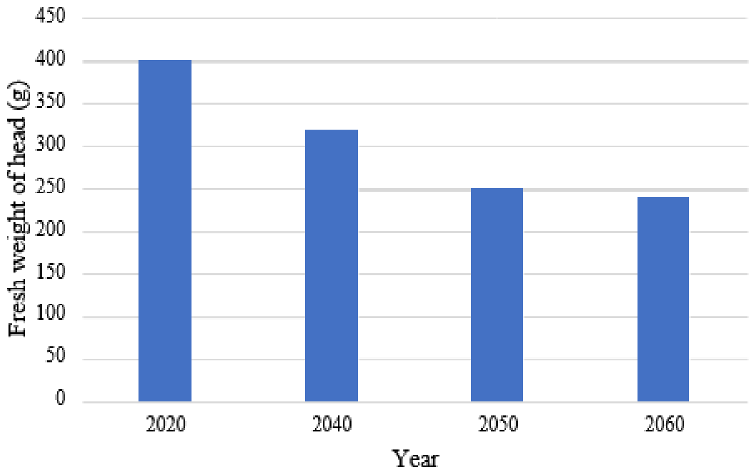


Figure 3. Variation of fresh weight of heads of cabbage in simulated years

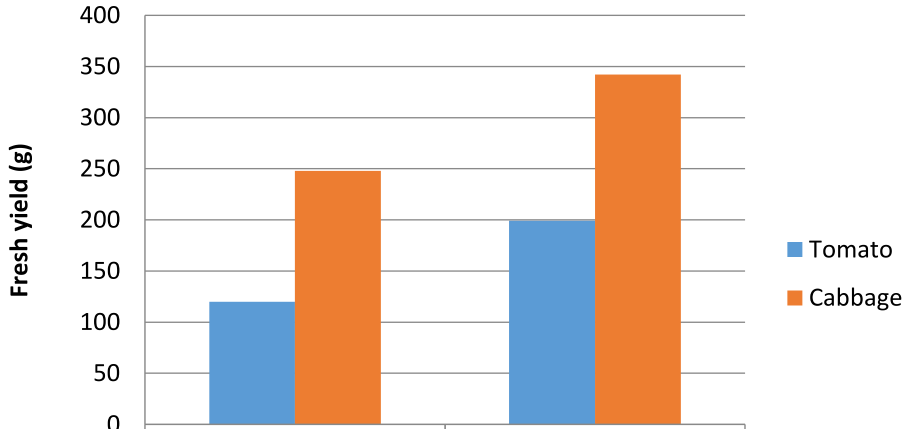
Evaluation of Mitigation Strategy: Efficiency of ZEBA Application

The routine crop management operations evolved through each season suggest that the variation realized in yields arises mostly due to variation in climatic conditions.

The simulated results clearly show that for the RCP 8.5 scenario, the experimental field will experience combined stress of increased maximum and minimum air temperature, increased solar radiation, and decreased precipitation. The primary conclusion is that sustained application of current crop management at mid-century would lead to a yield loss of approximately 40% for both tomato and cabbage. This demands identification and implementation of appropriate adaptation methods, such as changing management practices, employing new adaptation technology, or cultivating new, heat-resistant varieties.

By 2060, the high temperature forecast is projected to hit towards an average of some 36^0C This maximum temperature was specifically employed on a batch of tomato and cabbage plants in a polytunnel at the same moment as applying the Super Absorbent Polymer, ZEBA, to test how efficient it would be in reducing the impact of this high thermal stress on crop yield.The results of the controlled environment trial were highly notable. wherever ZEBA was used under the high-temperature conditions of the 2060 scenario, the outcome was a marvelous increase in yields above the simulated 2060 yields (Figure 4).

Tomato yield increased by 67.8% and Cabbage yield increased by 36.7%.



	Without ZEBA	With ZEBA
Tomato	120	199
Cabbage	248	342

Figure 4. Efficiency of ZEBA Aoolication

This indicates that ZEBA is an effective technological application, maybe by controlling the temperature environment around the roots and giving the best water supply, thereby reimbursing the extreme loss of yield simulated by the model under severe heat and water stress.The adoption of ZEBA, a corn-starch-based super-absorbent polymer (SAP), offers a promising pathway for climate-resilient farming, though its success depends on economic scalability. As a biodegradable and non-toxic amendment, ZEBA minimizes long-term environmental costs compared to synthetic alternatives (Malik et al., 2022). From an economic perspective, the initial cost of the polymer is mitigated by significant input savings; studies indicate that SAPs can reduce irrigation water requirements by 25–40% while simultaneously decreasing nutrient leaching (Satriani et al., 2018). For smallholder farmers in the Colombo region, this translates to a higher benefit-cost ratio through reduced labor for irrigation and lower fertilizer expenditures. Scalability is further supported by the work of Rasanjali et al. (2020), which demonstrated that using ZEBA allows for extending irrigation intervals up to five days without significant yield reduction, making it a viable tool for water-scarce periods.

The simulations were localized to the Colombo region. While this offers high-resolution data for a major horticultural hub, the results may vary across Sri Lanka's diverse agro-ecological zones. As noted by Ranasinghe et al.(2022), multi-location trials and multi-model ensembles are essential to fully validate the regional scalability of such adaptation strategies. Future research should expand these simulations to include diverse microclimates, such as the Central Highlands, to ensure a comprehensive national food security strategy.

CONCLUSION and RECOMMENDATION

The integration of DSSAT crop simulation with controlled environment experimentation could quantitatively measure the impending climate risk and validate a principal mitigation strategy for tomato and cabbage cultivation in the Colombo region.The anticipated climatic values under the RCP 8.5 pathway confirms a definitive and accelerating thermal and hydrologic shift by mid-century. The maximum air temperature is to increase exponentially, from a reference of 32^0C for 2020 to 33.2^0C in 2040, 34.3^0C in 2050, and as high as 36.1^0C in 2060. This is coupled with an alarming reduction in annual rainfall, which is forecast to reduce from 1760.9 mm in 2020 to 1501.7 mm in 2060.In these cumulative stresses, the model's yield predictions were clear:

Tomato (Var. Thilina): Fresh fruit per plant is estimated to decrease by approximately 42 %

Cabbage (Var. Exotic-F1): Weight of the fresh head is estimated to decrease by approximately 40%.

These findings cumulatively underscore the unprecedented vulnerability of current agriculture practices to the cumulative effects of heightened temperature and lower precipitation.

Above all, the experimental component of this research validated the great promise of Super Absorbent Polymers (SAPs) as an effective adaptive technology. The ZEBA treatment under 36^0C conditions produced remarkable yield enhancements over the

2060 baseline simulated scenario: tomato yields increased by 65.8% and cabbage yields by 37.9%. This finding strongly validates that SAPs can possess the capacity to significantly counteract the harmful impacts of temperature and water stress on crop development and yield.Therefore, the application of SAPs will be a strong adaptation technology to counter the impact of high temperature and low rainfall in future crop production. But to advance these results to productive agricultural policy, large-scale, location-specific studies covering various agro-ecological zones of Sri Lanka and various species of high-value crops must be conducted to form strong, generalized recommendations for farmers to apply SAPs.

Conflict of Interest

The authors have declared that there are no competing interests

Authors Contribution

KGA Iresha Rasanjali conceptualized the study, designed the methodology, and conducted the data collection. The experiments were executed by KGA Iresha Rasanjali with technical support from CS De Silva and LKR Jayakody. Furthermore, KGA Iresha Rasanjali drafted the initial manuscript, which underwent critical review by the co-authors.

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