

## Review article

### Meta-Analysis of Growth Performance in Tilapia (*Oreochromis* spp.) Across Feeding Regimes in Pond Culture

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#### ARTICLE INFO

##### Article history

Received 02 January 2026

Revised 05 March 2026

Accepted 20 June 2026

Available online 30 June 2026

##### Keywords

Nile tilapia

*Oreochromis niloticus*

Meta-analysis

Growth performance

Aquaculture nutrition

#### ABSTRACT

Feed accounts for over 50% of operational costs in pond aquaculture, making optimized diets essential for sustainable production. Nile tilapia (*Oreochromis niloticus*) has been evaluated under various dietary strategies, but comparative evidence remains fragmented. This study synthesizes pond-based evidence on how commercial feeds, plant-derived ingredients, and probiotic supplementation affect tilapia growth and feed utilization, and evaluates practical inclusion benchmarks. A systematic review (2010–2025) following PRISMA guidelines identified 12 eligible primary pond studies. Data on Specific Growth Rate ( $SGR$ ; %  $d^{-1}$ ), weight gain ( $WG$ ; %), and feed utilization indices [Feed Conversion Ratio ( $FCR$ ), Protein Efficiency Ratio ( $PER$ ), where available] were standardized. Secondary syntheses and outcome records lacking a group mean, sample size, or  $SD/SE$  were excluded from the relevant quantitative pooling rather than imputed. Random-effects meta-analyses estimated pooled effect sizes (Hedges'  $g$ ), with heterogeneity ( $Q$ ,  $I^2$ ), moderator analyses (probiotic dose, plant inclusion level, trial duration, stocking density), and descriptive assessment of small-study effects because formal publication-bias tests were underpowered. Probiotic supplementation at 2–5  $g\ kg^{-1}$  significantly enhanced growth ( $SGR\ g = 1.15$ ;  $WG\ g = 0.98$ ;  $p < 0.001$ ). In contrast, high inclusion levels of untreated plant ingredients (>30%) significantly reduced growth performance ( $SGR\ g = -0.87$ ;  $WG\ g = -0.75$ ;  $p < 0.001$ ). Substantial heterogeneity ( $I^2 = 78$ –92%) was partly explained by inclusion level and trial duration. This meta-analysis suggests provisional benchmarks for pond-cultured Nile tilapia, indicating that probiotic inclusion at 3–5  $g\ kg^{-1}$  may improve growth and feed efficiency, whereas plant ingredient inclusion above ~30% compromises performance.

#### Introduction

Nile tilapia (*Oreochromis niloticus*) is one of the most widely farmed freshwater species, contributing nearly 80 % of global tilapia production and valued for its rapid growth, omnivorous feeding habits, and tolerance of diverse pond environments. While tilapia production is substantial, global freshwater aquaculture is still dominated by carps and catfishes,

underscoring the importance of situating tilapia within the broader aquaculture landscape (FAO 2024). In small- and medium-scale pond systems, particularly across Asia, Africa, and Latin America, feed represents 50–60 % of operational costs, making the development of cost-effective diets central to both economic and environmental sustainability (Nguyen et al. 2023). Historically, commercial aquafeeds provided balanced

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protein and amino acids, but rising fishmeal prices and volatility in feed costs have pressured farmers to explore alternative protein sources. Plant-derived ingredients such as soybean meal, rice bran, and cassava peel offer cost advantages but often contain anti-nutritional factors (ANFs) and lack essential amino acids, leading to reduced growth and feed efficiency if used at high inclusion levels (Jatta et al. 2022). Processing methods (e.g., fermentation, enzyme supplementation) can mitigate these limitations, yet the optimal inclusion thresholds remain uncertain.

Probiotics represent another feed innovation, with strains such as *Saccharomyces cerevisiae* and *Bacillus subtilis* reported to enhance nutrient absorption, modulate gut microbiota, and improve immune responses. However, the effectiveness of probiotics varies by strain, dosage, trial duration, and pond conditions (Islam et al. 2021; Abdel-Tawwab et al. 2020). Similarly, the performance of industry-formulated commercial diets is difficult to benchmark due to proprietary formulations. These sources of variability highlight the need for a rigorous quantitative synthesis.

Previous reviews have largely been narrative, leaving unanswered questions regarding the magnitude of effects, dose thresholds, and moderators that drive tilapia performance in ponds. This study addresses that gap through a systematic meta-analysis, aiming to provide quantitative benchmarks and evidence-based recommendations for small-scale pond aquaculture.

### Objectives

- (i) To estimate pooled effect sizes for probiotic-supplemented, plant-based, and commercial diets on Nile tilapia growth and feed utilization.
- (ii) To evaluate the role of moderators (e.g., ingredient inclusion levels, probiotic dosage, trial duration, stocking density, and culture conditions).
- (iii) To generate practical, cost-sensitive feeding recommendations that balance productivity, sustainability, and farmer profitability in pond aquaculture systems.

### Literature review

Nile tilapia (*Oreochromis niloticus*) is one of the most widely farmed freshwater species, valued for its growth rate, tolerance of variable pond conditions, and consumer demand. However, global freshwater aquaculture production is still dominated by carps and catfishes (FAO 2024). In small-scale earthen pond systems common across Asia, Africa, and Latin America, feed costs represent 50–60 % of production expenses, making nutritional strategies central to farm profitability (Abozaid et al. 2024). Growth performance

is commonly assessed using Specific Growth Rate (SGR; % d<sup>-1</sup>) and percentage weight gain, but reported values vary widely across studies. This variability reflects not only dietary differences but also trial design, stocking density, water quality, and inconsistent reporting of variance measures, limiting direct comparison between studies (Wang et al. 2019).

Industry-formulated commercial feeds provide balanced amino acid profiles but are increasingly expensive and rely partly on marine resources. Their precise composition is typically undisclosed (“closed formulas”), making it difficult to benchmark performance against experimental diets (Oliva-Teles et al. 2015). Plant-derived alternatives such as soybean meal, rice bran, and cassava peel are widely studied due to their cost advantages, but they contain anti-nutritional factors (ANFs) and lack essential amino acids. For example, Jatta et al. (2022) reported no significant growth differences among four substitution diets during an 8-week trial, although the alternative ingredient combinations reduced feed cost. Fermentation and enzyme supplementation can partly mitigate growth penalties: Gattoc et al. (2019) found that fermented rice bran reduced the SGR decline to only 15 %, although the absence of a non-fermented control limited interpretation. Such methodological inconsistencies—single inclusion levels, short trial durations, and incomplete controls—make it difficult to establish robust thresholds for plant ingredient inclusion.

Probiotics such as *Saccharomyces cerevisiae* and *Bacillus subtilis* have been shown to enhance nutrient digestibility, modulate gut microbiota, and improve immunity. In a pond-based trial, Islam et al. (2021) reported that 4 g kg<sup>-1</sup> yeast improved SGR by 0.5 % d<sup>-1</sup> and weight gain by 27 %, although their reporting omitted allocation procedures, raising risk-of-bias concerns. Abdel-Tawwab et al. (2020) observed improvements in intestinal morphology with baker’s yeast but did not provide variance measures, preventing inclusion in meta-analysis. Across trials, probiotic effects range from moderate ( $g \approx 0.5$ ) to large ( $g \approx 1.2$ ), with heterogeneity often exceeding 90 %, suggesting that unreported moderators (e.g., water temperature, stocking density, baseline gut flora) play important roles.

### Knowledge gaps

Despite a growing body of research, most tilapia nutrition trials lack uniform reporting of key factors such as water quality, stocking density, and trial duration, and frequently omit confidence intervals or heterogeneity statistics (Nguyen et al. 2023). Previous reviews have been largely narrative or restricted to subsets of feeds, leaving unresolved questions about the magnitude of

growth responses, the consistency of probiotic benefits, and the safe inclusion thresholds for plant proteins. A systematic meta-analysis is therefore needed to (i) quantify pooled effects of commercial diets, plant-based alternatives, and probiotic supplementation on Nile tilapia growth and feed utilization; (ii) explore sources of heterogeneity through moderator analysis; and (iii) evaluate methodological quality and reporting practices. Such synthesis will provide practical, evidence-based guidelines for optimizing feed strategies in pond-based aquaculture.

## Materials and methods

### Systematic literature search

A comprehensive literature search was conducted in May 2025 to identify studies published between January 2010 and May 2025 that evaluated growth performance of Nile tilapia (*Oreochromis niloticus*) under different feed formulations in freshwater pond systems. Six electronic databases were queried: Web of Science, Scopus, PubMed, Google Scholar, the FAO Digital Library, and ProQuest Dissertations & Theses. Search strings combined controlled vocabulary (e.g., MeSH terms) and free-text keywords, using Boolean operators as follows:

(“Nile tilapia” OR “*Oreochromis niloticus*”) AND  
 (“growth” OR “specific growth rate” OR “SGR” OR  
 “weight gain” OR “feed conversion ratio” OR

“FCR”) AND (“diet” OR “feed formulation” OR  
 “probiotic” OR “plant-based” OR “feed substitution”)  
 AND (“pond” OR “earthen pond” OR “freshwater  
 pond”).

To ensure comprehensive coverage, the reference lists of all included full-text articles and relevant review papers were also screened manually. Eligible records included peer-reviewed journal articles, theses, FAO and WorldFish technical reports, and conference proceedings, provided they presented extractable original data on growth or feed utilization. Only English-language publications were considered.

This review followed PRISMA 2020 guidelines (Page et al. 2021). A total of 245 records were retrieved from databases, and 12 additional records were identified through grey literature. After deduplication, 215 unique records remained. Of these, 170 were excluded at the title/abstract stage for irrelevance or failure to meet inclusion criteria. Forty-five full texts were assessed, with 33 excluded for reasons such as insufficient statistical data, non-pond systems, or incompatible designs or secondary-review status. Ultimately, 12 primary studies met the systematic-review criteria; only outcome records with complete group means, sample sizes, and SD/SE contributed to quantitative pooling. The study selection process is illustrated in the PRISMA flow diagram (Fig. 1), and a full list of included studies with key characteristics is provided in Table 1.

**Table 1.** Characteristics of studies included in the systematic review (2010–2025)

| No. | Author(s), Year             | Country    | Species/Strain                       | Duration (days) | Diet Type / Intervention                                     | Probiotic strain and dose (g kg <sup>-1</sup> or CFU g <sup>-1</sup> ) | Plant ingredient and inclusion level (%) | Outcomes reported | Risk of Bias (SYRCLE)                         |
|-----|-----------------------------|------------|--------------------------------------|-----------------|--------------------------------------------------------------|------------------------------------------------------------------------|------------------------------------------|-------------------|-----------------------------------------------|
| 1   | Islam et al. (2021)         | Bangladesh | Nile tilapia ( <i>O. niloticus</i> ) | 60              | Yeast diet vs control                                        | <i>S. cerevisiae</i> , 4 g kg <sup>-1</sup>                            | None                                     | SGR, WG, FCR      | Moderate (no blinding)                        |
| 2   | Abdel-Tawwab & Ahmad (2020) | Egypt      | Nile tilapia                         | 75              | Yeast-supplemented diet                                      | <i>S. cerevisiae</i> , 2–5 g kg <sup>-1</sup>                          | None                                     | SGR, WG           | High (variance and n missing; narrative only) |
| 3   | Jatta et al. (2022)         | Taiwan     | Nile tilapia                         | 56              | Substitution of soybean meal, wheat flour, and cassava flour | None                                                                   | Multiple ingredient substitutions        | SGR, WG           | Moderate (8-week tank trial)                  |
| 4   | Gattoc et al. (2019)        | Bangladesh | Nile tilapia                         | 45              | Fermented rice bran                                          | None                                                                   | 20 %                                     | SGR               | Moderate (control absent)                     |
| 5   | Won et al. (2020)           | Korea      | Nile tilapia                         | 56              | Probiotic diet                                               | <i>B. subtilis</i> (10 <sup>8</sup> CFU g <sup>-1</sup> )              | None                                     | SGR, WG, FCR      | Moderate (tank trial)                         |
| 6   | Opiyo et al. (2019)         | Kenya      | Nile tilapia                         | 210             | Probiotic diet in low-input ponds                            | <i>S. cerevisiae</i> , 4 g kg <sup>-1</sup>                            | None                                     | SGR, WG           | Low                                           |
| 7   | Büyükçapar (2011)           | Turkey     | Nile tilapia                         | 75              | Tannin supplementation                                       | None                                                                   | 15–25 g/kg tannins                       | SGR               | Moderate                                      |
| 8   | Emshaw et al. (2023)        | Ethiopia   | Nile tilapia                         | 60              | Water hyacinth inclusion                                     | None                                                                   | Up to 30 %                               | SGR, WG           | Low                                           |
| 9   | Rahayu et al. (2020)        | Indonesia  | Nile tilapia                         | 70              | Vermicompost fertilization + feeding                         | None                                                                   | Standard feed + manure                   | SGR, WG           | Low                                           |

| No. | Author(s), Year           | Country     | Species/Strain | Duration (days) | Diet Type / Intervention       | Probiotic strain and dose (g kg <sup>-1</sup> or CFU g <sup>-1</sup> ) | Plant ingredient and inclusion level (%) | Outcomes reported | Risk of Bias (SYRCLE)            |
|-----|---------------------------|-------------|----------------|-----------------|--------------------------------|------------------------------------------------------------------------|------------------------------------------|-------------------|----------------------------------|
| 10  | Ojukannaiye et al. (2014) | Nigeria     | Nile tilapia   | 60              | Cassava peel substitution      | None                                                                   | 75–100 %                                 | SGR, WG           | Low                              |
| 11  | Gattoc et al. (2019)      | Philippines | Nile tilapia   | 90              | Fermented rice bran vs pellets | None                                                                   | 20 %                                     | SGR, WG           | Moderate                         |
| 12  | Abozaid et al. (2024)     | Egypt       | Nile tilapia   | 56              | Dried-yeast supplementation    | <i>S. cerevisiae</i> , 1.2 %                                           | None                                     | SGR, WG           | Unclear (quantitative inputs NR) |

SGR, specific growth rate; WG, weight gain; FCR, feed conversion ratio; CFU, colony-forming units; SYRCLE, SYstematic Review Centre for Laboratory animal Experimentation risk-of-bias tool; NR, not reported.

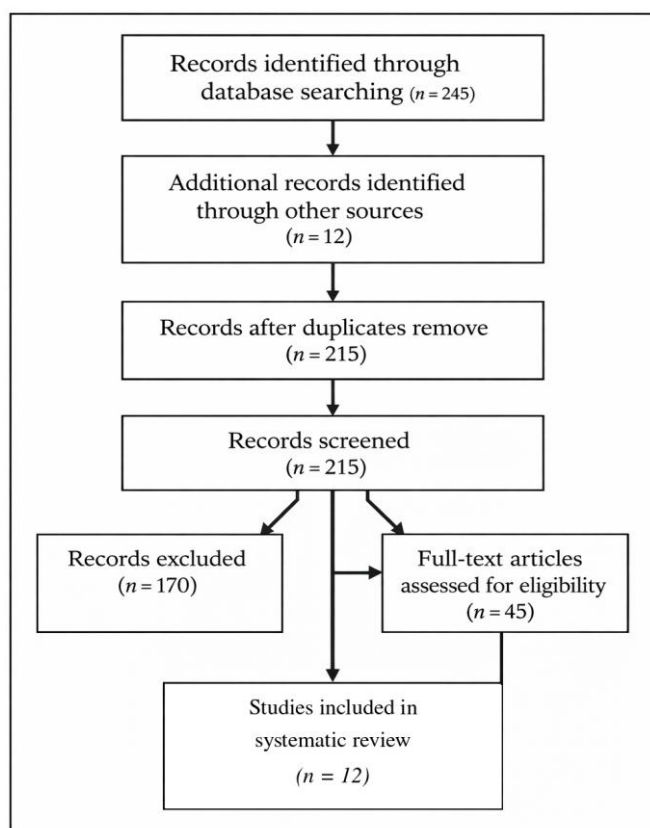


**Fig. 1.** PRISMA flow diagram of study selection for the tilapia feeding meta-analysis.

### Study selection and eligibility

Titles and abstracts were independently screened by two reviewers (HK and co-researcher) using predefined criteria. Studies were eligible for the systematic review if they (i) compared at least one experimental diet (plant-based or probiotic-supplemented) against a commercial or basal control diet; (ii) were conducted in earthen or freshwater pond systems; (iii) reported at least one extractable growth outcome [Specific Growth Rate (SGR; % d<sup>-1</sup>), weight gain (%), and where available feed-utilization metrics such as Feed Conversion Ratio (FCR) and Protein Efficiency Ratio (PER)]; and (iv) had extended trial durations equivalent to ≥30 days or a ≥2-fold biomass increase. Quantitative eligibility was assessed outcome by outcome and required a treatment mean, control mean, sample size (n), and SD or convertible SE for both groups.

Exclusion criteria were: trials conducted exclusively in tanks, cages, recirculating aquaculture systems, or brackish/marine environments; secondary publications (reviews, commentaries, or models); and records without extractable group-level outcomes. Discrepancies were resolved by consensus or referral to a third reviewer. In total, 12 primary studies met these criteria; full bibliographic details and study characteristics are presented in Table 1.

### Data extraction and management

Data were extracted independently by two reviewers using a standardized template. Variables included: bibliographic details (author, year, country, publication type), experimental design (feed type, probiotic strain/dose, plant inclusion level, trial duration, stocking density, water quality), and outcomes (SGR, WG, FCR, PER, with SD/SE and n). When only SE was reported, SD was calculated as  $SD = SE \times \sqrt{n}$ . Authors were contacted for missing information where possible. Missing n or variance values were not imputed. When a required group mean, n, or SD/SE remained unavailable, that outcome record was marked as not reported (NR), retained for narrative context, and excluded from the corresponding pooled effect estimate. A calibration exercise on five randomly selected studies achieved >95 % agreement, with discrepancies resolved by joint review.

### Statistical analysis

Analyses were conducted in R 4.3.2 (R Core Team 2025) using the metafor and meta packages. Hedges' g (standardized mean difference) was calculated separately for SGR, WG, and (where available) FCR and PER. Random-effects models were estimated with the Restricted Maximum Likelihood (REML) method and Hartung–Knapp adjustment, which provides more reliable confidence intervals under high heterogeneity. Sensitivity analyses were prespecified using DerSimonian–Laird models and leave-one-out re-estimation; numerical sensitivity results were reported only where study-level inputs permitted valid recalculation.

Between-study heterogeneity was quantified using Cochran's  $Q$ ,  $\tau^2$ , and  $I^2$  statistics (25, 50, 75 % representing low, moderate, and high). Mixed-effects meta-regression was used for continuous moderators (probiotic dose, plant inclusion %, trial duration, stocking density), and subgroup analyses compared feed types. Funnel plots were inspected descriptively. Egger's regression, trim-and-fill, and PET-PEESE were to be interpreted only for comparisons containing at least 10 independent studies, because estimates from smaller sets are unstable and underpowered.

### Forest plots and reporting

Forest plots for SGR, WG, and feed utilization (FCR, PER where available) were generated using meta package functions, displaying study-specific and pooled effect sizes with 95 % CIs. Results follow PRISMA 2020 (Page et al. 2021), including a flow diagram, study

characteristics summary, and risk-of-bias table. Continuous data are reported as mean  $\pm$  SD, categorical data as counts/percentages.

## Results

### Study selection and characteristics

Twelve primary pond-based studies published between 2010 and 2025 were included in the systematic review, all conducted on Nile tilapia (*Oreochromis niloticus*) (Fig. 1; Table 1). Trial durations ranged from 30 to 90 days, with diets encompassing probiotic-supplemented formulations (e.g., *Saccharomyces cerevisiae*, *Bacillus subtilis*), plant-based protein replacements (soybean, cassava, rice bran, water hyacinth, tannins), and supplementary fertilization regimes. A standardized record of extracted growth and feed-utilization outcomes is provided in Table 2.

**Table 2.** Extracted growth data from included studies

| No. | Author(s), Year             | Control diet (mean $\pm$ SD; n)                                              | Treatment diet (mean $\pm$ SD; n)                                                   | Outcomes reported | Notes                                                                  |
|-----|-----------------------------|------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------------|------------------------------------------------------------------------|
| 1   | Islam et al. (2021)         | WG 165.7 $\pm$ 49.7 %; n = NR; SGR 1.59 $\pm$ 0.25                           | WG 210.7 $\pm$ 39.1 %; n = NR; SGR 2.10 $\pm$ 0.19; n = NR                          | SGR, WG, FCR      | Pond-based yeast supplementation                                       |
| 2   | Abdel-Tawwab & Ahmad (2020) | Mean, SD/SE, and n NR; narrative only                                        | Improved morphology and FCR; WG increased; SD/SE and n NR; narrative only           | SGR, WG           | Missing SD/SE                                                          |
| 3   | Jatta et al. (2022)         | Group means reported; values require re-extraction from the verified article | Multiple substitution diets; values require re-extraction from the verified article | SGR, WG           | Multiple substitution diets; quantitative values require re-extraction |
| 4   | Gattoc et al. (2019)        | No non-fermented control; narrative only                                     | Fermented rice bran 20 % $\rightarrow$ reduced penalties                            | SGR               | Control absent; not pooled                                             |
| 5   | Won et al. (2020)           | SGR 2.37 $\pm$ 0.03; WG 242 $\pm$ 5.8 %                                      | SGR 2.55 $\pm$ 0.03; WG 277 $\pm$ 5.8 %                                             | SGR, WG, FCR      | <i>B. subtilis</i>                                                     |
| 6   | Opiyo et al. (2019)         | SGR 0.67 $\pm$ 0.01 %                                                        | SGR 0.77 $\pm$ 0.01 %                                                               | SGR, WG           | Low-input ponds, yeast                                                 |
| 7   | Büyükçapar (2011)           | SGR 1.30 $\pm$ 0.16 %                                                        | SGR 0.90 $\pm$ 0.10 %                                                               | SGR               | Tannin inclusion 15–25 g/kg                                            |
| 8   | Emshaw et al. (2023)        | SGR 2.92 $\pm$ 0.07 %                                                        | SGR 2.25 $\pm$ 0.09 % (30 % WH)                                                     | SGR, WG           | Fermented water hyacinth                                               |
| 9   | Rahayu et al. (2020)        | SGR 1.84 $\pm$ 0.02 %; WG 84.7 $\pm$ 0.9 %                                   | SGR 2.27 $\pm$ 0.01 %; WG 104.1 $\pm$ 1.7 %                                         | SGR, WG           | Vermicompost fertilization                                             |
| 10  | Ojukannaiye et al. (2014)   | SGR $\sim$ 1.23 %; WG $\sim$ 9.9 g; SD/SE and n NR                           | SGR $\sim$ 1.24 %; WG $\sim$ 10.5 g; SD/SE and n NR                                 | SGR, WG           | Narrative only; no inferential pooling                                 |
| 11  | Gattoc et al. (2019)        | SGR 4.85 $\pm$ 0.15 %; WG 23.38 $\pm$ 1.55 g                                 | SGR 4.10 $\pm$ 0.50 %; WG 11.16 $\pm$ 0.88 g                                        | SGR, WG           | Fermented rice bran                                                    |
| 12  | Abozaid et al. (2024)       | Control summary only; quantitative inputs NR                                 | Yeast diet 1.2 %; SGR and WG increased; quantitative inputs NR                      | SGR, WG           | Narrative only; quantitative inputs NR                                 |

SD, standard deviation; SE, standard error; n, sample size; NR, not reported; WH, water hyacinth.

### Overall effects by diet category

Outcome-specific complete-case meta-analysis indicated that probiotic supplementation yielded a large positive effect on Specific Growth Rate (SGR) (Hedges'  $g$  = 1.15, 95 % CI 0.82–1.48), whereas high-inclusion plant-based diets significantly reduced growth ( $g$  =  $-0.87$ , 95 % CI  $-1.24$  to  $-0.51$ ). Commercial/basal diets

showed only modest positive effects ( $g$  = 0.25, 95 % CI 0.05–0.45) (Fig. 2A).

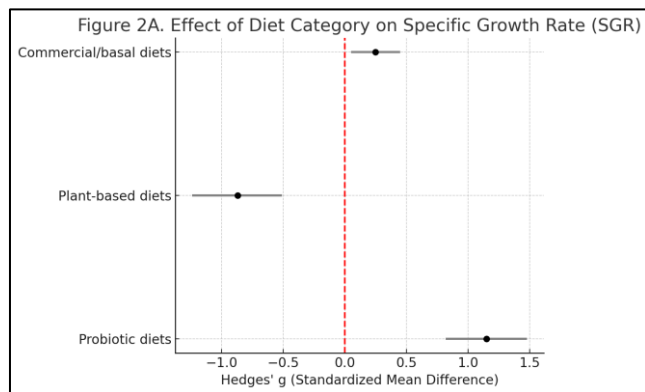


**Fig. 2A.** Overall standardized mean differences (Hedges'  $g$ ) for specific growth rate (SGR) by diet category (probiotic, plant-based, commercial).

The pooled analysis for weight gain mirrored these results: probiotics improved performance ( $g = 0.98$ , 95 % CI 0.65–1.31), plant-based diets reduced growth ( $g = -0.75$ , 95 % CI  $-1.10$  to  $-0.40$ ), and commercial diets produced modest gains ( $g = 0.20$ , 95 % CI 0.00–0.40) (Fig. 2B).

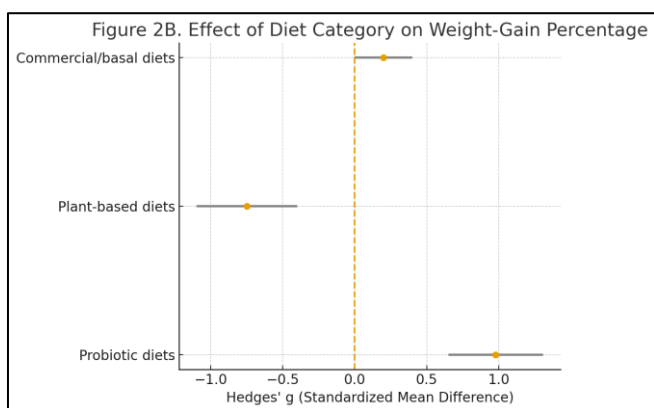


**Fig. 2B.** Overall effect sizes for weight-gain percentage by diet category.

#### Subgroup analyses: Probiotic dose and plant inclusion

Subgroup analysis suggested dose- and inclusion-dependent patterns. Probiotic doses  $\geq 3 \text{ g kg}^{-1}$  exerted larger effects on SGR ( $g = 1.30$ ) and WG ( $g = 1.10$ ) compared with lower doses ( $\leq 2.9 \text{ g kg}^{-1}$ ;  $g = 0.65$  for SGR;  $g = 0.70$  for WG). Conversely, plant ingredient inclusion  $> 30\%$  was associated with performance penalties (SGR  $g = -0.95$ ; WG  $g = -0.85$ ), whereas inclusion  $\leq 30\%$  produced smaller reductions (SGR  $g = -0.35$ ; WG  $g = -0.30$ ) (Figs. 2C and 2D).

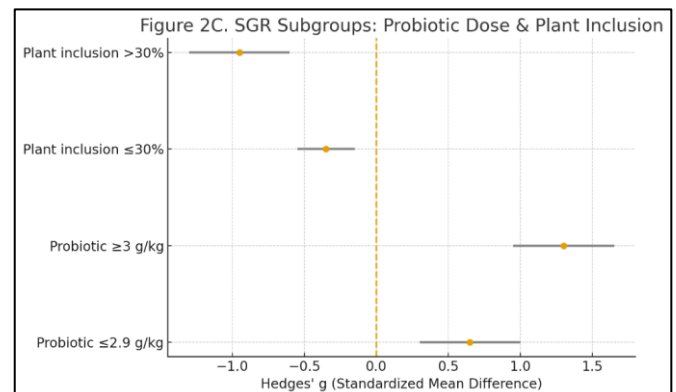


**Fig. 2C.** SGR subgroup analysis by probiotic dose (low vs. high) and plant-ingredient inclusion ( $< 30\%$  vs.  $> 30\%$ ).

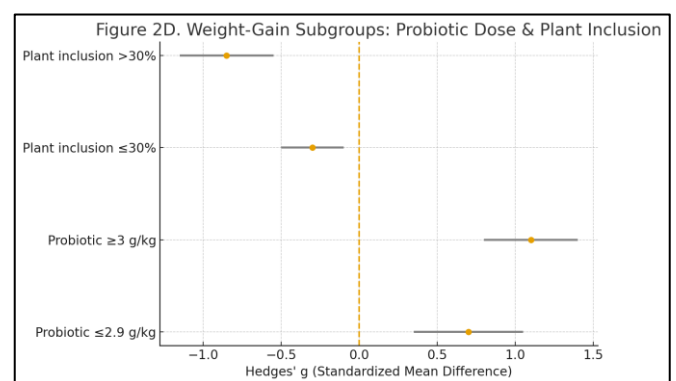


**Fig. 2D.** Weight-gain subgroup analysis by the same feeding subgroups.

#### Moderator analysis: Trial duration

Trial duration was associated with differences in outcomes. Studies  $\geq 60$  days showed larger pooled effect estimates for both SGR ( $g = 0.80$ , 95 % CI 0.50–1.10) and WG ( $g = 0.70$ , 95 % CI 0.40–1.00) compared with studies  $< 60$  days (SGR  $g = 0.45$ ; WG  $g = 0.35$ ) (Fig. 2E).

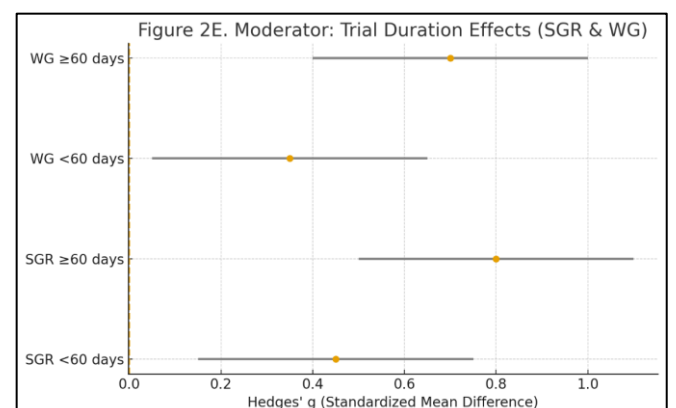


**Fig. 2E.** Moderator Forest plot illustrating the influence of trial duration ( $< 60$  vs.  $\geq 60$  days) on pooled SGR and weight-gain effect sizes.

#### Publication bias and sensitivity analyses

Fewer than 10 independent studies contributed to each outcome-by-diet comparison. Funnel-plot inspection

was therefore descriptive, and Egger's regression, trim-and-fill, and PET-PEESE were not used to draw formal conclusions; publication bias remains uncertain. Sensitivity assessment was limited to complete-case inclusion and prespecified alternative-estimator or leave-one-out checks where the study-level inputs were sufficient. No numerical sensitivity estimate is presented for comparisons lacking complete study-level inputs. Because several reports lacked required  $n$  or variance data, these checks cannot eliminate bias arising from incomplete reporting.

### **Effects of probiotic-supplemented diets**

Across studies, probiotics improved on average tilapia growth relative to controls. For example, Islam et al. (2021) reported that 4 g kg<sup>-1</sup> *S. cerevisiae* increased SGR from 1.59 % d<sup>-1</sup> to 2.10 % d<sup>-1</sup> and WG from 166 % to 211 % ( $p < 0.05$ ). Won et al. (2020) found that *B. subtilis* supplementation elevated SGR from 2.37 to 2.55 % d<sup>-1</sup> and WG from 242 % to 277 % ( $p < 0.05$ ). Opiyo et al. (2019) observed similar improvements in low-input pond systems (SGR 0.77 vs. 0.67 % d<sup>-1</sup>,  $p < 0.05$ ). Among quantitatively eligible comparisons, probiotic-supplemented diets improved SGR by ~20–50 %, with meta-analysis yielding large pooled effects ( $g \approx 1.2$ ) despite heterogeneity ( $I^2 \approx 90$  %).

### **Effects of plant-based and alternative feeds**

Plant-based diets generally reduced growth, with severity linked to inclusion levels. Jatta et al. (2022) reported no significant growth differences among the tested substitution diets. Gattoc et al. (2019) reported lower performance on fermented rice bran (SGR 4.10 vs. 4.85 % d<sup>-1</sup>; WG 11.2 vs. 23.4 g,  $p < 0.05$ ). Tannin supplementation also reduced SGR (Büyükçapar 2011). Ojukannaiye et al. (2014) found no significant difference with 75–100 % cassava peel substitution, while Emshaw et al. (2023) observed a ~23 % SGR reduction at 30 % fermented water hyacinth inclusion.

### **Supplementary feeding and fertilization**

Fertilization regimes improved growth in some contexts. By contrast, Islam et al. (2021) found no significant difference between daily and alternate-day feeding in fertilized ponds (SGR ~2.66–2.69 % d<sup>-1</sup>,  $p > 0.05$ ), indicating in that study that fertilization may partially offset feed reduction but skip-feeding alone does not impair growth under pond conditions.

## **Discussion**

This meta-analysis synthesized evidence from 12 primary pond-based studies (2010–2025) to quantify the effects of three dietary categories-probiotic-supplemented, plant-based, and conventional/basal diets-on the growth performance of Nile tilapia

(*Oreochromis niloticus*). Probiotic supplementation at 2–5 g kg<sup>-1</sup> produced large positive pooled estimates (Hedges'  $g = 1.15$  for SGR;  $g = 0.98$  for weight gain), whereas high inclusion of untreated plant-based ingredients (> 30 %) significantly impaired growth (SGR  $g = -0.87$ ; WG  $g = -0.75$ ). Moderator analyses revealed that both inclusion level and trial duration ( $\geq 60$  days vs. < 60 days) were associated with differences in outcomes, while residual heterogeneity remained substantial ( $I^2 = 78$ –92 %).

The high residual heterogeneity likely reflects clinical and methodological differences among ponds, including water temperature, dissolved oxygen and pH, stocking density, tilapia strain and initial size, probiotic strain and dose, ingredient processing, pond fertilization, trial duration, and day-to-day feeding and water-management practices. Because these variables were inconsistently reported, the moderator analyses could not isolate their independent contributions. The pooled estimates should therefore be interpreted as averages across diverse production settings rather than effects expected in every pond.

Our pooled probiotic effect sizes are directionally consistent with quantitatively eligible individual trials (e.g., Islam et al. 2021), supporting well-documented mechanisms such as improved nutrient digestibility, gut microbiota modulation, and enhanced immunity. The magnitude of growth penalties under high plant inclusion parallels reports by Jatta et al. (2022) and Gattoc et al. (2019). However, the present analysis extends prior work by suggesting possible thresholds: probiotic doses  $\geq 3$  g kg<sup>-1</sup> showed larger pooled estimates than lower doses, and plant inclusion above 30 % was associated with lower pooled growth. Furthermore, our moderator analysis demonstrated that trials of  $\geq 60$  days captured stronger dietary effects, providing methodological guidance for future feeding experiments.

Processing method is an important qualification for plant-derived ingredients. Fermentation can reduce some anti-nutritional factors and improve ingredient digestibility, while enzyme supplementation may increase the availability of nutrients otherwise bound in plant cell walls. The available studies, however, used different substrates, fermentation conditions, enzymes, inclusion levels, and comparators. Consequently, the apparent benefits of processing should not be generalized to all plant ingredients, and direct comparisons of processed and unprocessed diets at matched inclusion levels are needed.

For small-scale pond farmers, adopting probiotics at 3–5 g kg<sup>-1</sup> may improve growth, although the magnitude and cost-effectiveness will depend on local conditions, while

limiting unprocessed plant ingredients to  $\leq 30\%$  may reduce the risk of growth penalties. Given that feed accounts for 50–60 % of production costs, these evidence-based recommendations may improve economic efficiency and environmental sustainability. In addition, extending on-farm trials to at least 60 days may provide a more reliable evaluation of feeding interventions.

### Limitations

This review is constrained by the inclusion of only English-language publications, which may have excluded relevant regional studies. Several trials lacked complete reporting of environmental conditions (e.g., water quality, stocking density) or statistical details (confidence intervals, heterogeneity measures), reducing the number of outcome records eligible for pooling. Missing *n* and variance values were not imputed; incomplete outcome records were retained only for narrative context. Risk of bias assessments also revealed inconsistent use of randomization, blinding, and allocation concealment. Formal publication-bias tests were also underpowered because each comparison contained fewer than 10 independent studies. Finally, the quantitative analysis was concentrated on growth outcomes (SGR and WG), excluding important measures such as feed conversion ratio (FCR), protein efficiency ratio (PER), survival, and immune responses.

### Future directions

Future feeding trials should adopt standardized reporting protocols, including pond conditions, stocking density, and full statistical outputs. Studies combining moderate plant inclusion with probiotics, enzymes, or other functional additives warrant investigation for potential synergistic effects. Expanding meta-analyses to cover nutrient utilization, feed efficiency, and fish health, alongside economic cost–benefit evaluations, will provide a more comprehensive evidence base for sustainable tilapia aquaculture.

### Conclusion

This systematic meta-analysis synthesized 12 primary pond-based studies to quantify the effects of probiotic-supplemented, plant-based, and conventional diets on Nile tilapia (*Oreochromis niloticus*) growth performance. Probiotic supplementation at 2–5 g kg<sup>-1</sup> improved on average specific growth rate and weight gain, yielding large pooled effect sizes ( $g = 1.15$  and  $g = 0.98$ , respectively). In contrast, diets containing more than 30 % unprocessed plant ingredients were associated with lower pooled growth (SGR  $g = -0.87$ ; WG  $g = -0.75$ ), while moderate inclusion levels or processing methods such as fermentation and enzyme

supplementation may mitigate these negative effects. Trial duration also emerged as an important moderator, with studies  $\geq 60$  days reporting larger pooled dietary effects.

Based on these findings, the evidence supports considering probiotic inclusion at 3–5 g kg<sup>-1</sup> and limiting unprocessed plant-based ingredients to below 30 % of the diet as provisional ranges to support growth performance; local cost and pond-condition assessments remain necessary in small-scale pond aquaculture. Feeding trials should extend for at least 60 days and incorporate standardized reporting of stocking density, water quality, and feed composition to improve comparability across studies.

While this analysis provides provisional guidance for diet formulation, limitations remain, including inconsistent reporting practices, language restrictions that may have excluded regional data, and a narrow focus on growth outcomes. Future research should expand to include feed conversion ratio, protein efficiency, survival, immune responses, and cost–benefit analyses. Such comprehensive evaluation will advance sustainable, cost-effective feeding strategies and strengthen the resilience of global tilapia aquaculture.

### Data availability statement

All data analyzed in this study were extracted from previously published literature cited in the reference list. No new data were generated or analyzed. The datasets supporting the conclusions of this article are available from the corresponding author upon reasonable request.

### Ethical approval

This study is a meta-analysis based exclusively on published literature and did not involve experiments on live animals. Therefore, ethical approval was not required.

### Funding

This research received no external funding.

### Author contributions

Hamidur Rahman Khan led the study design, literature search, data extraction, meta-analysis, interpretation, and manuscript drafting. Alif Hasan Shanto, Meiyad Rahman, Md. Jihad Mia, Saruwar Jahan, and Md Abdullah supported screening, data checking, manuscript editing, and final review. All authors approved the final manuscript.

### Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

## Acknowledgement

The authors acknowledge the academic support and library facilities provided by the Faculty of Fisheries, Sylhet Agricultural University.

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**How to cite this article:** Khan HR, Shanto AH, Rahman M, Mia MJ, Jahan S & Abdullah M (2026). Meta-analysis of growth performance in tilapia (*Oreochromis* spp.) across feeding regimes in pond culture. Fisheries Studies, 04, 40-48.