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Demographic Responses of *Myzus persicae* on Potato to Elevated CO_2

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Abstract

Elevated atmospheric CO_2 can alter crop-herbivore interactions, but its effects on *Myzus persicae* demography on potato remain poorly understood. We monitored 180 aphids on detached leaves of potato cv. Longshu 23 at nominal CO_2 concentrations of 400, 600, and 800 μL L^{-1}. Concentrations were rotated among three incubators across three runs, and treatment comparisons used nine incubator-run units in an additive Latin square model. Tukey-adjusted comparisons showed a shorter pre-adult duration and total pre-reproductive period at 600 μL L^{-1} than at both other concentrations. At 600 μL L^{-1}, the intrinsic rate of increase (0.3665 d^{-1}) exceeded that at 800 μL L^{-1}, whereas the finite rate of increase (1.4428) exceeded estimates at both other concentrations. No significant overall effects were detected on lifetime fecundity, net reproductive rate, or mean generation time. Pooled life-table projections yielded the highest 90-day abundance at 600 μL L^{-1} under constant demographic schedules without density dependence or resource limitation. These findings are exploratory. Because aphids and source plants shared the assigned CO_2 treatment, direct and plant-mediated effects could not be separated. Leaf chemistry, phloem composition, and feeding behavior were not measured.

Keywords: *Myzus persicae*; elevated CO_2; age-stage; two-sex life table; demographic parameters; population projection

1. Introduction

Rising atmospheric carbon dioxide (CO_2) concentrations can influence crop–herbivore interactions through changes in plant physiology and host quality. Evidence from free-air CO_2 enrichment experiments shows that crop productivity and nutritional responses depend on plant genotype and growing conditions [1]. A recent synthesis and meta-analysis further shows that CO_2, temperature, water availability and nutrient conditions can affect herbivore consumption and development through both direct and plant-mediated pathways [2]. Experiments with wheat and the grain aphid *Sitobion miscanthi* demonstrate that CO_2 enrichment and drought can jointly modify plant nutritional and resistance traits and aphid performance [3]. These findings indicate that increased plant productivity need not translate into improved herbivore performance. Changes in host quality can subsequently affect insect development, survival and reproduction, with implications for trophic interactions and pest management [4,5]. Assessing pest responses to CO_2 enrichment therefore requires demographic measurements that integrate these life-history components.

Potato (*Solanum tuberosum* L.) is an important crop affected by insect pests and environmental stress [6]. The green peach aphid, *Myzus persicae* (Sulzer), damages plants through

Check for updates

Academic Editor: Fajun Chen

Received: 20 October 2026
Revised: 16 November 2026
Accepted: 17 November 2026
Published: 24 November 2026

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phloem feeding and transmits plant viruses [7]. Aphid host use and performance depend on interactions with plant nutritional and defensive traits [8]. CO_2-induced changes in host quality may further depend on other environmental conditions, as demonstrated in a wheat-aphid system [3]. Host genotype can also modify responses to environmental stress, as shown by studies of potato-aphid interactions under drought [9–12]. Although these studies do not directly establish CO_2 effects, they highlight the need to evaluate aphid responses within a defined host and growing environment.

Previous experiments with *M. persicae* have reported contrasting responses to elevated CO_2. Dáder et al. [13] documented changes in bell pepper growth and chemistry accompanied by altered aphid life history, feeding behavior and virus transmission, whereas Ahn and Choi [14] reported increased demographic performance under their elevated-CO_2 conditions. A more recent synthesis identified variation in herbivore responses among climatic factors and response traits and emphasized the limited evidence from experiments manipulating multiple factors [2]. Findings from one host or concentration range therefore cannot be assumed to apply to other systems. For *M. persicae* on potato, the relationship between CO_2 concentration, reproductive output and population growth remains insufficiently characterized.

Age-stage, two-sex life-table analysis integrates individual development, survival and reproduction while accounting for variation in developmental rates and overlapping stages [15–18]. It provides estimates of net reproductive rate (R_0), intrinsic rate of increase (r), finite rate of increase (λ) and mean generation time (T), together with survival, life expectancy and reproductive value functions [19,20]. These measures help distinguish changes in lifetime offspring production from changes in reproductive timing. Life-table-based projections further describe potential population growth and stage structure under specified demographic schedules [20,21]. Applications to aphids on pepper cultivars [21], under elevated CO_2 [14] and on drought-stressed potato cultivars [12] demonstrate the usefulness of this framework. Treatment inference nevertheless requires replication at the level at which environmental conditions are assigned.

We examined the development, survival, reproduction, and population growth potential of *M. persicae* on potato cv. Longshu 23 at nominal CO_2 concentrations of 400, 600, and 800 μL L^{-1}. We hypothesized that exposing aphids and their host plants to different CO_2 concentrations would alter aphid developmental and reproductive schedules, resulting in differences in population growth potential. Given the contrasting findings of previous studies, we did not predict a consistent increase or decrease in population growth across concentrations. We explored whether the observed response was monotonic across the three tested concentrations and examined growth-rate estimates alongside reproductive timing and lifetime fecundity. Treatment comparisons were based on nine incubator–run units arranged in a 3 × 3 Latin square. Pooled age–stage, two-sex life tables were used separately to describe cohort schedules and project conditional population trajectories over 90 d.

2. Materials and Methods

2.1. Insect Colony

A laboratory colony of *M. persicae* was established from apterous aphids collected in July 2025 from a potato field in Taishi Town, Lintao County, Gansu Province, China (35.662° N, 103.7426° E). The colony was maintained on potato plants (*S. tuberosum* L. cv. Longshu 23) at the College of Plant Protection, Gansu Agricultural University, Lanzhou, China (36.091° N, 103.700° E), at 25 ± 1 °C, 65 ± 5% relative humidity (RH), and a 16:8 h (L:D) photoperiod for at least three generations before the experiment. To obtain cohorts within a 24-h birth window, apterous adult females were allowed to reproduce on fresh

potato leaves for 24 h. First-instar nymphs produced during this interval were used to initiate the experimental cohorts.

2.2. Plant Material and CO_2 Treatments

Potato tubers (cv. Longshu 23) of similar size were planted individually in plastic pots (17 cm diameter × 13 cm height) filled with commercial potting soil. Plants were maintained in illuminated, CO_2-controlled incubators (SPX-250-GB-CO; Shanghai Yuejin Medical Instruments Co., Ltd., Shanghai, China) at nominal CO_2 set points of 400, 600 or 800 μL L^{-1}, at 25 ± 1 °C, 65 ± 5% RH and a 16:8 h (L:D) photoperiod. The incubator light level was set to 500 lx. No additional fertilizer was applied after planting in commercial potting soil. Plants were watered as needed according to the condition of the potting soil.

CO_2 was regulated by the incubators' built-in control systems. The built-in CO_2 sensors were calibrated, and the controller readings were checked daily during each run. No separate calibrated sensor was used to verify these readings during the experiment. The daily readings were not retained in sufficient detail to summarize their range or temporal variability.

Healthy leaves of comparable size were collected from uniform, 30-day-old plants for the aphid bioassays. Both initial and replacement leaves were obtained from plants grown under the same nominal CO_2 treatment as the corresponding aphid cohort. Pots were periodically repositioned within each incubator.

2.3. Experimental Design and Aphid Bioassay

The experiment comprised three temporally separated runs, each including all three CO_2 treatments in separate incubators. Concentrations were rotated among incubators so that each physical incubator received every treatment once across the three runs. This arrangement formed a 3 × 3 Latin square, with run and incubator identity as blocking factors. After each change in CO_2 set point, the next run began only after the reading on the incubator controller display had stabilized near the new set point. The elapsed stabilization time was not recorded. Each incubator-run unit contained 20 individually monitored first-instar nymphs, giving three experimental units and 60 aphids per concentration (180 aphids in total). The incubator-run combination was the experimental unit for treatment assignment; individual aphids were subsamples.

Each nymph was placed on a fresh potato leaf in an individual 9-cm Petri dish with a perforated lid to facilitate gas exchange with the incubator atmosphere. Moist filter paper and cotton surrounding the petiole limited leaf desiccation. Leaves were renewed every 2 d or sooner if they deteriorated, and dishes were periodically repositioned within each incubator. Aphids were examined every 24 h until death to record moulting, developmental stage, survival, adult emergence and offspring production. Developmental durations and longevity were derived from these records. Newborn nymphs were counted and removed at each observation. Individuals dying before adulthood remained in the life-table dataset, and terminal death codes in the TWOSEX-MSChart input were excluded from offspring counts.

2.4. Age-Stage, Two-Sex Life-Table Analysis

Life histories were analyzed using TWOSEX-MSChart (version 2024.03.30) following age-stage, two-sex life-table theory [15–18]. Survival, fecundity, life expectancy and reproductive value functions, together with the intrinsic rate of increase (r), finite rate of increase (λ), net reproductive rate (R_0) and mean generation time (T), were calculated using the definitions and equations in Table S1.

Developmental and reproductive traits included instar durations, pre-adult duration and survival, adult female longevity, total lifespan, the total pre-reproductive period ($TPRP$),

reproductive days, and lifetime fecundity [17,19]. Instar-duration means included only individuals completing the corresponding instar, as indicated by a subsequent instar record or adult emergence after the fourth instar. Time spent in an unfinished terminal instar was excluded from instar-duration means but retained in lifespan and survival analyses. Pre-adult duration was calculated for individuals reaching adulthood. Adult female longevity was measured from adult emergence to death, whereas total lifespan was measured from birth to death and summarized separately for all initial individuals and for adult females. Lifetime fecundity and reproductive days included all adult females, including nonreproducing females. *TPRP* was the interval from birth to first reproduction and was calculated only for reproducing females. Survival and demographic parameters were estimated from the complete initial cohort, including individuals dying before adulthood.

2.5. Statistical Analysis

Each developmental, survival, longevity, reproductive, and demographic response was analyzed separately using an additive 3 × 3 Latin square model (response-CO_2 + run + incubator). CO_2 concentration, experimental run, and physical incubator were fitted as categorical fixed effects. Each model used nine equally weighted incubator-run units, with one estimate per unit for the response being analyzed. Individual aphids were subsamples within these units. Unit-level instar-duration means followed the completion criteria in Section 2.4. The model accounted for additive treatment and blocking effects; treatment interactions with either blocking factor could not be estimated separately. A common residual variance was assumed across units within each response and estimated separately for each response.

Tables 1–3 report model-estimated treatment means ± model-based standard errors (SEs). Treatment means were obtained by averaging model predictions equally over run and incubator levels. In this balanced design, the SE of each treatment mean was $\mathrm{SE} = \sqrt{\frac{\mathrm{MSE}}{3}}$, where MSE is the response-specific residual mean square and 3 is the number of experimental units per concentration. Pointwise 95% confidence intervals were calculated as the estimated mean ± $t_{0.975,2}$ × SE, where $t_{0.975,2}$ is the 97.5th percentile of the t distribution with two residual degrees of freedom. Figure 1 displays unit-level estimates and model-estimated means with these intervals for selected responses. Estimates for all nine units are provided in Table S5; response-specific residual mean squares, model-based SEs, and overall test statistics are reported in Table S6.

For pre-adult survival, the response was the number of aphids reaching adulthood divided by the 20 aphids initially assigned to each experimental unit. Analysis on the proportion scale gave equal weight to units with the same initial cohort size. Because the variance of a proportion can depend on the underlying survival probability, a common residual variance on this scale was treated as a working assumption that could not be assessed reliably with the available replication.

Overall CO_2 effects were evaluated using F tests with two numerator and two residual degrees of freedom. Pairwise comparisons were Tukey-adjusted within each response to control the family-wise error rate across the three concentration comparisons. In Tables 1–3, means within a row that do not share a lowercase letter differ at an adjusted $p < 0.05$; shared letters indicate that a significant difference was not detected. No adjustment across response variables was applied to the overall tests or pairwise comparisons. Because residual variance was estimated from only two degrees of freedom, model-based SEs, confidence intervals, and treatment tests were interpreted cautiously and conditional on the additive model assumptions. Treatment comparisons were regarded as exploratory, and nonsignificant results were not interpreted as evidence of equivalence. Nonsignificant results were not interpreted as evidence of equivalence. Because $\lambda = \exp(r)$ within each

experimental unit, these parameters were treated as related demographic measures rather than independent evidence.

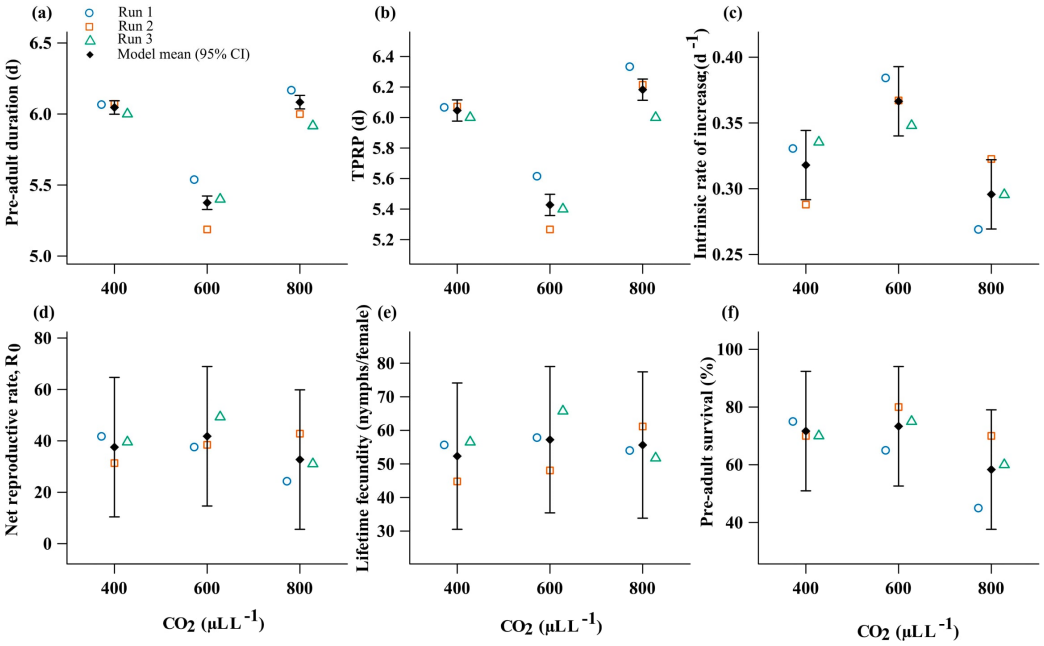


Figure 1. Unit-level estimates and Latin square model means for selected traits: (**a**) pre-adult duration; (**b**) *TPRP*; (**c**) intrinsic rate of increase; (**d**) net reproductive rate; (**e**) lifetime fecundity; and (**f**) pre-adult survival. Open circles, squares, and triangles represent estimates from runs 1, 2, and 3, respectively; horizontal offsets separate the runs. Black diamonds show model-estimated treatment means, and error bars indicate pointwise 95% confidence intervals calculated with two residual degrees of freedom. Pre-adult survival is expressed as a percentage. Confidence intervals reflect the additive model and should not be interpreted as pairwise tests.

Individual life histories were pooled across runs within each CO_2 concentration for descriptive life-table analysis. Bootstrap SEs were estimated in TWOSEX-MSChart using 100,000 nonparametric resamples of complete individual life histories, conducted separately within each pooled cohort. Pooled estimates and bootstrap SEs are reported in Tables S2–S4 [17,18]. These SEs quantify uncertainty conditional on the pooled cohorts, do not account for variation among incubator-run units, and were not used to test CO_2 effects. Pooled life tables were used to construct life-table curves and generate population projections in TIMING-MSChart.

The Latin square models; estimation of treatment means and their model-based SEs and confidence intervals; Tukey-adjusted comparisons; and preparation of figures and tables were implemented in R (version 4.6.1) using RStudio (version 2026.09.0+174). The individual life-history records, experimental-unit and model estimates, and R script for reproducing the Latin square analyses and Tukey-adjusted comparisons are provided in Supplementary Materials.

Residual-versus-fitted plots were prepared for pre-adult duration and the total pre-reproductive period, with each experimental unit identified by run and incubator (Figure S1). These plots complement the residual mean squares in Table S6 and were used for descriptive inspection of residual patterns and individual observations. With only two residual degrees of freedom, assessment of model assumptions was limited. Formal normality and homogeneity-of-variance tests were not performed, and the residual plots were not interpreted as establishing normality or constant residual variance.

2.6. Population Projection

Stage-specific population development was projected for 90 d using TIMING-MSChart (version 2024.03.30), starting with 10 newly emerged first-instar nymphs and using the pooled age–stage, two-sex life table for each CO_2 concentration [18,20,21]. Predicted abundance at day t and stage j (N_{tj}) was displayed as $\log_{10}(N_{tj} + 1)$. The projections assumed that the input survival and reproductive schedules remained constant across generations, without density dependence, resource limitation, predation, or environmental variability. These deterministic projections describe conditional population-growth potential. Because they were derived from the pooled life-table schedules, they did not provide independent tests of treatment effects or predictions of field abundance.

3. Results

3.1. Developmental Duration, Survival, and Longevity of M. persicae

Model-estimated pre-adult durations were 6.05 ± 0.01, 5.38 ± 0.01, and 6.08 ± 0.01 d at 400, 600, and 800 µL L^{-1} CO_2, respectively (Table 1). The overall concentration effect was statistically significant ($F_{2,2} = 1308.095$, $p = 0.0008$). The residual mean square for this model was 0.00036409 d^2 (Table S6). Pre-adult duration was shorter at 600 µL L^{-1} than at either 400 or 800 µL L^{-1} (Tukey-adjusted $p < 0.001$ for both comparisons). No difference was detected between 400 and 800 µL L^{-1} (Tukey-adjusted $p = 0.2414$). The overall tests did not detect significant concentration effects on individual instar durations ($p = 0.1390$–0.3511). Pooled estimates for completed instars are presented in Table S2.

Model-estimated adult female longevity was 20.42 ± 0.54, 17.08 ± 0.54, and 20.27 ± 0.54 d, and total lifespan among adult females was 26.46 ± 0.54, 22.45 ± 0.54, and 26.35 ± 0.54 d at 400, 600, and 800 µL L^{-1} CO_2, respectively. Overall tests did not detect significant concentration effects on adult female longevity ($F_{2,2} = 11.996$, $p = 0.0769$), total lifespan among adult females ($F_{2,2} = 18.214$, $p = 0.0520$), or total lifespan across all initial individuals ($F_{2,2} = 1.211$, $p = 0.4523$; Table 1). Pre-adult survival was 0.7167 ± 0.0481, 0.7333 ± 0.0481, and 0.5833 ± 0.0481 at the three concentrations, respectively, with no significant overall concentration effect ($F_{2,2} = 2.920$, $p = 0.2551$).

The pooled age–stage survival curves showed overlap among nymphal stages, reflecting variation in developmental timing among individuals (Figure 2). Treatment comparisons of mean pre-adult duration were based on the incubator–run units and are reported in Table 1.

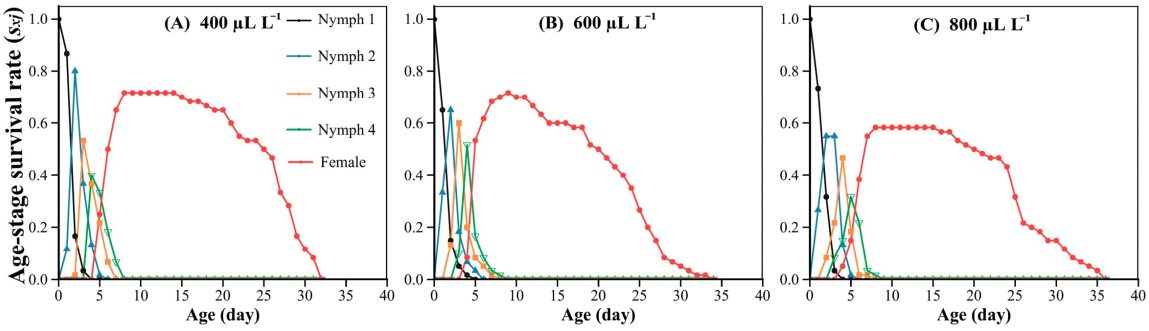


Figure 2. Age–stage-specific survival rate (s_{xj}) of *M. persicae* reared on detached potato leaves under three CO_2 concentrations: (**A**) 400 µL L^{-1}, (**B**) 600 µL L^{-1}, and (**C**) 800 µL L^{-1}. Here, x represents age in days and j represents the developmental stage. The overlap among stage-specific survival curves reflects individual variation in developmental rates. Curves are based on the pooled cohort at each CO_2 concentration and are presented for descriptive purposes. Experimental-unit estimates of pre-adult survival and model-based 95% confidence intervals for the treatment means are shown in Figure 1.

Table 1. Development, survival and longevity of *M. persicae* on potato under three CO_2 concentrations: Latin square model estimates and overall treatment tests.

Parameter	400 µL L^{-1} Estimate ± SE	600 µL L^{-1} Estimate ± SE	800 µL L^{-1} Estimate ± SE	$F_{2,2}$	p
First instar (d)	2.08 ± 0.06 [a]	1.88 ± 0.06 [a]	2.08 ± 0.06 [a]	3.619	0.2165
Second instar (d)	1.46 ± 0.08 [a]	1.31 ± 0.08 [a]	1.52 ± 0.08 [a]	1.848	0.3511
Third instar (d)	1.33 ± 0.03 [a]	1.18 ± 0.03 [a]	1.29 ± 0.03 [a]	6.192	0.1390
Fourth instar (d)	1.19 ± 0.08 [a]	1.00 ± 0.08 [a]	1.26 ± 0.08 [a]	3.042	0.2474
Pre-adult duration (d)	6.05 ± 0.01 [a]	5.38 ± 0.01 [b]	6.08 ± 0.01 [a]	1308.095	0.0008
Pre-adult survival (proportion)	0.7167 ± 0.0481 [a]	0.7333 ± 0.0481 [a]	0.5833 ± 0.0481 [a]	2.920	0.2551
Adult female longevity (d)	20.42 ± 0.54 [a]	17.08 ± 0.54 [a]	20.27 ± 0.54 [a]	11.996	0.0769
Total lifespan, all individuals (d)	20.30 ± 1.48 [a]	17.68 ± 1.48 [a]	17.30 ± 1.48 [a]	1.211	0.4523
Total lifespan, adult females (d)	26.46 ± 0.54 [a]	22.45 ± 0.54 [a]	26.35 ± 0.54 [a]	18.214	0.0520

Values are model-estimated treatment means ± model-based SE from nine incubator-run units (three per concentration), with run and incubator as fixed blocks. Each unit initially contained 20 aphids. Instar durations include completed instars only; pre-adult duration and adult female traits include individuals reaching adulthood. Total longevity (all individuals) includes immature deaths. Survival is the proportion reaching adulthood. SE use the common residual variance and are therefore equal across concentrations within each response. F and p test the overall concentration effect (df = 2, 2); p values are nominal and unadjusted across endpoints. Different lowercase letters within a row indicate Tukey-adjusted $p < 0.05$; shared letters indicate no detected difference. Tukey adjustment covers the three concentration comparisons within each response, not comparisons across responses. Individual sample sizes and pooled bootstrap summaries are given in Table S2.

3.2. Reproductive Performance of *M. persicae*

Age-specific survival (l_x), fecundity (m_x) and net maternity ($l_x m_x$) varied with age in the pooled cohorts (Figure 3). Reproduction first occurred at age 5 d at 400 µL L^{-1} and age 4 d at 600 and 800 µL L^{-1}. Differences in curve shape and reproductive timing are descriptive and were not subjected to treatment comparisons.

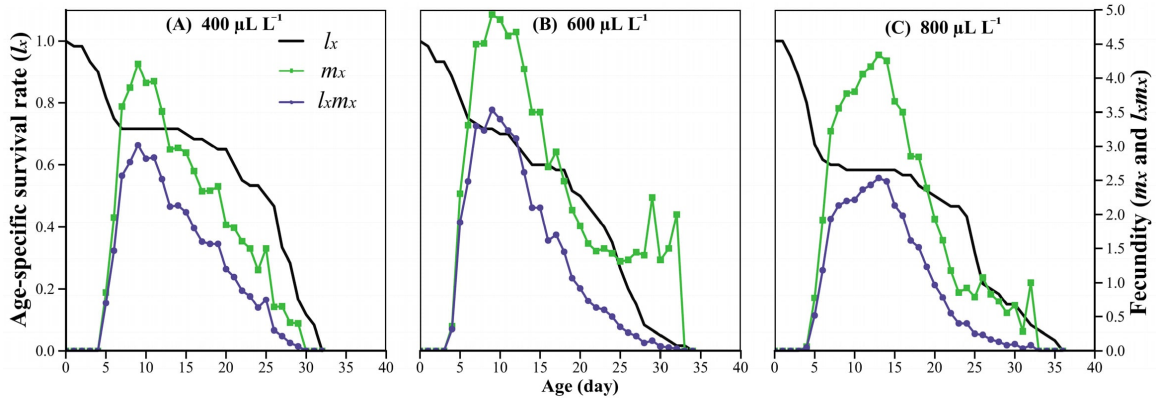


Figure 3. Age-specific survival rate (l_x), age-specific fecundity (m_x), and age-specific net maternity ($l_x m_x$) of *M. persicae* reared on detached potato leaves under three CO_2 concentrations: (**A**) 400 µL L^{-1}, (**B**) 600 µL L^{-1}, and (**C**) 800 µL L^{-1}. The l_x values are plotted against the left vertical axis, whereas m_x and $l_x m_x$ are plotted against the right vertical axis.

Model-estimated total pre-reproductive periods (*TPRP*) were 6.05 ± 0.02, 5.43 ± 0.02, and 6.18 ± 0.02 d at 400, 600, and 800 µL L^{-1} CO_2, respectively (Table 2). The overall concentration effect was statistically significant ($F_{2,2} = 619.180$, $p = 0.0016$). The residual

mean square for this model was 0.00078468 d^2 (Table S6). TPRP was shorter at 600 µL L^{-1} than at 400 and 800 µL L^{-1} (Tukey-adjusted $p = 0.0025$ and 0.0017, respectively). *TPRP* was also shorter at 400 than at 800 µL L^{-1} (Tukey-adjusted $p = 0.0488$).

Lifetime fecundity was 52.32 ± 5.07, 57.21 ± 5.07 and 55.63 ± 5.07 offspring per female, and reproductive days were 15.30 ± 1.17, 14.23 ± 1.17 and 16.14 ± 1.17 d at the three concentrations, respectively. The overall tests did not detect significant differences among CO_2 concentrations in lifetime fecundity ($F_{2,2} = 0.243$, $p = 0.8043$) or the number of reproductive days ($F_{2,2} = 0.669$, $p = 0.5991$; Table 2). No pairwise differences were detected for either trait after Tukey adjustment. Pooled reproductive estimates are presented in Table S3.

Table 2. Reproductive traits of *M. persicae* on potato under three CO_2 concentrations: Latin square model estimates and overall treatment tests.

Parameter	400 µL L^{-1} Estimate ± SE	600 µL L^{-1} Estimate ± SE	800 µL L^{-1} Estimate ± SE	$F_{2,2}$	p
TPRP (d)	6.05 ± 0.02 [b]	5.43 ± 0.02 [c]	6.18 ± 0.02 [a]	619.180	0.0016
Lifetime fecundity (offspring/female)	52.32 ± 5.07 [a]	57.21 ± 5.07 [a]	55.63 ± 5.07 [a]	0.243	0.8043
Reproductive days (d)	15.30 ± 1.17 [a]	14.23 ± 1.17 [a]	16.14 ± 1.17 [a]	0.669	0.5991

Values are model-estimated treatment means ± model-based SE from nine equally weighted incubator-run units (three per concentration), with run and incubator as fixed blocks. *TPRP* is the interval from birth to first reproduction and includes reproducing females only. Fecundity and reproductive days include all adult females, including one nonreproducing female at 600 µL L^{-1}. Across the pooled cohorts, adult female sample sizes were 43, 44 and 35, and reproducing female sample sizes were 43, 43 and 35 at 400, 600 and 800 µL L^{-1}, respectively. F and p test overall concentration effects (df = 2, 2); p values are nominal. Different lowercase letters within a row indicate Tukey-adjusted $p < 0.05$; shared letters indicate no detected difference. Tukey adjustment covers the three concentration comparisons within each response, not comparisons across responses. Pooled bootstrap summaries are reported separately in Table S3.

3.3. Population Parameters of M. persicae

Model-estimated intrinsic rates of increase (r) were 0.3180 ± 0.0061, 0.3665 ± 0.0061 and 0.2957 ± 0.0061 d^{-1} at 400, 600 and 800 µL L^{-1} CO_2, respectively; corresponding finite rates of increase (λ) were 1.3747 ± 0.0078, 1.4428 ± 0.0078 and 1.3444 ± 0.0078 (Table 3). Overall concentration effects were detected for both r ($F_{2,2} = 34.931$, $p = 0.0278$) and λ ($F_{2,2} = 41.486$, $p = 0.0235$). Tukey-adjusted comparisons showed that r was higher at 600 than at 800 µL L^{-1} ($p = 0.0266$), whereas differences between 400 and 600 µL L^{-1} ($p = 0.0550$) and between 400 and 800 µL L^{-1} ($p = 0.2161$) were not significant. For λ, estimates were higher at 600 than at both 400 and 800 µL L^{-1} ($p = 0.0460$ and 0.0226, respectively), with no significant difference between 400 and 800 µL L^{-1} ($p = 0.1961$). Because λ was calculated as $\exp(r)$ within each experimental unit, these results describe related demographic responses rather than independent evidence.

Model-estimated net reproductive rates (R_0) were 37.55 ± 6.30, 41.78 ± 6.30 and 32.72 ± 6.30 offspring per initial individual, and mean generation times (T) were 11.41 ± 0.24, 10.19 ± 0.24 and 11.71 ± 0.24 d at the three concentrations, respectively. Neither parameter showed a significant overall concentration effect (R_0: $p = 0.6589$; T: $p = 0.0831$), and no significant pairwise differences were detected following Tukey adjustment. Pooled life-table estimates underlying the descriptive curves and population projections are presented in Table S4.

Table 3. Demographic parameters of *M. persicae* on potato under three CO_2 concentrations: Latin square model estimates and overall treatment tests.

Parameter	400 µL L^{-1} Estimate ± SE	600 µL L^{-1} Estimate ± SE	800 µL L^{-1} Estimate ± SE	$F_{2,2}$	p
Net reproductive rate, R_0 (offspring/initial individual)	37.55 ± 6.30 ^{a}	41.78 ± 6.30 ^{a}	32.72 ± 6.30 ^{a}	0.518	0.6589
Intrinsic rate of increase, r (d^{-1})	0.3180 ± 0.0061 ^{ab}	0.3665 ± 0.0061 ^{a}	0.2957 ± 0.0061 ^{b}	34.931	0.0278
Finite rate of increase, λ (per day)	1.3747 ± 0.0078 ^{b}	1.4428 ± 0.0078 ^{a}	1.3444 ± 0.0078 ^{b}	41.486	0.0235
Mean generation time, T (d)	11.41 ± 0.24 ^{a}	10.19 ± 0.24 ^{a}	11.71 ± 0.24 ^{a}	11.034	0.0831

Values are model-estimated treatment means ± model-based SE from nine equally weighted incubator–run units (three per concentration). Demographic parameters were obtained from each complete initial unit cohort of 20 aphids, including immature deaths. The model includes concentration, run and incubator as fixed effects. R_0 is offspring per initial individual; r is in d^{-1}; λ is the finite multiplication factor over one day; T is in days. F and p test overall concentration effects (df = 2, 2); p values are nominal. Different lowercase letters within a row indicate Tukey-adjusted $p < 0.05$; shared letters indicate no detected difference. Tukey adjustment covers the three concentration comparisons within each response, not comparisons across responses. Since unit-level $\lambda = \exp(r)$, treatment means of λ need not equal exp of treatment means of r. Pooled cohort estimates and bootstrap SE are reported in Table S4.

3.4. Life Expectancy (e_{xj}) and Reproductive Value (v_{xj}) of M. persicae

In the pooled life tables, life expectancy at birth (e_{01}) was 20.30, 17.68 and 17.30 d at 400, 600 and 800 µL L^{-1} CO_2, respectively, corresponding to the mean lifespan of all initial individuals (Figure 4; Table S2). Life expectancy at subsequent ages and stages represents expected remaining lifespan conditional on survival to the specified age and stage. These pooled estimates are descriptive and do not establish treatment differences in longevity.

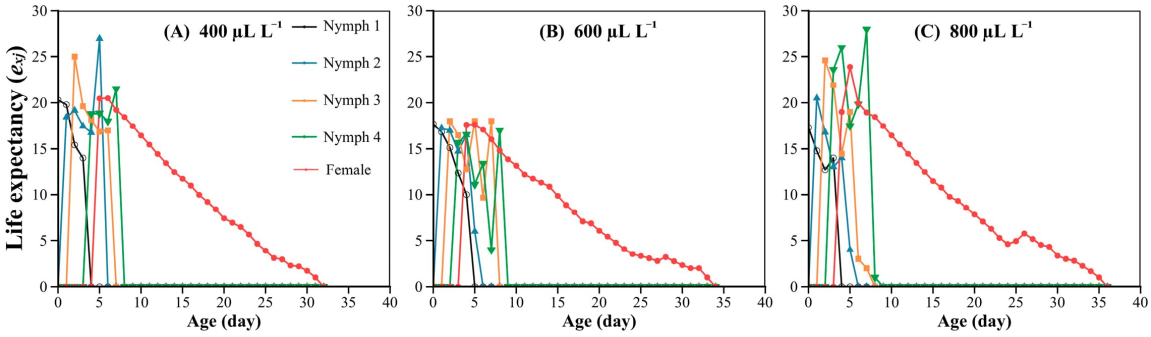


Figure 4. Age–stage-specific life expectancy (e_{xj}) of *M. persicae* reared on detached potato leaves under three atmospheric CO_2 concentrations: (**A**) 400 µL L^{-1}, (**B**) 600 µL L^{-1}, and (**C**) 800 µL L^{-1}. The parameter e_{xj} represents the expected remaining lifespan of an individual at age x and developmental stage j.

Age–stage-specific reproductive value (v_{xj}) represents expected future offspring production discounted by the intrinsic rate of increase, conditional on survival to a given age and stage (Figure 5). In the pooled life tables, female reproductive value generally peaked early in adulthood and declined thereafter, with some fluctuations at later ages (Figure 5). These patterns are descriptive; neither peak magnitude nor peak timing was tested for differences among CO_2 treatments.

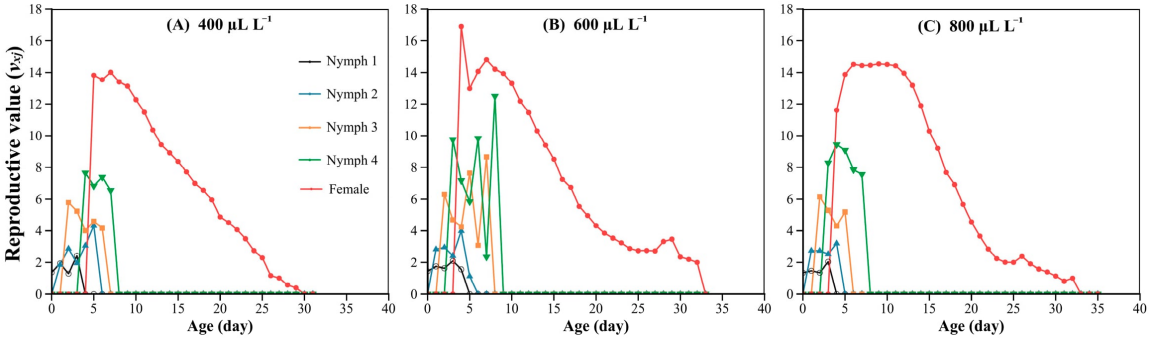


Figure 5. Age–stage-specific reproductive value (v_{xj}) of *M. persicae* reared on detached potato leaves under three atmospheric CO_2 concentrations: (**A**) 400 μL L^{-1}, (**B**) 600 μL L^{-1}, and (**C**) 800 μL L^{-1}. The parameter v_{xj} represents the contribution of an individual at age x and developmental stage j to future population growth.

3.5. Population Projection of M. persicae

Projections based on the pooled life tables showed early fluctuations in stage composition followed by sustained population growth over 90 d (Figure 6). At day 90, projected stage-specific abundances were numerically highest at 600 μL L^{-1} and lowest at 800 μL L^{-1}. This ordering arose from the survival and reproductive schedules used as inputs and was consistent with the ordering of the pooled intrinsic rates of increase in Table S4. The projected trajectories describe conditional growth potential under the stated assumptions and do not constitute independent evidence of CO_2 treatment effects.

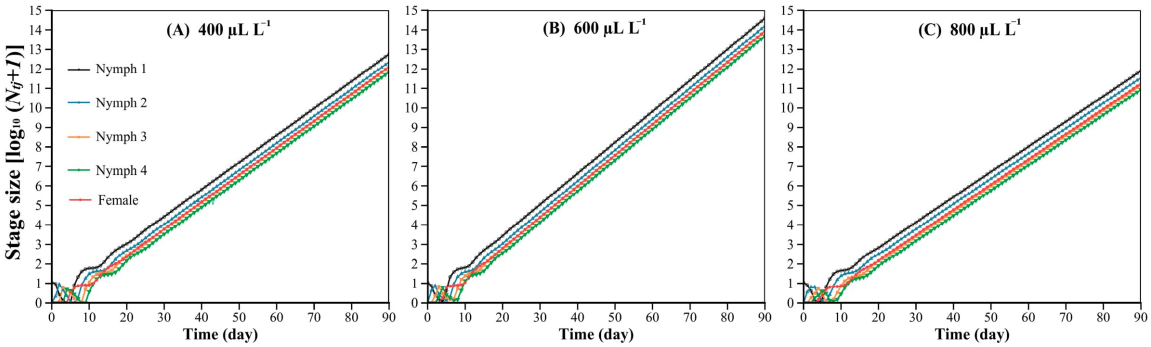


Figure 6. Stage-specific population projections of *Myzus persicae* based on pooled age–stage, two-sex life tables obtained from aphids reared on detached potato leaves at three nominal CO_2 concentrations: (**A**) 400 μL L^{-1}, (**B**) 600 μL L^{-1}, and (**C**) 800 μL L^{-1}. Projections started with 10 newly emerged first-instar nymphs and extended over 90 d. Abundance is expressed as $\log_{10}(N_{tj} + 1)$, where N_{tj} is the projected number of individuals in stage j on day t. Survival and reproductive schedules were held constant across generations, without density dependence or resource limitation. These trajectories represent conditional population-growth potential and do not provide field predictions or independent tests of CO_2 treatment effects.

4. Discussion

CO_2 concentration affected the developmental and reproductive timing of *M. persicae* on potato cv. Longshu 23, with corresponding differences in population growth parameters. Pre-adult duration and *TPRP* were shorter at 600 than at 400 and 800 μL L^{-1}. Tukey-adjusted comparisons showed a higher intrinsic rate of increase (r) at 600 than at 800 μL L^{-1}, whereas the difference between 600 and 400 μL L^{-1} was not significant. The finite rate of increase (λ) was higher at 600 than at both other concentrations. Because $\lambda = \exp(r)$ within each experimental unit, these results represent related demographic responses; the differing pairwise significance outcomes reflect analyses on different scales rather than independent

biological effects. No significant overall effects were detected on lifetime fecundity, net reproductive rate (R_0) or mean generation time (T). The findings therefore emphasize reproductive timing alongside total offspring production, without establishing an optimal CO_2 concentration or a general dose–response relationship.

The observed responses should be interpreted in the context of contrasting results from previous CO_2–aphid studies. Ahn and Choi [14] reported increased reproductive and population parameters of *M. persicae* under elevated CO_2, whereas Dáder et al. [13] documented adverse effects on several life-history traits on bell pepper. Differences in host plants, exposure conditions and concentration ranges limit direct comparisons among these studies. More recent evidence shows that climatic factors can alter herbivore performance through direct and plant-mediated pathways [2], while a wheat–aphid experiment demonstrates that responses to elevated CO_2 can be modified by drought [3]. Research on bottom-up regulation further highlights the importance of host traits and growing conditions [4,5,22]. Thus, the growth-rate differences between 600 and 800 $\mu L\ L^{-1}$ in the present experiment should be interpreted within the tested host and exposure conditions.

Earlier development and reproduction provide a plausible demographic explanation for the higher growth-rate estimates at 600 $\mu L\ L^{-1}$. In the Euler–Lotka equation, offspring produced earlier contribute more strongly to the intrinsic rate of increase than the same number produced later [15–17]. Shorter pre-adult duration and *TPRP* can therefore accompany higher growth rates without a detectable increase in lifetime fecundity. However, the present analysis did not partition the contributions of reproductive timing, survival and offspring production to changes in r. Moreover, the nonsignificant fecundity and R_0 results do not demonstrate that these traits were unaffected. Together, these findings support examining reproductive schedules alongside lifetime reproductive output when interpreting demographic responses [12,21,23].

Changes in host-plant quality are one possible pathway by which elevated CO_2 may influence aphid performance. Free-air CO_2 enrichment (FACE) studies have documented changes in crop productivity and nutritional composition [1], and research on aphid host specificity highlights the roles of plant defenses and aphid adaptation [8]. In wheat, CO_2 and drought treatments altered plant nutritional and resistance traits as well as aphid performance [3]. In bell pepper, changes in plant traits under elevated CO_2 were accompanied by changes in the development, reproduction, and feeding behavior of *M. persicae* [13]. In our experiment, the aphids and the potato plants supplying their leaves were exposed to the same assigned CO_2 concentration. The observed demographic responses may therefore reflect direct effects on the aphids, effects mediated by the host plant, or both; the design did not distinguish these pathways. Leaf chemistry, phloem composition, and aphid feeding behavior were not measured. Consequently, the available data do not allow us to attribute the demographic differences to improved host nutrition, altered plant defenses, or changes in aphid feeding. Testing these explanations would require independent manipulation of plant and aphid CO_2 exposure together with measurements of plant traits and aphid feeding [5,24].

Host genotype and water availability may further modify these responses. Studies of potato–aphid interactions under drought demonstrate variation among cultivars [9–12], and recent studies in other plant–aphid systems show that water stress can alter host quality and aphid performance [25–28]. These responses depend on stress intensity and the plant–aphid system, as illustrated by experimental and meta-analytic evidence [25,26,28]. Drought responses alone cannot be assumed to predict CO_2 responses; experiments combining the two factors provide a more direct basis for assessing their interaction [3]. Experiments involving additional potato cultivars and independently sourced aphid populations, includ-

ing combined CO_2, temperature, and water treatments, would help assess the generality of the observed concentration pattern.

The pooled life-table curves complement the unit-level analyses by describing variation in development, survival and reproductive timing. Overlapping stages reflect differences in individual developmental rates, while late-age fluctuations in conditional life expectancy and reproductive value may be influenced by the small number of surviving individuals [17–19]. These curve features were not tested statistically and do not provide additional treatment replication. Their value is descriptive, as in related life-table applications across hosts and environmental conditions [12,21,29].

The population projections translate the pooled survival and reproductive schedules into conditional trajectories of abundance and stage composition [18,20,21]. Their ranking follows from these input schedules and therefore does not independently confirm the treatment differences identified by the experimental-unit analyses. Holding demographic schedules constant while excluding density dependence and resource limitation permits sustained growth and potentially very large projected populations. These outputs illustrate how the observed laboratory schedules would propagate under the specified assumptions; they do not predict attainable field abundance or the likelihood of pest outbreaks.

The Latin square rotation accounted for additive differences among runs and incubators. Treatment comparisons were based on nine incubator–run units (three per CO_2 concentration), with individual aphids treated as subsamples. For pre-adult duration and the total pre-reproductive period (*TPRP*), small residual mean squares yielded small model-based SEs, while the large *F* statistics reflected the size of the treatment mean squares relative to the residual mean squares (Table S6). However, each residual variance estimate was based on only two degrees of freedom, and interactions of CO_2 concentration with run or incubator could not be estimated separately. Verification of the calculations confirmed numerical reproducibility but did not resolve the uncertainty associated with estimating residual variance from so few degrees of freedom. Consequently, small SEs and large *F* statistics do not establish the robustness of the treatment comparisons. The estimates, confidence intervals, and tests remain conditional on the additive model and its assumptions and should be considered alongside the unit-level observations (Figure 1). The residual-versus-fitted plots for pre-adult duration and *TPRP* (Figure S1) provide descriptive checks but do not establish normality or constant residual variance. For pre-adult survival, a common residual variance on the proportion scale was a working assumption that could not be assessed reliably with the available replication; the nonsignificant overall test does not establish equivalent survival among concentrations. Tukey adjustment controlled the family-wise error rate across the three comparisons within each response, but no adjustment was made across responses. Given these limitations, the observed differences should be regarded as exploratory findings under the tested conditions and require confirmation with greater replication at the treatment-assignment level.

The use of a single potato cultivar, a single laboratory aphid colony, and detached-leaf bioassays limits generalization to other host genotypes, aphid populations, and field environments. Daily observations of cohorts born within a 24-h window also limit the temporal resolution of the life-history records. CO_2 monitoring relied on daily checks of the incubator controller displays without independent verification during the experiment. Although the built-in sensors were calibrated, detailed concentration records and sufficient information to quantify sensor accuracy during the runs were unavailable. These gaps limit assessment of temporal variability and measurement accuracy, leaving uncertainty about how closely chamber concentrations tracked the nominal set points throughout each run. Additional experimental units would help assess reproducibility, while independent monitoring of chamber and within-dish CO_2 would strengthen exposure verification. Measurements of

plant traits and aphid feeding, combined with independent manipulation of plant and aphid CO_2 exposure, would help distinguish direct from plant-mediated effects [2,5].

5. Conclusions

Pre-adult duration and the total pre-reproductive period of *M. persicae* on potato cv. Longshu 23 were shorter at 600 μL L^{-1} CO_2 than at either 400 or 800 μL L^{-1}. The total pre-reproductive period was also shorter at 400 than at 800 μL L^{-1}. The intrinsic rate of increase (r) was higher at 600 than at 800 μL L^{-1}, with no significant difference detected between 600 and 400 μL L^{-1}. The finite rate of increase (λ) was higher at 600 than at both other concentrations. No significant overall concentration effects were detected for lifetime fecundity or net reproductive rate.

With three experimental units per concentration and only two residual degrees of freedom, these findings provide exploratory evidence under the tested conditions and require confirmation with greater replication at the treatment-assignment level. Aphids and the potato plants supplying their leaves were exposed to the same assigned CO_2 concentration, so the experiment could not distinguish direct effects on the aphids from effects mediated by the host plant. Leaf chemistry, phloem composition, and aphid feeding behavior were not measured, leaving the mechanisms underlying the demographic differences unresolved. The results do not establish an optimal CO_2 concentration or predict field population growth.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy16232376/s1, Table S1: Life-table definitions and equations [15,17,19,29–33]; Tables S2–S4: Pooled cohort estimates and bootstrap standard errors; Table S5: Estimates for the nine incubator-run experimental units; Table S6: Residual mean squares, model-based standard errors, and overall CO_2 test statistics; Figure S1: Residual-versus-fitted plots for pre-adult duration and the total pre-reproductive period.

Author Contributions: Conceptualization, Y.G.; methodology, Y.G.; software, Y.G. and H.Y.; validation, Y.G.; formal analysis, Y.G. and H.Y.; investigation, C.L., T.Z. and X.Q.; resources, C.L., T.Z. and X.Q.; data curation, Y.G. and M.L.; writing-original draft preparation, Y.G. and H.Y.; writing-review and editing, Y.G.; visualization, Y.G.; supervision, Y.G.; project administration, Y.G. and T.Z.; funding acquisition, Y.G. and T.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Disciplinary Team Construction Project (GAU-XKTD-2026-066), Identification of Insect Pest Species of Oilseed Crops in the Yancheng Region (Project No. 03626034), Gansu Agricultural University Public Recruitment Doctoral Research Start-up Project (GAU-KYQD-2021-27) and the National Natural Science Foundation of China (32560261).

Data Availability Statement: The original contributions presented in this study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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