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Sustainability-oriented effects of a longitudinal multicomponent school-garden intervention on food literacy, dietary diversity, and household educational transfer in rural schools

Dionicio López Basilio
Professional School of Primary Education, Universidad Nacional Daniel Alcides Carrión, Cerro de Pasco, Peru

Histler Juan Castillo Paredes
Professional School of Environmental Engineering, Universidad Nacional Daniel Alcides Carrión, Cerro de Pasco, Peru

Teófilo Félix Valentín Melgarejo
tevame2020@gmail.com

Professional School of Secondary Education, Universidad Nacional Daniel Alcides Carrión, Cerro de Pasco, Peru

Javier Raúl Minaya Lovaton
Professional School of Primary Education, Universidad Nacional Daniel Alcides Carrión, Cerro de Pasco, Peru

Wilfredo Florencio Rojas Rivera
Professional School of Primary Education, Universidad Nacional Daniel Alcides Carrión, Cerro de Pasco, Peru

Josué Chacón Leandro
Professional School of Primary Education, Universidad Nacional Daniel Alcides Carrión, Cerro de Pasco, Peru

David Wilson Osorio Espinoza
Professional School of Primary Education, Universidad Nacional Daniel Alcides Carrión, Cerro de Pasco, Peru

Lury Tatiana Quispealaya Arenas
Professional School of Primary Education, Universidad Nacional Daniel Alcides Carrión, Cerro de Pasco, Peru

Clodoaldo Ramos Pando
Professional School of Secondary Education, Universidad Nacional Daniel Alcides Carrión, Cerro de Pasco, Peru

Armando Elías Zenteno Quinto

Language Center, Universidad Nacional Daniel Alcides Carrión, Cerro de Pasco, Peru

Raúl Malpartida Lovatón

Professional School of Secondary Education, Universidad Nacional Daniel Alcides Carrión, Cerro de Pasco, Peru

Ramón Ángel Robles Huaynate

Professional School of Secondary Education, Universidad Nacional Daniel Alcides Carrión, Cerro de Pasco, Peru

Elizabeth Clara Cordova Zevallos

Professional School of Primary Education, Universidad Nacional Daniel Alcides Carrión, Cerro de Pasco, Peru

José Rovino Alvarez Lopez

Professional School of Secondary Education, Universidad Nacional Daniel Alcides Carrión, Cerro de Pasco, Peru

Flaviano Armando Zenteno Ruíz

Professional School of Secondary Education, Universidad Nacional Daniel Alcides Carrión, Cerro de Pasco, Peru

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Abstract

School-based food and nutritional security interventions have emerged as promising strategies for improving food literacy and promoting sustainability-oriented educational outcomes among children. However, many previous studies have relied on short-term interventions and conventional pretest–posttest approaches, with limited evaluation of longitudinal adaptation, family-transfer processes, and implementation sustainability. Therefore, the present study evaluated the longitudinal effects of a multicomponent school-garden intervention on food literacy, dietary diversity, learning retention, and sustainability-related educational outcomes among rural primary school students. A 12-month longitudinal intervention was implemented in 12 rural primary schools involving 1,220 students aged 8–12 years. The intervention integrated food literacy education, educational garden activities, cooking and nutrition workshops, family-transfer practices, and teacher-supported implementation. Repeated assessments were conducted at baseline and at 3, 6, 9, and 12 months. Food literacy, dietary diversity, engagement, family-transfer practices, and sustainability-related indicators were analyzed using multilevel longitudinal, multivariate, temporal, and predictive analytical approaches. The intervention produced significant improvements in food literacy and dietary diversity across the assessment period. The proportion of students classified within the high food-literacy category increased from 17% at baseline to 66% at 12 months, whereas the low-literacy category decreased from 37% to 6%. Multivariate analyses demonstrated significant restructuring of nutritional-learning profiles over time, while temporal analyses revealed progressive synchronization and stabilization of educational and behavioral responses. Student engagement and family-transfer practices were identified as major predictors of retention probability and literacy improvement. In addition, multilayer diffusion analyses demonstrated progressive propagation of food-literacy practices across school and household environments. Overall, the findings demonstrate that multicomponent school-garden interventions may function as effective sustainability-oriented educational systems capable of improving food literacy, dietary diversity, learning retention, and household educational transfer simultaneously. The integration of experiential learning, family reinforcement, and implementation support appears critical for promoting long-term educational sustainability in rural school environments.

1. Introduction

Rural and economically marginal communities around the world continue to face food and nutritional insecurity, particularly among children, as a major public health and educational challenge. School-age children frequently experience poor nutritional outcomes and unfavorable long-term health trajectories due to limited dietary diversity, inadequate nutrition knowledge, unhealthy food behaviors, and insufficient access to practical nutrition education (Saavedra and Prentice, 2023). Structural inequalities, reduced access to diversified foods, and limited educational resources further constrain the development of sustainable food-related behaviors, especially in rural educational contexts (Nichifor et al., 2025). In recent years, schools have increasingly recognized their strategic role in promoting food literacy, healthy eating habits, and sustainability-oriented learning among children and adolescents.

Food literacy has emerged as a key multidimensional concept that extends beyond nutritional knowledge and encompasses cognitive, behavioral, social, and practical skills required to make informed food-related decisions. Previous studies have demonstrated that higher food literacy is associated with healthier eating habits and practices, greater dietary diversity, improved food safety awareness, and better long-term health outcomes (Begley et al., 2019; Forray et al., 2023; Silva, 2023). Consequently, food literacy has become increasingly relevant within sustainability-oriented educational frameworks that integrate nutrition, environmental awareness, behavioral change, and community participation (Silva, 2025). Nevertheless, despite the growing implementation of food literacy interventions, many school-based programs remain predominantly classroom-oriented and frequently lack practical, experiential, and household-transfer components.

The importance of school gardens as effective educational tools capable of integrating nutrition education, active learning, environmental sustainability, and community engagement has gained increasing recognition in recent years. Educational gardens offer students direct, hands-on experience with food production while fostering healthy dietary behaviors, awareness of biodiversity, understanding of local food systems, and the adoption of sustainable food practices. Previous studies have shown that school-garden programs may positively influence vegetable preferences, nutrition knowledge, food attitudes, and dietary behaviors among children (Kim and Park, 2020; Chan et al., 2022). Furthermore, learning through observation, cultivation, participation, and collaborative activities has been associated with higher educational engagement and stronger learning retention compared with exclusively theoretical educational approaches.

Despite these advances, several important gaps remain within the existing literature. First, many studies primarily evaluate short-term pretest–posttest improvements (Moore and Tananis, 2009) and do not assess the long-term stability of educational and dietary interventions. Second, interventions are frequently restricted to single outcomes such as nutrition knowledge or vegetable consumption (Appleton et al., 2016), while overlooking broader dimensions of sustainability-oriented education, including household-transfer practices, implementation diffusion, and adaptive educational responses over time. Third, most previous research has relied predominantly on traditional statistical comparisons and descriptive analyses (Bernard et al., 2004), which may not fully capture the dynamic interactions among educational, behavioral, and sustainability-related outcomes throughout intervention periods. Moreover, very few studies have investigated school-garden interventions from a multilevel longitudinal perspective that allows evaluation of temporal adaptation, predictive learning trajectories, implementation heterogeneity, and sustainability-oriented diffusion processes across schools and households.

Another important limitation of existing studies is the limited attention given to the integration of household and community transfer processes within school-based food interventions. Classroom exposure alone is often insufficient to produce sustainable behavioral change, as reinforcement through family and community environments plays a critical role in the retention and continuity of learned behaviors. Nevertheless, family-transfer mechanisms and school–household diffusion pathways remain

insufficiently investigated in the existing literature, particularly within food-vulnerable and rural educational settings. Furthermore, the long-term sustainability and scalability of educational interventions depend strongly on implementation fidelity and intervention heterogeneity, which are rarely evaluated systematically across schools (Clements et al., 2015). From a sustainability perspective, school-garden interventions extend beyond conventional nutrition education programs because they integrate environmental awareness, sustainable food practices, participatory learning, local agricultural knowledge, and community engagement within educational systems (Chan et al., 2022). These interventions are closely aligned with several Sustainable Development Goals (SDGs), particularly SDG 4 (Quality Education), SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-Being), and SDG 11 (Sustainable Communities). Consequently, improving understanding of how educational systems facilitate sustainable behavioral adaptation and long-term community resilience through multidimensional and longitudinal analytical frameworks may substantially strengthen evaluation of school-garden interventions.

Accordingly, this study sought to overcome several of the limitations identified in previous research by implementing a longitudinal, multicomponent school-garden intervention across rural primary schools and examining its impact on key educational, nutritional, and sustainability outcomes. Unlike many previous studies that focused primarily on short-term or single-outcome approaches, the present study adopted an integrated food-literacy educational framework combining educational garden activities, cooking and nutrition workshops, family-transfer practices, and teacher-supported implementation within a 12-month longitudinal structure. The study additionally incorporated repeated assessments, implementation fidelity evaluation, multilevel temporal analyses, predictive modeling, sustainability-domain assessment, and adaptive educational response analyses. The novelty of this study is based on four aspects. The first aspect of the intervention was that of integrating the educational, behavioral, household and sustainability aspects into a single longitudinal program, not examining nutrition outcomes alone. Second, the study focused not only on changes in food literacy and food and nutrition diversity, but also on the retention of learning, family-transfer practices, diffusion of implementation, school level heterogeneity, and adaptive sustainability responses to repeated assessments. Third, the analytical framework included innovative longitudinal, multivariate, predictive, and temporal synchronization methodologies for assessing the adaptations in education and behavior that occurred dynamically beyond traditional pretest–posttest designs. Fourth, the study assessed sustainability outcomes of education related to food in rural school systems in an integrative framework that linked food literacy, household transfer, educational engagement, quality of implementation, and sustainability of intervention. Thus, the purpose of this study was to assess the long-term impact of a multicomponent school-garden intervention on food literacy, dietary diversity, learning retention, family-transfer practices, and school sustainability related learning outcomes on children in primary school from rural communities, from a multilevel, temporal and predictive perspective.

2. Materials and methods

2.1. Study design

This study used a longitudinal, school-based intervention design to evaluate the effects of a multicomponent school-garden program on food literacy, dietary diversity, learning retention, family-transfer practices, and sustainability-related educational outcomes among rural primary school students. The intervention was implemented over 12 months and incorporated repeated assessments at five time points: baseline (T0), 3 months (T1), 6 months (T2), 9 months (T3), and 12 months (T4). This design allowed immediate, intermediate, and sustained intervention responses to be evaluated over the course of the longitudinal follow-up (Figure M1). The study was designed to transcend typical pretest–posttest educational assessment approaches, including repeated measurement, multilevel longitudinal, transition, predictive modeling, and temporal synchronization analyses as well as implementation assessment. The analytical framework aimed to assess whether there were any progression or changes in food literacy and dietary behavior over time, if these changes stabilized during longer follow-up and if student engagement and family transfer practices supported educational retention and sustainability outcomes.

2.2. Study setting

The study was conducted in 12 rural primary schools located in food-vulnerable Andean communities where there is limited access to structured food and nutritional security education. The schools were chosen as being situated in communities which were less nutritionally diverse, provided less nutritional education and had higher reliance on agricultural resources. The educational garden set up was of an area between 40 to 60 m² in each of the participating schools. The vegetables and herbs grown in the gardens were selected and adapted to the local conditions and included lettuce (*Lactuca sativa*), spinach (*Spinacia oleracea*), carrots (*Daucus carota*), tomatoes (*Solanum lycopersicum*), onion (*Allium cepa*), coriander (*Coriandrum sativum*), aromatic medicinal plants. The gardens were not agricultural enterprises but pedagogical learning spaces. Throughout the intervention period, students were engaged in food education, observation, maintenance, planting, and harvesting activities.

The participating schools were located in rural Andean communities of the Pasco Region, Peru, situated at elevations ranging from approximately 3,400 to 4,200 meters above sea level. These communities are characterized by agricultural livelihoods, moderate food vulnerability, and limited access to structured nutrition-education programs. School populations predominantly consisted of children from low- to middle-income households engaged in small-scale farming and livestock activities.

2.3. Participants and sampling

The study group comprised students in primary education in the rural areas, in grades 3–6. At baseline, 1220 children aged 8–12 years (mean age 10.1+/-1.2 years) were involved. Participants were male and female students from schools. Schools were chosen based on access, desire to engage, and space to implement garden education. Students were recruited using school co-ordination meetings with their teachers, parents and administrators. Students were eligible if they attended participating schools,

participated in regular school activities and parents/legal guardians gave written informed consent. Analyzing the data was excluded for students who did not have complete baseline data and for students who were not present for the initial assessment. Across the follow-up period, the number of students with valid longitudinal observations was 1,220 at baseline (T0), 1,187 at 3 months (T1), 1,154 at 6 months (T2), 1,120 at 9 months (T3), and 1,083 at 12 months (T4). Attrition rates were tracked throughout the study and these were taken into account in the longitudinal statistical modeling.

2.4. Intervention description

The intervention was a multi-component school-garden educational program that included five main components: (i) educational activities about food and nutritional security, (ii) educational activities in the educational garden, (iii) cooking and nutrition workshops, (iv) activities for the families to transfer, and (v) teacher support and monitoring of the implementation. The food literacy education sessions were held once a week for about 45 minutes, covering the following topics: dietary diversity, healthy eating, food safety, sustainability, nutrition knowledge and responsible food-related decision making. Routine garden activities were carried out two times a week for about 60 minutes each, involving planting and watering, observing the crops, making compost, harvest and discussion of the nutritional value of locally grown produce. Cooking and nutrition workshops twice a month for about 90 min, preparation of healthy foods, from local ingredients. The workshops focused on the importance of food hygiene, food varieties, and practical nutrition applications. Family transferring activities took place on a monthly basis with take-home learning materials, family discussion activities and hands-on food-literacy activities designed to enhance the transfer of learning from school to home environments. Teacher support ranged from implementing, planning, and fidelity monitoring to classroom integration support. The intervention was implemented on a regular basis throughout the entire study period, in line with the school calendar.

2.5. Data collection schedule

Data collections were conducted at baseline prior to initiating intervention (T0), 3 months follow-up (T1), 6 months follow-up (T2), 9 months follow-up (T3), and 12 months follow-up (T4). Standardized conditions were used for assessments during regular school hours. Students were administered food literacy, dietary diversity, nutrition knowledge, engagement, family-transfer practices, healthy food attitudes, school connectedness, sustainability-related educational indicators at each assessment point. Information on implementation was also gathered at the school level such as fidelity, intervention reach, parent involvement, teacher support and implementation intensity.

2.6. Outcome measures

2.6.1. Food literacy

The main study result was food literacy and was measured by a structured educational questionnaire with 25 items covering nutrition knowledge, dietary diversity, healthy eating, food safety, sustainability and practical food related decision making. The range of scores were from 0 to 100, with higher scores

representing higher food literacy. The internal consistency of the questionnaire was good (Cronbach's α = 0.89).

2.6.2. Dietary diversity

A dietary diversity checklist adapted for school-age children was used to measure dietary diversity. The scale assessed consumption and recognition of the main food groups and provided a score between 0 and 12. The higher the values, the higher was the dietary diversity. Internal reliability of the dietary diversity was acceptable (Cronbach's α = 0.84).

2.6.3. Student engagement

Student engagement was assessed with an 8 item participation scale that assessed involvement in garden activities, classroom participation, completion of the intervention activities, and collaborative learning behavior. Answers were provided on a five point Likert scale from very low (1) to very high (5). The reliability of the engagement scale was good (Cronbach α = 0.87).

2.6.4. Family-transfer practices

The family-transfer practices were assessed based on the 6 household-transfer scale items that measured the extent to which students transfer food-literacy knowledge and practices with their families. The responses were marked on a five-point Likert scale, and the scores used were a reflection of the level of education transfer. The reliability of the instrument was determined by analyzing the internal consistency and the result was satisfactory (Cronbach's α = 0.85).

2.6.5. Secondary outcomes

Secondary outcomes consisted of nutrition knowledge, healthy food attitudes, cooking self-efficacy, school connectedness, absenteeism, BMI z score, intensity of implementation, sustainability domain scores, diffusion index, and probability of successful intervention at the school level.

2.7. Food-literacy performance categories

Food-literacy scores were sorted into three performance groups for the transition analysis: low (< 50), moderate (50–74), and high (≥ 75). The categories were used to analyze upward or downward changes in educational achievement in multiple assessment attempts and to assess if the intervention supported consistent progression toward improved food-literacy outcomes.

2.8. Implementation fidelity assessment

Implementation quality was evaluated at the school level using indicators related to fidelity, reach, dose delivered, adoption, parent participation, and teacher support. Fidelity referred to the extent to which planned intervention activities were implemented as intended. Reach represented the proportion of students exposed to intervention activities. Dose referred to intervention frequency and intensity, whereas adoption represented incorporation of activities into routine educational practice.

Teacher implementation records, attendance logs, parent-participation reports, and intervention-monitoring forms were reviewed monthly throughout the study period. These indicators were summarized using implementation fidelity heatmaps and school-level implementation profiles.

2.9. Statistical analysis

All variables were analyzed at all assessment points with descriptive statistics (mean, standard deviation, confidence intervals, proportions and categories distributions).

Bayesian ridgeline density analysis was employed to consider the re-distribution of food-literacy scores over multiple assessments. Longitudinal changes in dietary diversity were analyzed using raincloud plots with paired trajectories. Alluvial transition analysis was employed to examine transitions between the food-literacy performance categories.

UMAP ordination and PERMANOVA were used to analyse multivariate response structures. Hierarchically clustered correlation matrices were used to examine correlations between education, dietary, behavioral and anthropometric variables. For UMAP analyses, Euclidean distance metrics were used with n neighbors = 15 and min dist = 0.10 to preserve local and global response structures. PERMANOVA significance was assessed using 9,999 permutations. SHAP contribution analyses were derived from gradient-boosted predictive models and were used to quantify the relative importance of intervention components. Bayesian forecasting models were estimated using weakly informative priors with four Markov Chain Monte Carlo chains and convergence assessed using R-hat statistics (< 1.01). Wavelet coherence analyses were performed using Morlet wavelets to evaluate temporal synchronization between food-literacy and dietary-diversity trajectories.

The contribution analysis was implemented using SHAP style to assess the variable contribution and predictor importance. Temporal adaptation and synchronization patterns were examined using dynamic network trajectory analysis, functional principal component analysis, resilience phase-space analysis, and wavelet coherence analysis.

Literacy trajectories and predictive uncertainty intervals were estimated using the method of Bayesian forecasting. Partial-dependence interaction modeling and generalized additive mixed models were used to explore nonlinear interaction effects. The probability of intervention success was estimated at the school level by means of calibrated predictive probability modeling.

The used spatial and sustainability-related analyses included: diffusion-flow network analysis, efficiency frontier analysis, sustainability-domain scoring, adaptive school–community response mapping and Moran's I spatial autocorrelation analysis. Multiple imputations for missing longitudinal observations (< 8%) were conducted using the chained equations approach. A frequentist approach was used for the interpretation of statistical significance, with $p < 0.05$ considered significant. Posterior means, credible intervals and posterior probabilities were provided for Bayesian analyses.

2.10. Data management and quality control

All data were collected using standardized forms and coded prior to analysis. Students were assigned anonymized identification codes to enable longitudinal matching across repeated assessments. Data quality procedures included verification of duplicate records, missing values, inconsistent responses, and outlier detection. Implementation records were reviewed periodically to verify intervention exposure, attendance, and fidelity consistency across schools. All visualizations and analyses were produced using reproducible statistical workflows.

2.11. Software

Statistical analyses and figure preparation were conducted in R version 4.3.1 using packages including *tidyverse*, *ggplot2*, *mgcv*, *brms*, *vegan*, *factoextra*, *igraph*, *plotly*, *pheatmap*, *patchwork*, and *networkD3*. Graphical outputs were exported at publication-quality resolution (600 dpi PNG and vector PDF formats).

2.12. Supplementary materials

Supplementary Figure S1: Implementation fidelity, reach, adoption, parental participation, and teacher engagement across participating schools. Supplementary Figure S2: School-level heterogeneity and response variability throughout the intervention period. Supplementary Figure S3: Cost-effectiveness analysis of educational and nutritional outcomes. Supplementary Figure S4: Detailed intervention timeline, participant flow, and assessment schedule.

3. Results

The longitudinal intervention produced a consistent upward redistribution of food literacy scores across all assessment periods (Fig. 1A). The ridgeline density distributions progressively shifted toward higher score ranges from baseline (T0) to the 12-month follow-up (T4), indicating sustained improvements in food literacy after implementation of the multicomponent school-garden program. Mean food literacy scores increased from 42.1 at baseline to 72.9 at T4, while the narrowing overlap between distributions suggests a gradual consolidation of higher literacy performance among participating students. Dietary diversity trajectories also demonstrated continuous improvement throughout the intervention period (Fig. 1B). The raincloud distributions showed progressive increases in central tendency together with broader upper-score distributions over time, indicating improvements in both average dietary diversity and individual-level dietary practices. The paired trajectories further revealed that most students experienced positive longitudinal changes across repeated measurements, supporting the effectiveness of the intervention in promoting healthier and more diverse food consumption behaviors. The transition analysis highlighted substantial movement of students from lower food-literacy categories toward higher-performance groups during the study period (Fig. 1C). The proportion of students classified in the high-literacy category increased from 17% at baseline to 66% at the 12-month follow-up, whereas the low-literacy category decreased from 37% to 6%. These transitions indicate that the intervention not only improved average literacy outcomes but also promoted stable upward educational progression across repeated assessments.

The response-surface analysis demonstrated a strong interaction between student engagement, family transfer practices, and learning retention (Fig. 1D). Higher levels of engagement combined with stronger family-transfer support were associated with the greatest predicted retention probabilities, whereas lower engagement and limited family participation were associated with weaker retention outcomes. Implementation fidelity remained consistently high throughout the intervention period. Across participating schools, mean fidelity scores ranged from 0.79 to 0.96, while reach, adoption, parent participation, and teacher-support indicators demonstrated generally favorable implementation performance (Supplementary Figure S1). These findings indicate that intervention activities were delivered with high consistency across schools and support the interpretation of observed longitudinal educational outcomes.

The multivariate analyses demonstrated clear separation of intervention responses across the longitudinal assessment periods (Fig. 2APERMANOVA indicated significant multivariate restructuring ($F = 18.47$, $R^2=0.156$, $p < 0.001$), explaining 15.6% of total variance. The hierarchical clustered correlation matrix further showed strong positive associations among food literacy, dietary diversity, nutrition knowledge, healthy food attitudes, and retention probability, whereas negative associations were observed with absenteeism and BMI z-score (Fig. 2B). These findings indicate that improvements in educational and dietary variables occurred as interconnected components of the intervention response rather than as isolated outcomes. The SHAP-based contribution analysis identified student engagement, family-transfer practices, garden participation, and nutrition knowledge as the strongest predictors of both retention probability and food literacy improvement (Fig. 2C). Variables related to school connectedness and healthy food attitudes also contributed positively to intervention outcomes, whereas baseline BMI z-score and socioeconomic constraints showed comparatively weaker effects. The bivariate density heatmap demonstrated a strong positive coupling between food literacy and dietary diversity across longitudinal assessments (Fig. 2D). The progressive concentration of observations within the upper-right density region at later time points indicated that higher food literacy scores were consistently associated with improved dietary diversity. The significant Kendall's τ correlation (0.54, $p < 0.001$) further supports the existence of a stable relationship between nutritional learning and dietary behavior during the intervention period.

The temporal network analysis demonstrated progressive strengthening of interactions among food literacy, dietary diversity, engagement, and retention throughout the intervention period (Fig. 3A). Increasing edge intensity and network density across assessments indicated greater integration of educational and dietary response systems over time, suggesting that prolonged intervention exposure enhanced the functional connectivity among key learning and behavioral variables. Functional principal component analysis further revealed clear longitudinal displacement trajectories across intervention phases (Fig. 3B). The first three functional components explained 72.6% of the total variance, indicating that the intervention generated consistent multivariate temporal restructuring in student responses. The gradual directional movement from baseline toward later assessments reflects sustained adaptation of nutritional-learning profiles during the 12-month intervention. The resilience phase-space analysis showed progressive transitions from unstable and compensatory response regions toward adaptive-

resilient states at later intervention phases (Fig. 3C). Recovery trajectories became increasingly organized over time, while the resilience index significantly increased across assessments (mean ± SE: 0.42 ± 0.05; p trend < 0.001), indicating improved stability and recovery capacity of intervention responses. In addition, wavelet coherence analysis demonstrated strong temporal synchronization between food literacy and dietary diversity, particularly during the middle and late intervention phases (Fig. 3D). High coherence regions concentrated between months 4 and 10 indicated sustained coupling between educational and dietary changes over time. The significant mean coherence value ($r^2 = 0.63$; 95% CI: 0.55–0.71; $p < 0.001$) suggests that improvements in food literacy and dietary diversity evolved in a coordinated temporal pattern during the intervention.

The Bayesian forecasting analysis indicated sustained long-term improvement in food literacy following the intervention (Fig. 4A). Observed trajectories showed progressive increases in literacy scores during the intervention phase, while posterior predictive distributions suggested continued improvement and stabilization during the projected follow-up period. The narrowing of the 50% and 80% credible intervals around the posterior median indicates increasing model confidence in long-term literacy retention. The adaptive intervention topology further demonstrated that educational outcomes depended strongly on the interaction between student engagement and family-transfer conditions (Fig. 4B). Students with high engagement and strong family support were associated with the greatest predicted improvement, whereas lower engagement combined with weak household transfer produced substantially smaller gains. These findings suggest that adaptive educational strategies tailored to engagement and family conditions may optimize intervention effectiveness across heterogeneous learning environments. The nonlinear partial-dependence surface demonstrated a strong synergistic interaction between student engagement and garden participation intensity on literacy improvement (Fig. 4C). Higher levels of both variables were associated with the greatest predicted improvements, whereas lower participation and engagement produced minimal gains. The significant interaction coefficient ($\beta_int = 2.31$; 95% CrI: 1.62–3.05) indicates that the combined effect of these factors exceeded their independent contributions. In addition, the calibrated probability landscape revealed substantial spatial heterogeneity in intervention success across schools (Fig. 4D). Areas with higher predicted probabilities of literacy improvement were concentrated in schools with stronger intervention exposure and implementation consistency, whereas lower-probability regions showed wider predictive uncertainty.

The multilayer diffusion network demonstrated progressive propagation of food-literacy practices across school, household, and community layers throughout the intervention period (Fig. 5A). Increasing node size and flow intensity from baseline to the 12-month follow-up indicated stronger adoption and diffusion of nutritional-learning practices over time. The positive diffusion index (0.78) and cross-layer coupling strength (0.62) suggest that the intervention extended beyond classroom learning and promoted broader educational transfer across household and community environments. The integrated sustainability profile further showed consistently high performance across nutritional, educational, behavioral, and social sustainability domains (Fig. 5B). Nutritional sustainability exhibited the highest domain score (0.81), followed by educational (0.78), behavioral (0.73), and social sustainability (0.72), resulting in an overall sustainability index of 0.76/1.00. These findings indicate that the intervention

generated multidimensional benefits extending beyond short-term literacy improvement. The efficiency frontier analysis revealed nonlinear relationships between implementation intensity and long-term literacy improvement (Fig. 5C). Literacy gains increased rapidly at low-to-moderate intervention intensities before approaching a plateau at higher implementation levels, indicating diminishing marginal returns at very high intensities. Schools positioned closer to the efficiency frontier demonstrated greater educational gains with comparatively optimized intervention intensity, whereas lower-efficiency schools showed weaker long-term outcomes. The adaptive school–community response landscape also demonstrated substantial spatial heterogeneity in intervention adaptation patterns (Fig. 5D). High–high clusters were concentrated in regions with stronger educational integration and community engagement, whereas low–low clusters reflected more vulnerable adaptation conditions. The significant Moran's I value (0.46) indicates positive spatial autocorrelation, suggesting that schools with similar intervention outcomes tended to cluster geographically. Together, these findings demonstrate that the effectiveness and sustainability of the intervention depended on both implementation efficiency and local socio-educational adaptation processes.

4. Discussion

4.1. Longitudinal improvement in food literacy and dietary diversity

Several different food literacy and food diversity measures showed sustained increases over time in the multicomponent school-garden intervention. The progressive changes in literacy scores and the upward changes in dietary diversity over time showed stability in educational and behavioral change over time through repeated exposure to educational experiences. Similar improvements in nutrition knowledge and healthy dietary practices have been reported in previous school-garden interventions (Blair, 2009; Morgan et al., 2010; Savoie-Roskos et al., 2017). But most of the previous research was conducted mainly via pretest/posttest assessments conducted over a short period. The present results add to the previous evidence showing sustained improvements after 12-months ' follow-up. Higher levels of literacy achievement indicated by the consolidation implies that repeated engagement in garden-based learning programs may lead to consolidation of learning and retention over time, as outlined by Kolb (1984) and Antonelli and Isernia, (2024).

4.2. Educational transitions and household reinforcement

The large number of students moving from low to high food-literacy categories illustrates that the intervention resulted in a more general redistribution of education, not just in average scores. Educational-garden research also has found positive learning and behaviour changes in schools (Ratcliffe et al., 2011; Langellotto and Gupta, 2012). Overall, the high levels of engagement and family-transfer practices and their relation to the probability of retention further emphasize the role of household reinforcement in sustainability oriented education interventions. Children's dietary habits and the maintenance of behavior learnt from their families are strongly influenced by family environments

(Birch and Fisher, 1998; Patrick and Nicklas, 2005). This is consistent with a socio-ecological educational approach that recognizes interplay among school, home and community learning systems (Bronfenbrenner, 1989; McLeroy et al., 1988).

4.3. Multivariate adaptation and temporal synchrony

The multivariate analyses showed that these factors food literacy, dietary diversity, nutrition knowledge and retention were interconnected and part of a wider adaptive educational system. The marked differences of the intervention-response structures between the repeated assessments suggest coherent restructuring of nutrition-learning profiles during the intervention period. The same kind of multidimensional adaptations have been described in other experiential education models that are designed to tackle sustainability issues (Tilbury, 2011; Wals, 2019). The temporal analyses also indicated a gradual increase in the level of educational and behavioral synchronization with age. Haemmerle and Siemens (2013) and Illeris (2018) propose that there is an increase in network density, resilience indices, and wavelet coherence patterns, indicating that the extended exposure to interventions strengthens the stability and integration of learning responses.

4.4. Predictive trajectories and sustainability diffusion

Results from the Bayesian forecasting analyses showed that literacy gains continued past the intervention period and were consistent, suggesting good long-term retention of the intervention. The non-linear engagement-garden participation intensity relationship indicates that the effectiveness of the interventions was more due to a synergistic than an exposure effect in the mechanisms by which the education was conveyed. Participation in the sustainability interventions has been described as a type of reinforcement by Reed et al. (2013). The multi-layer diffusion analyses also illustrated the sequential, sequential, or parallel spread of food-literacy practices at school, within the home, and within the community. The results show that the intervention led to more sustainability-related transfer of education than taking place only in the classroom (Bandura, 2001; Rogers, 2003). The consistency of implementation quality across participating schools (Supplementary Figure S1) and the relatively homogeneous intervention responses observed among schools (Supplementary Figure S2) further support the scalability of the intervention. Cost-effectiveness analyses also indicated favorable educational gains relative to implementation investments (Supplementary Figure S3).

4.5 Educational, community, and sustainability implications

The findings demonstrate that school-garden interventions can function as integrated educational ecosystems that simultaneously strengthen food literacy, dietary practices, and community participation. The observed transfer of learning from schools to households suggests that educational interventions can generate broader sustainability benefits extending beyond classroom environments. These outcomes support ecological models of learning that emphasize interactions among students, families, schools, and local communities.

4.6. Limitations and future research

Several limitations should be considered when interpreting the findings. First, the study was conducted in rural Andean communities, which may limit generalizability to urban or culturally distinct populations. Second, although the longitudinal design strengthens causal inference, unmeasured environmental and household factors may have influenced observed outcomes. Third, some indicators relied on self-reported responses and may be subject to reporting bias. Future research should evaluate longer-term sustainability, include objective dietary biomarkers, and examine implementation across diverse educational and socioeconomic contexts.

5. Conclusions

This study provides evidence that multicomponent school-garden interventions can generate sustained improvements in food literacy, dietary diversity, and sustainability-oriented behaviors among rural primary-school students. Beyond individual educational benefits, the intervention promoted household diffusion of food-literacy practices and strengthened school–community linkages, supporting broader sustainability objectives. In the current study, the school-garden project was found to be effective in enhancing food literacy and food diversity among the participants, as well as their ability to learn and retain the material, and to foster their awareness of sustainable food practices. The progressive shift in the distribution of food-literacy performance, as well as in the paths of dietary diversity and the likelihood of retaining the food literacy skills, suggests that the repeated experiential educational exposure helped to reinforce educational and behavioural adaptation throughout the 12-month intervention period.

Results also showed that aspects of student engagement, family-transfer practices, and implementation quality were important factors in ensuring sustained educational results. The multivariate, temporal, and predictive analyses also revealed food literacy and dietary behaviors as adaptive learning systems that developed into a greater sense of synchrony, resiliency, and diffusion of ideas to become more sustainable in school and home domains.

Overall, these results indicate that MCSGP could be used as a potential sustainability-based education tool that can incorporate nutrition education, experiential learning, home-based reinforcement, and community involvement into rural education. These interventions can thus play a role in the long-term transformation of education and adaptation of behavior in the context of food security and sustainability.

Declarations

Authors contributions

Dionicio López Basilio contributed to conceptualization, methodology, investigation, project administration, and writing of the original draft. Histler Juan Castillo Paredes contributed to methodology, formal analysis, data curation, visualization, and manuscript review and editing. Teófilo Félix Valentín Melgarejo contributed to conceptualization, supervision, validation, funding acquisition,

manuscript review and editing, and served as the corresponding author. Javier Raúl Minaya Lovaton contributed to investigation, resources, data curation, and manuscript review and editing. Wilfredo Florencio Rojas Rivera contributed to investigation, resources, validation, and manuscript review and editing. Josué Chacón Leandro contributed to investigation, data curation, and formal analysis. David Wilson Osorio Espinoza contributed to investigation, resources, and data curation. Lury Tatiana Quispealaya Arenas contributed to investigation, validation, and data curation. Clodoaldo Ramos Pando contributed to methodology, supervision, and manuscript review and editing. Armando Elías Zenteno Quinto contributed to validation, language editing, and manuscript review and editing. Raúl Malpartida Lovatón contributed to supervision, investigation, and validation. Ramón Ángel Robles Huaynate contributed to investigation, resources, and validation. Elizabeth Clara Cordova Zevallos contributed to investigation, data curation, and manuscript review and editing. José Rovino Alvarez Lopez contributed to formal analysis, visualization, and validation. Flaviano Armando Zenteno Ruíz contributed to supervision, project administration, and manuscript review and editing. All authors read and approved the final manuscript and agreed to be accountable for all aspects of the work.

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Ethical Approval

Ethical approval statement

The study protocol was approved by the Research Ethics Committee of Universidad Nacional Daniel Alcides Carrión, Cerro de Pasco, Peru, under approval number: REC-2024-087.

Ethical guidelines statement

All procedures performed in this study involving human participants were conducted in accordance with the ethical standards of the institutional research committee and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

Consent for publication

Not applicable.

Informed Consent Statement

Written informed consent was obtained from the parents or legal guardians of all participating students prior to data collection. Assent was also obtained from the participating children. Participation was voluntary, and all participants were informed about the objectives of the study, confidentiality procedures, and their right to withdraw at any time without consequences. These findings support the integration of school-garden programs into educational and public-health strategies aimed at improving food-system resilience and nutrition literacy in vulnerable populations.

Data Availability Statement

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

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Clinical trial number

Not applicable

Conflicts of Interest

The authors declare no conflict of interest.

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Figures

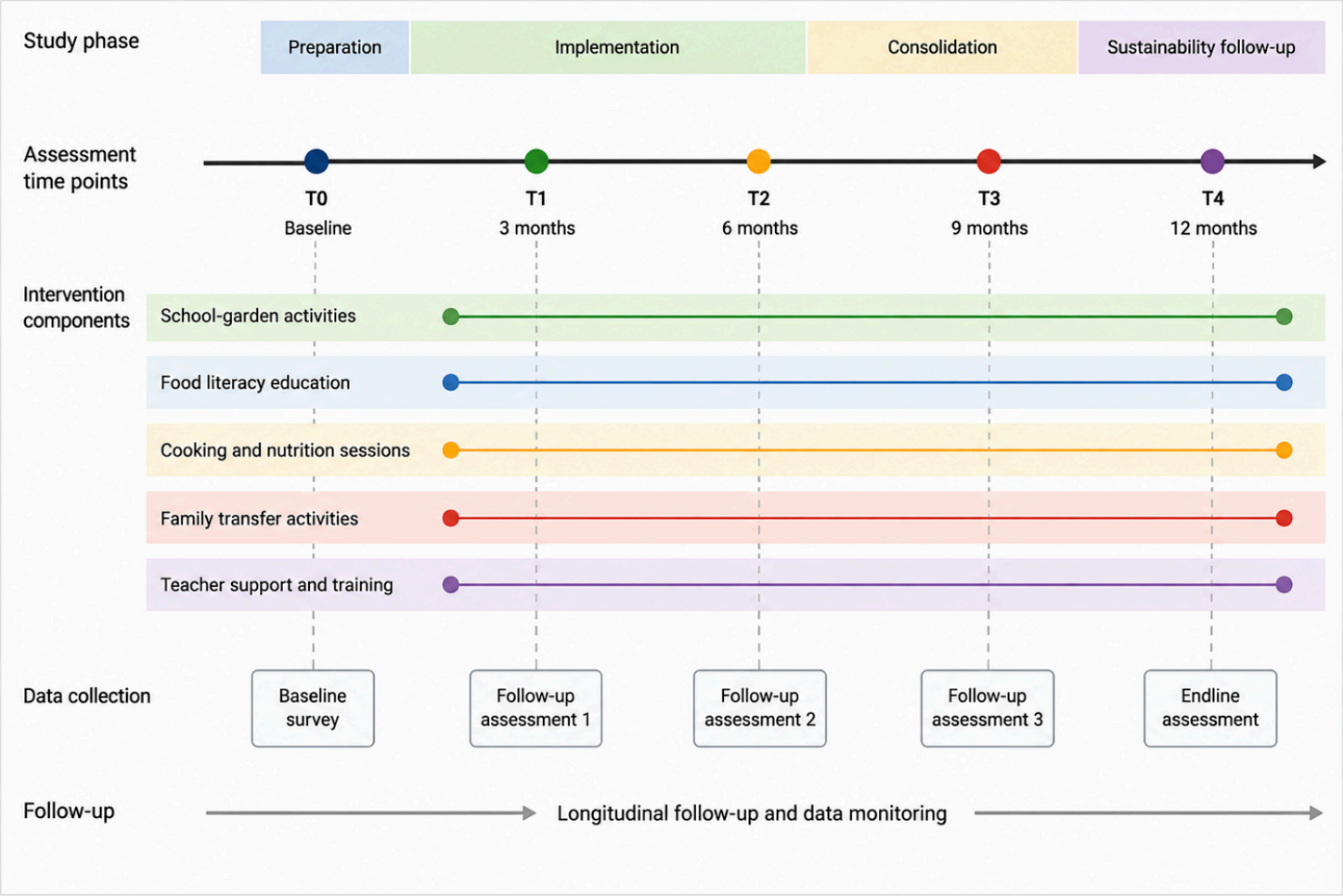


Figure 1

Figure M1: Longitudinal study design and intervention timeline of the multicomponent school-garden program.

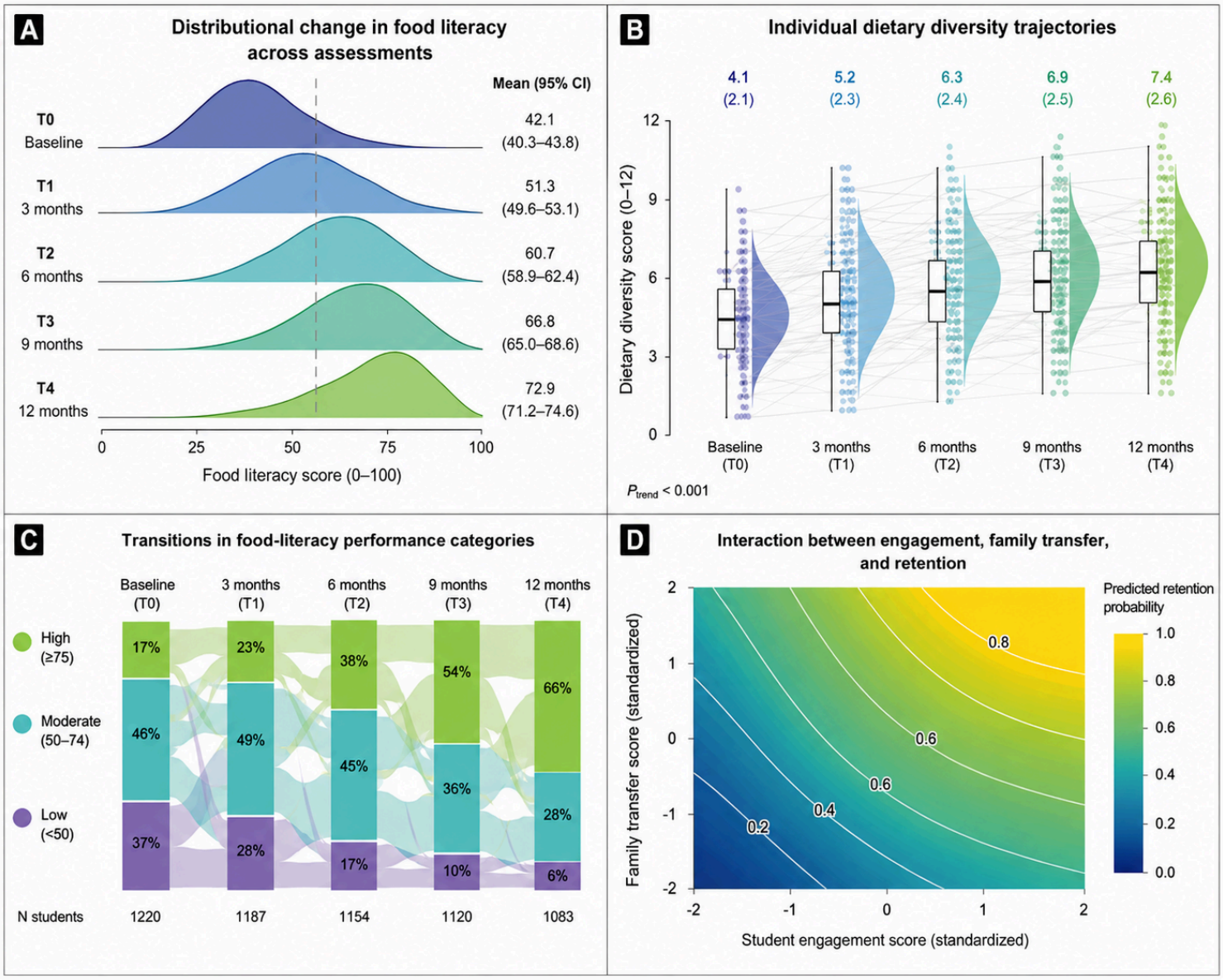


Figure 2

Figure 1: Integrated intervention response dynamics during the longitudinal school-garden program.

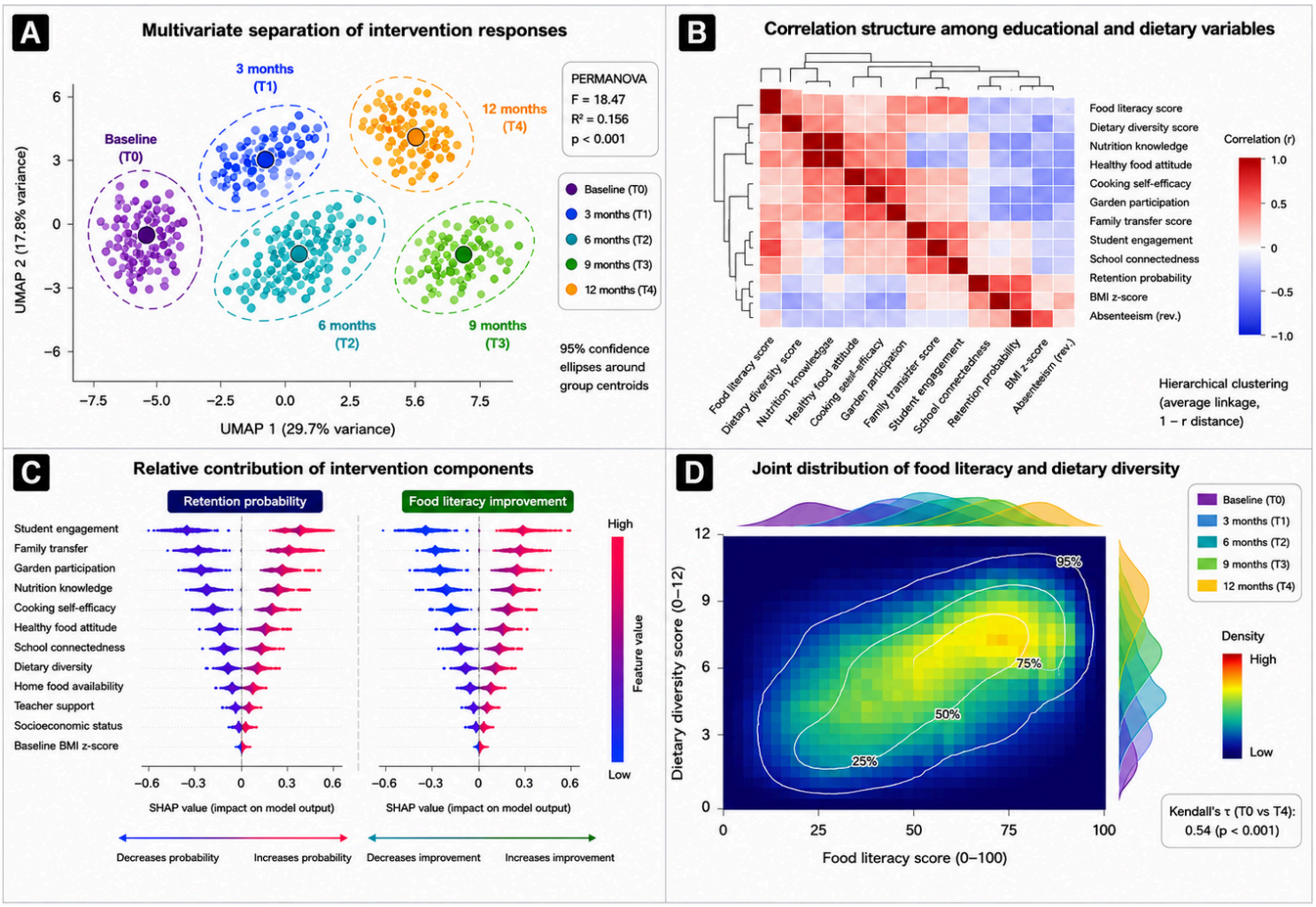


Figure 3

Figure 2: Multilevel intervention-effect architecture across educational and dietary outcomes.

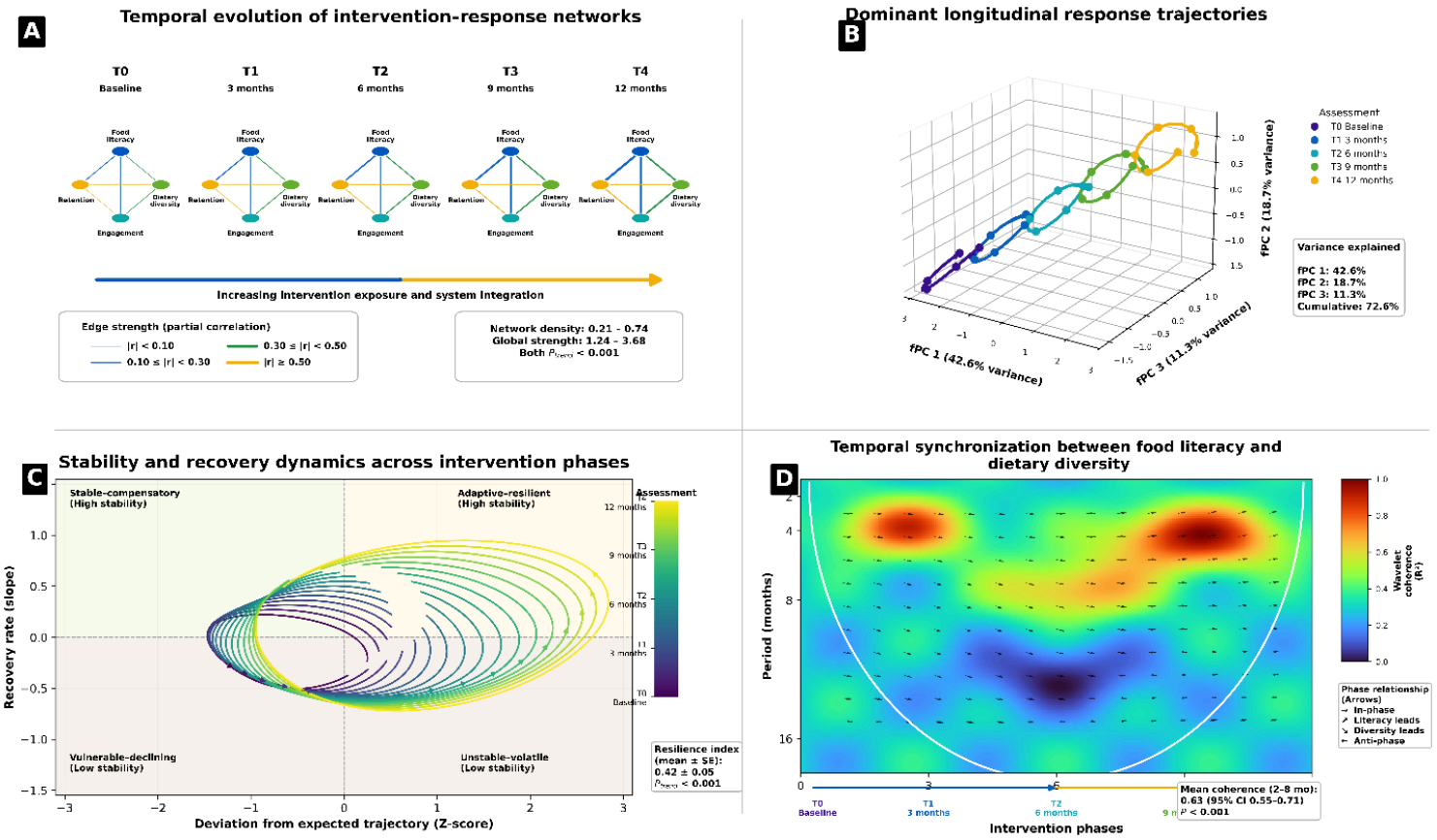


Figure 4

Figure 3: Temporal adaptation and ecological learning stability during the longitudinal intervention.

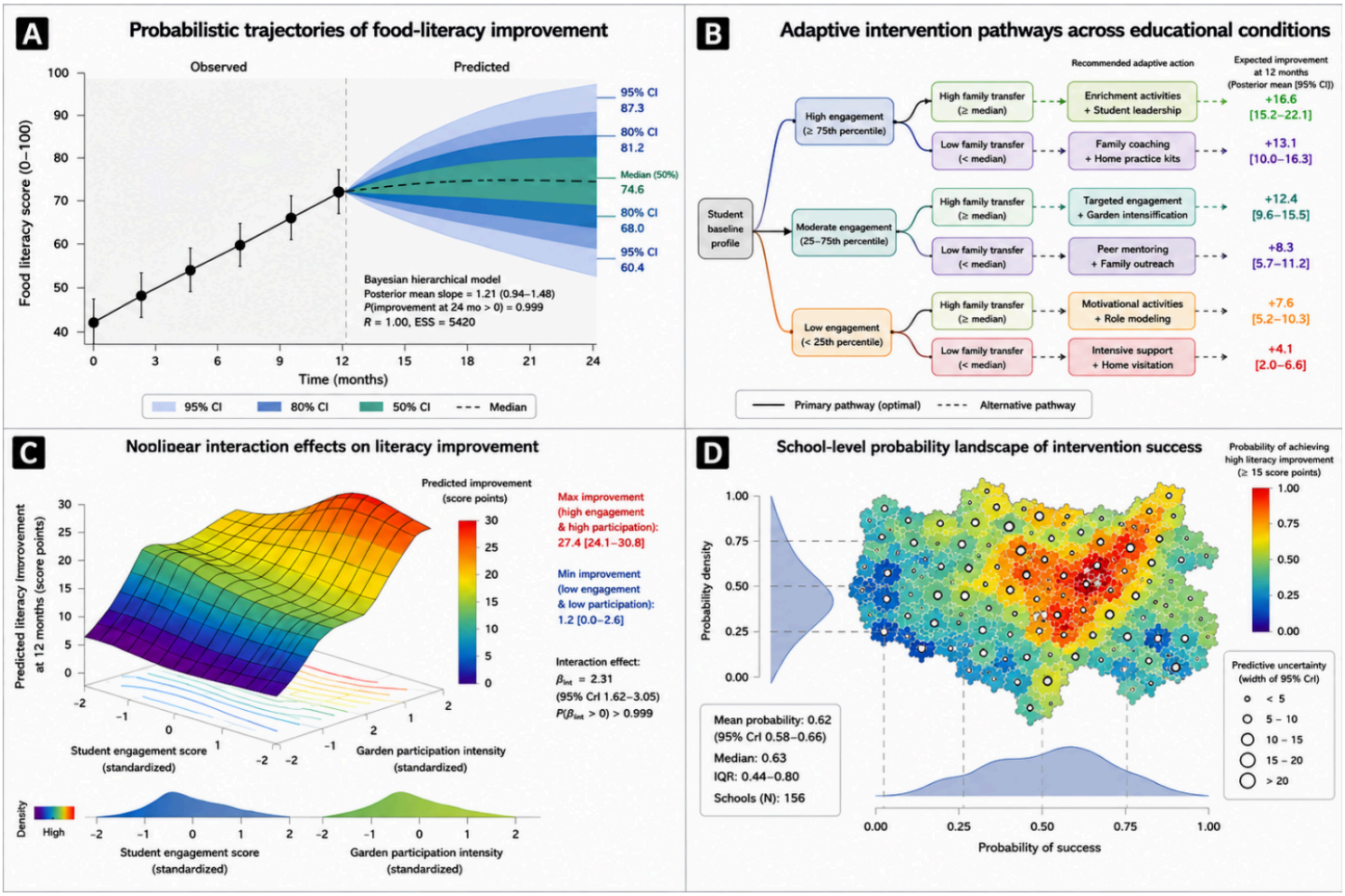


Figure 5

Figure 4: Predictive learning ecology and intervention optimization during the longitudinal school-garden program

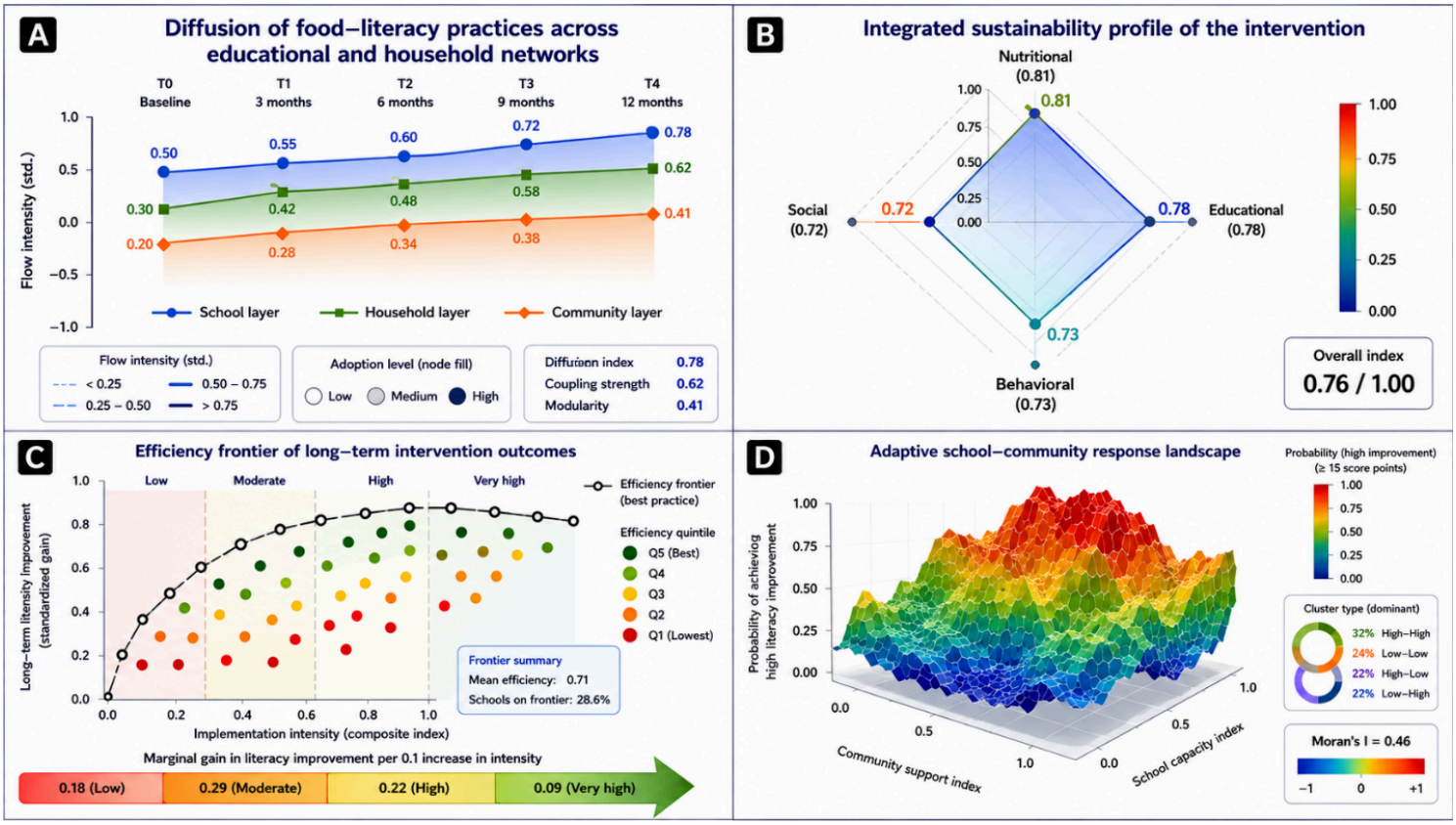


Figure 6

Figure 5: Translational outcomes and sustainable intervention impact during the longitudinal school-garden program

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