



Global impact of antimicrobial growth promoters on livestock productivity: A meta-analysis for economic modeling[☆]

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ABSTRACT

The use of Antimicrobial Growth Promoters (AGPs) in livestock production is under increasing scrutiny due to concerns about Antimicrobial Resistance (AMR). However, the economic consequences of AGPs withdrawal remain insufficiently quantified, partly because globally representative estimates of their effects on productivity are lacking. This study addresses this gap through a systematic review and meta-analysis evaluating the impact of AGPs on broilers, pigs, and cattle across diverse production settings. Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, we screened 95 studies encompassing 128 trial observations published between 2000 and 2023, covering diverse geographic regions, income levels, and antimicrobial classes. Funnel plot analysis and Egger's test were used to detect publication bias. AGPs significantly improved Average Daily Gain (ADG) in broilers (1.78 g/day), pigs (28.15 g/day), and cattle (30 g/day); and improved Feed Conversion Ratio (FCR) in broilers (-0.05) and pigs (-0.09). Feed Efficiency (FE) in cattle also improved (0.0043). Regional differences in ADG improvement were notable in broilers. For broiler production, FCR effects varied significantly according to antimicrobial importance, with Critically Important Antimicrobials (CIAs) showing the largest effect sizes. The study revealed significant data gaps in the available scientific evidence, which limit the direct use of current findings for comprehensive economic modelling. Nevertheless, the results provide key parameters to inform the design of economic models assessing the costs and benefits of AGP withdrawal in livestock production systems.

1. Introduction

Recent projections indicate that global antibiotic use in livestock could increase by nearly 30% by 2040 if current practices continue, with significant implications for public health and sustainable animal production (Acosta et al., 2025). Against this backdrop, the use of Antimicrobial Growth Promoters (AGPs) has come under increasing scrutiny due to their contribution to antimicrobial resistance (AMR). In response, international organizations have called for restrictions on AGPs use. The Food and Agriculture Organization (FAO) has recommended limiting their use in animal agriculture (FAO, 2015), and the World Organisation for Animal Health (WOAH) has committed to phasing out antibiotics used solely for growth promotion (WOAH,

2016). More recently, the 2023 Codex Alimentarius Commission adopted global food safety and quality standards that directly address AGPs use in livestock systems (FAO, 2023). These policy developments reflect a growing international consensus on the need to balance livestock productivity with One Health objectives.

Despite this momentum, significant uncertainty remains regarding the economic implications of AGPs withdrawal. This uncertainty stems largely from the lack of globally representative productivity parameters that account for heterogeneity across production systems, animal species, and regional contexts. For example, global projections by Laxminarayan et al. (2015) estimate that banning AGPs could reduce meat production by 1.3–3%, based on species-specific assumptions of relative reductions in daily weight gain (ADG) ranging from 7% to 3% for cattle,

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9–1 % for pigs, and 4–0.7 % for poultry under high- and low-impact scenarios. While informative, these projections are based on fixed parameters that do not account for geographic, management, or antimicrobial class.

Previous meta-analyses have consistently demonstrated that AGPs enhance livestock performance; however, much of the evidence remains concentrated in high-income, high-biosecurity production systems. El-Fateh et al. (2024) pooled 42 broiler trials and reported a 2.8 % improvement in feed conversion ratio (FCR), yet over 80 % of the studies were conducted in Europe or the United States. Similarly, Cardinal et al. (2021) found a 6.5 % post-weaning weight gain advantage in pigs based on 103 trials drawn almost entirely from Brazil, the United States, and Western Europe. For cattle, Gadberry et al. (2022) synthesized 38 North American pasture-based trials and found that Monensin supplementation increased ADG by approximately 10.5 %, with no trials conducted in tropical systems.

This study contributes to broadening the empirical evidence on the productivity effects of AGPs by conducting a systematic and globally representative meta-analysis across broilers, pigs, and cattle. Unlike previous syntheses that tend to focus on single species or are primarily limited to high-income or temperate settings, this analysis draws on a diverse set of controlled trials spanning different geographic regions, income levels, and production systems, including low- and middle-

income countries (LMICs) and low-biosecurity environments. By estimating treatment effects systematically across species and contexts, the study aims to improve the consistency and applicability of productivity parameters used in economic models assessing the implications of AGPs reduction. In addition, it examines whether the classification of antimicrobials based on their importance to human medicine, as defined by the World Health Organization (WHO 2024), influences productivity outcomes, a dimension that has received limited attention in prior meta-analyses.

2. Methodology

2.1. Selection process

A systematic literature review was conducted to identify experimental studies evaluating the effects of AGPs on ADG and FCR in broilers, pigs, and cattle. The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021). To ensure the quality and relevance of the search strategy, the Population, Intervention, Comparison, Outcome (PICO) framework was applied, consistent with best practices for systematic reviews, including the Peer Review of Electronic Search Strategies (PRESS) approach (McGowan et al., 2016). The PICO criteria used in this

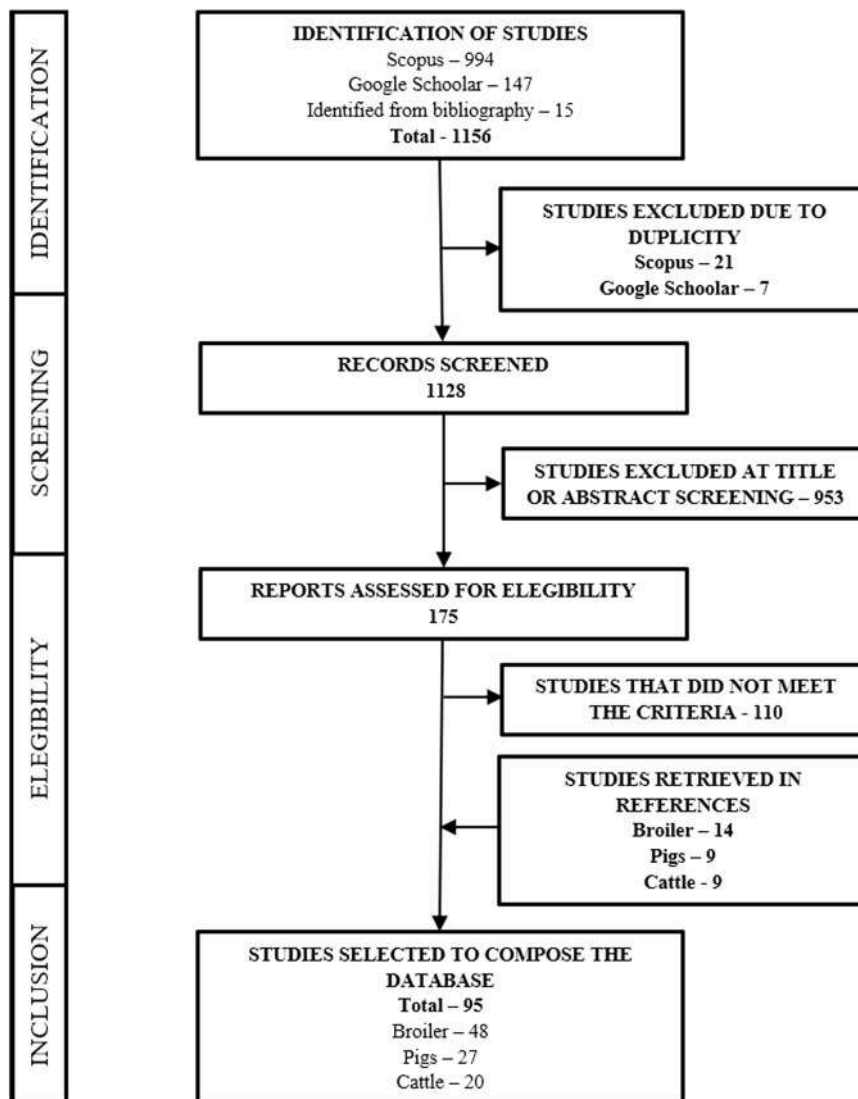


Fig. 1. PRISMA workflow diagram.

meta-analysis were as follows: Population (broilers, pigs, and cattle); Intervention (diet with AGPs); Comparison (diet without AGPs); Outcome (ADG, FCR and feed efficiency - FE). These criteria guided the formulation of research questions such as: “Does the use of AGPs improve livestock growth performance?”

The literature search was conducted in the Scopus database in October 2023. The complete search syntax is provided in [Annex 1](#). The study selection process is summarized in [Fig. 1](#).

The initial search used keywords such as “antibiotic growth promoter,” “antimicrobial growth promoters,” and “sub-therapeutic antibiotics,” combined with terms specific to livestock, including “swine,” “broiler,” and “cattle.” Boolean operators (“AND” and “OR”) were applied to enhance search efficiency. This process identified 994 articles in English.

To broaden the scope, additional studies were identified through:

- Bibliographic review: Examining references from the initially selected articles.
- Gray literature searches: Using Google Scholar to capture institutional reports and less formally published research (grey literature), following recommendations by [Haddaway et al. \(2015\)](#).
- Language expansion: Including studies published in Spanish and French to improve geographic representation.

The secondary search yielded 162 additional papers. A snowballing approach was also used by examining the reference lists of included studies, resulting in the identification of 32 additional articles.

2.2. Screening

After completing the search across databases, all studies were imported into a reference management tool (Mendeley) to facilitate duplicate removal and data organization. Articles were then tabulated in Excel for manual screening, which involved reviewing titles, abstracts, and full texts. Two independent researchers conducted the screening, and any disagreements were resolved through discussion. The selection process adhered to the following criteria:

Inclusion Criteria:

- Studies published between 2000 and 2023. This period was chosen to minimize the risk of bias from unobservable factors that may influence both the use of AGPs and, more importantly, livestock productivity, such as genetic improvements, policy changes, and institutional and regulatory shifts. Focusing on the last two decades ensures greater relevance to the current production context.
- Experimental studies reporting initial and final ADG (or total weight gain) and FCR or FE.
- Articles reporting *in vivo* experiments conducted on animals.
- Studies with both a control group (no AGPs) and a treatment group (with AGPs).
- Studies reporting both mean values and measures of variability (e.g., standard error of the mean, standard error, coefficient of variation, or standard deviation).

Exclusion Criteria:

- Studies examining non-AGPs additives, such as probiotics or essential oils, unless AGPs were also included in the treatment.
- Research with incomplete or inconsistent methodological reporting.
- Literature reviews or prior meta-analyses (e.g., [Cardinal et al., 2019; 2021](#)), as their inclusion could lead to overestimation or underestimation of the meta-analysis results due to overlapping data sources.
- Articles lacking dispersion statistics.

It is important to emphasize that during the study selection process, research involving health challenges (e.g., the presence of *Eimeria*, such

as in [Stanley et al., 2004](#)) was included only if experimental data from “healthy” livestock could be isolated. This allowed us to isolate the effects of AGPs on productivity, minimizing potential bias due to the animals' health status.

2.3. Database construction and data extraction

Following the screening, the selected articles were tabulated in a structured spreadsheet containing bibliographic information (author, title, publication year), methodological details (species, sex, treatment duration), and outcome data (ADG, FCR and FE). Cross-tabulation techniques were used, with variables organized in columns and observations in rows. Some studies included multiple treatment groups. In accordance with PRISMA guidelines — particularly Items 9 and 15 — each treatment was entered as a separate data point rather than averaged, allowing for more granular analysis ([Page et al., 2021](#)).

Data extraction was independently verified by two reviewers to minimize transcription errors and enhance reliability. Growth outcomes were originally reported using various units—such as total weight gain, ADG, and body weight before and after treatment—but were all converted to ADG for consistency and comparability across studies.

A full list of studies included in the meta-analysis is available in [Annex 2](#).

2.4. Risk of publication bias

The presence of publication bias was evaluated using a funnel plot, a scatter plot that depicts the effect size on the x-axis and the standard errors on the y-axis. A symmetric funnel plot suggests that the analysis is not substantially affected by publication bias, whereas asymmetry may indicate the selective reporting of significant results. To formally test for funnel plot asymmetry, the Egger test ([Egger et al., 1997](#)) was employed. This statistical test quantifies the degree of asymmetry and provides a p-value to assess the likelihood of bias.

In addition to examining publication bias, a certainty assessment was performed to evaluate the robustness and reliability of the findings. This assessment followed the GRADE framework ([Guyatt et al., 2008](#)) and was conducted using the GRADEpro tool ([Evidence Prime, Inc., 2024](#)).

Although GRADEpro is primarily used in clinical and public health research, we applied it to systematically assess the certainty of evidence across key outcomes in this meta-analysis. The assessment considered key factors such as:

- Study design: The methodological rigor of included studies.
- Consistency: The degree to which findings are similar across studies.
- Precision: The extent to which estimates are narrowly defined.
- Risk of bias: Potential methodological limitations that could influence results.

The combination of the funnel plot, Egger test, and certainty assessment ensures that the results of this meta-analysis are both transparent and reliable.

2.5. Meta-analysis

Data were extracted for both treated and control groups on the following variables: number of animals; ADG (g/day); FCR (feed intake/weight gain) for poultry and pigs; and FE (weight gain/feed intake) for cattle. These indicators were selected primarily due to data availability. For instance, ADG was used instead of total final body weight because it was more consistently reported across studies. Similarly, FCR was used for poultry and pigs, while FE was used for cattle, reflecting the standard metrics typically reported in studies of these species. FE is commonly used in ruminants as it directly reflects weight gain per unit of feed consumed, facilitating the selection of more productive animals. FCR, on the other hand, is preferred in non-ruminants because it practically

expresses the feed cost per kilogram of gain, which is essential in intensive systems.

When studies provided initial and final body weights, daily weight gain was calculated by subtracting the initial from the final weight to obtain total weight gain, then dividing by the number of days in the rearing period. For broiler studies that did not report the BW of the animals at the start of the experiment, all birds were assumed to weigh 45 g on day 1; this assumption allowed the calculation of ADG. Measures of variability (standard error, standard error of the mean, coefficient of variation) were recorded, and standard deviation was derived where necessary. When unit conversions (e.g., kg to g) were applied, corresponding adjustments to variability measures were made accordingly.

For broilers, data were collected for the total rearing period (typically 1–42 days). For pigs, both weaning and growing-finishing phases were included. For cattle, data were obtained from the growing-finishing period.

To evaluate each study individually, the relative improvement in ADG was calculated as a percentage, reflecting the performance gain associated with AGPs use.

2.5.1. Global meta-analysis

The overall effect of AGPs was estimated using the mean difference (MD) between treated and control groups. A random-effects model was adopted to account for variability between studies. Each study was weighted using the inverse variance method, and between-study variance (τ^2) was estimated via the restricted maximum-likelihood (REML) approach. 95 % confidence intervals (CI) were calculated for the overall MD, and heterogeneity was assessed using Higgins's Q test and the I^2 statistic. All analyses were conducted using RStudio software using the Meta packages (R Core team, 2024).

2.5.2. Subgroup meta-analysis

Subgroup analyses were conducted based on rearing phase, region, income level, antimicrobial classification, type of facility, and specific AGPs. This subgroup analysis was necessary to reduce the heterogeneity observed in the overall effect size. The selected subgroup categories were chosen because they were available in nearly all studies. Although other variables, such as indicators of biosecurity measures, could have provided insightful stratifications—particularly given their likely correlation with AGPs efficacy—such data were not consistently reported. The classification of AGPs by their importance for human medicine was included not only due to its widespread availability but also because it holds substantial policy relevance. Antimicrobials were categorized following WHO (2024) criteria into four groups: Critically Important, Highly Important, Important, and Not used in human medicine. For studies that employed more than one AGPs within the same treatment regimen, the overall classification was based on the molecule presenting the highest level of importance or risk ranking. This method ensured standardization by prioritizing the most critical antimicrobial used during the intervention period. International regulatory bodies, such as the Quadripartite, have strongly advocated for reducing the use of Critically Important Antimicrobials (CIAs) as an initial step towards AGPs-free production systems. The geographical location of each study was also recorded and classified by region, following the OECD-FAO *Agricultural Outlook* categories (Latin America and Caribbean, North America, Sub-Saharan Africa, Near East and North Africa, Asia Pacific, and Europe and Central Asia), as well as by income level (lower-middle income, upper-middle income, and high income). This framework was selected because it is widely applied in international economic analyses, including the AGLINK-COSIMO model, and ensures comparability with policy-oriented assessments. A random-effects model was employed for each subgroup, with heterogeneity assessed using Q tests (Q total) and I^2 statistics. Subgroup difference tests (Q between groups) were performed to evaluate whether AGPs effects varied significantly across categories.

2.5.3. Meta-regression analysis

To explore the sources of heterogeneity in the effect of antibiotic AGPs on animal ADG, mixed-effects meta-regression analyses were performed. Heterogeneity was assessed using Cochran's Q test and quantified by the I^2 statistic. The proportion of heterogeneity explained by the covariates included in the model was estimated using the R^2 index of the meta-regression.

Potential moderators investigated included geographical region and the importance of antimicrobials for human health. Income level and specific AGPs types were initially considered, but preliminary correlation analyses and data structure assessment revealed strong collinearity: income level was highly correlated with geographical region, and AGPs type with antimicrobial importance. Since these variables are categorical, we applied Chi-square tests and calculated Cramer's V to assess the strength of association. In both cases, Cramer's V exceeded 0.7, indicating a very high association. To avoid multicollinearity and maintain model interpretability, only region and antimicrobial importance were retained in the final models, as they represented key dimensions of potential variability.

Meta-regression analyses were implemented using the `metareg()` function from the `meta` package in R. Separate models were fitted for each animal species (broilers, pigs, and cattle) to assess species-specific variation in AGPs effects. The global meta-analysis object for each species—containing effect size estimates (mean differences) and their standard errors—served as input to the `metareg()` function. Between-study variance (τ^2) was estimated using the REML method, and statistical significance was set at $p < 0.05$.

3. Results

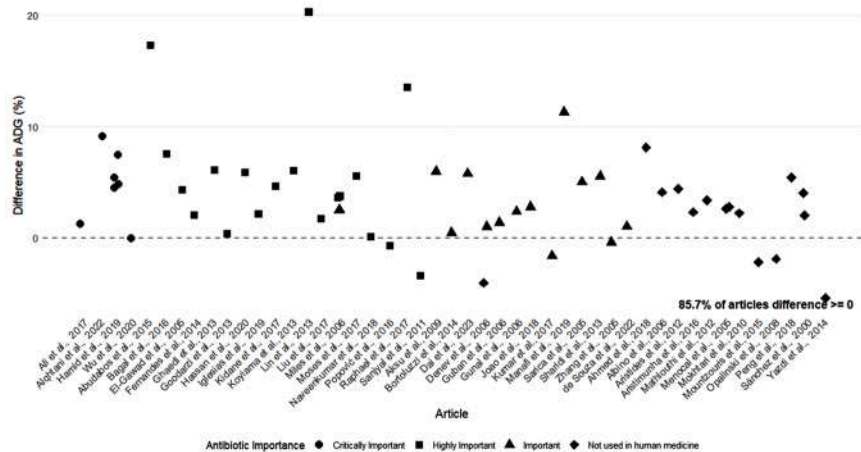
3.1. Results of the systematic review

A total of 95 studies, encompassing 128 trial observations, were included in the final analysis. These studies covered three major production systems: broilers (56 observations), pigs (32 observations), and cattle (40 observations). In terms of geographical distribution, the majority of studies originated from Asia Pacific and Latin America and Caribbean, both representing the largest shares at 31.6 %. These were followed by North America (16.8 %) and Europe and Central Asia (10.5 %). The regions with the fewest studies were Near East and North Africa (5.3 %) and Sub-Saharan Africa (4.2 %). In terms of income classification, studies were most frequently conducted in Upper-Middle-Income countries, which account for a combined share of 56.8 %. High-Income countries (HICs) represented 30.5 % of the studies, while Lower-Middle-Income countries accounted for 12.6 %.

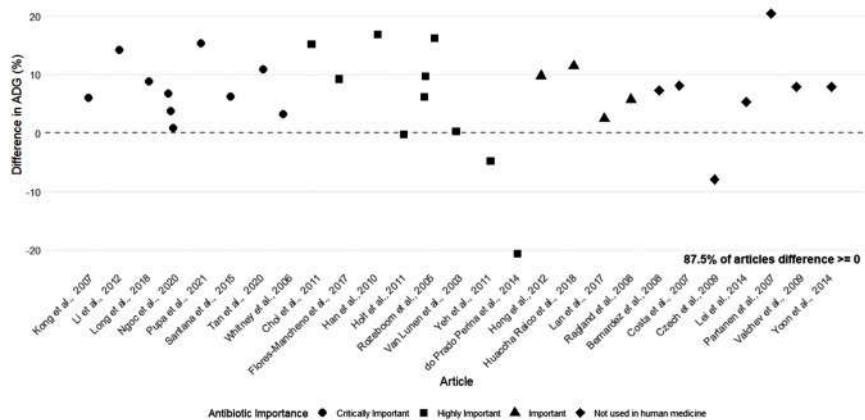
AGPs classified as Highly Important were the most frequently tested (37.1 %), followed closely by those Not used in human medicine (34.3 %). AGPs considered Important represented 17.1 % of the tested compounds, while those classified as CIA were the least frequently tested (11.4 %). In total, 22 AGPs were tested (Annex 3), with 14 in broiler trials, 13 in pigs trials, and 6 tested in cattle trials. The most frequently tested AGPs across studies were Virginiamycin (14.7 %), Avilamycin (14.7 %), Monensin (10.5 %), Colistin (9.4 %) and Bacitracin (8.4 %). By species, the most commonly tested AGPs in broilers were Avilamycin, Bacitracin, Flavomycin, and Virginiamycin; in pigs, Colistin, Avilamycin, and Tylosin were the most frequently used; while in cattle, Monensin and Virginiamycin were the most commonly tested.

Fig. 2 (panels a, b, and c) illustrates the overall impact of AGPs use on ADG in broilers, pigs, and cattle, respectively, categorized by WHO's classification of importance for human medicine. Each point represents an individual observation and indicates the percentage difference in ADG between animals receiving AGPs-supplemented diets and those under control (non-supplemented) conditions. In panel a (broilers), 85.7 % of the observations showed a non-negative effect (≥ 0 %) of AGPs on ADG. This proportion was 87.1 % for pigs (panel b) and 76.9 % for cattle (panel c).

(A) Broiler



(B) Pigs



(C) Cattle

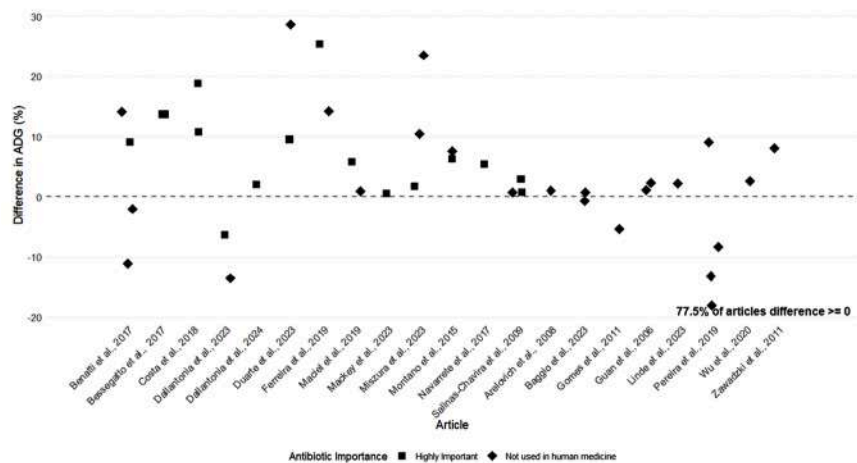


Fig. 2. Effects of AGPs on ADG (%) in different production systems: (A) Broilers, (B) Pigs, and (C) Cattle, according to the AGPs classification by importance for human health.

3.2. Risk of bias assessment and publication bias

Funnel plots (Figs. 3–5) for broilers, pigs, and cattle reveal relatively symmetrical distributions, aligning with the absence of substantial publication bias. Across all plots, panel (a) refers to ADG and panel (b) to FCR for broilers and pigs, and FE for cattle. In most cases, studies cluster in the upper sections of the funnels, indicating smaller standard errors and more precise estimates. Although a few outliers with higher standard errors appear—particularly for broiler and pig FCR—Egger’s test yielded *p*-values above 0.05, supporting the conclusion that statistically significant publication bias is unlikely.

The GRADE-based certainty assessment, detailed in the Summary of Findings table (Annex 4), further supports the robustness of the evidence across the three livestock categories. None of the core domains—risk of bias, inconsistency, indirectness, imprecision, or other considerations—were rated as serious, resulting in high-certainty rating for all species. This strengthens confidence in the reliability of the studies and generalizability of the meta-analysis results.

3.3. Meta-analysis results

Tables 1–3 present the ADG results for broilers, pigs, and cattle; Tables 4–7 present the FCR results for broilers and pigs, and the FE results for cattle. Forest plots are provided in Annex 5, along with graphical representations of the results in Table 1–6.

The meta-analysis of 56 observations for broilers (Table 1) showed a statistically significant positive effect of AGP use on ADG (MD = 1.78 g/day). However, heterogeneity among studies was substantial, indicating considerable variability in effect sizes across trials.

Regional differences in AGPs effects on ADG were statistically significant (Q between groups = 30.11, *p* < 0.0001), suggesting that the magnitude of impact varied notably by location. The largest increase in ADG was observed in Sub-Saharan Africa, followed by Near East and North Africa and North America. In Latin America and Caribbean and Asia Pacific, the effect was positive. In Europe and Central Asia, a positive effect was observed, but the 95 % confidence interval crossed the null value, indicating a non-significant result. Differences in AGPs effects by income level were not statistically significant (Q between groups = 0.63, *p* = 0.7283), indicating that while AGPs may influence ADG within income groups, the effect magnitudes do not differ substantially across income categories. In contrast, statistically significant differences were found in the classifications of antibiotic importance (Q between groups = 8.05, *p* = 0.0450), as well as in the type of AGP (Q between groups = 675.82, *p* < 0.001). Non-significant differences were found in relation to housing systems (Q between groups = 0.65, *p* = 0.4217).

Regarding individual AGPs, Colistin was associated with a high weight gain, while Virginiamycin also showed a positive and significant effect. Bacitracin, although associated with a smaller weight gain, did

not show a statistically significant effect.

The meta-analysis of 32 observations for pigs (Table 2) revealed a statistically significant positive effect of AGPs on ADG (MD = 28.15 g/day). Heterogeneity across studies was moderate, suggesting some variation in effect sizes. The test for differences between rearing phases (weaned pigs vs. grower-finisher phase) was not statistically significant (Q between groups = 0.58, *p* = 0.4465), indicating that AGPs effects on ADG did not differ substantially between these groups. For weaned pigs, the mean effect was 27.43 g/day with an associated heterogeneity of 50.9 %, while in grower-finisher phase, the effect reached 37.54 g/day with heterogeneity at 39.7 %.

Subgroup analysis by region did not reveal statistically significant differences (Q between groups = 2.78, *p* = 0.4276), suggesting a consistent AGPs effect across geographic settings. The highest mean effect was observed in Asia Pacific, followed by Europe and Central Asia, Latin America and Caribbean, and North America.

Income-level differences were also non-significant (Q between groups = 0.02, *p* = 0.9005), with similar effects in upper-middle-income countries and high-income countries. Likewise, no significant variation was detected across categories of antimicrobial importance (Q between groups = 2.22, *p* = 0.5287), suggesting that the WHO classification had limited explanatory power in this subgroup.

In contrast, the test for differences among AGPs subgroups was statistically significant (Q between groups = 24.63, *p* = 0.0167), indicating that the impact of AGPs molecule choice influences the magnitude of ADG effects. Notably, Colistin, Tylosin, and Avilamycin exhibited positive effects. These three agents were the most frequently studied, and therefore only their individual results are reported here.

The meta-analysis based on 40 observations for cattle (Table 3) revealed a statistically significant positive effect of AGPs on ADG (MD = 30 g/day). Heterogeneity among studies was moderate, indicating some variability in effect sizes across trials. Subgroup analysis by geographical region showed slight differences in AGPs effects, with a mean ADG increase of 30 g/day in Latin America and Caribbean and 20 g/day in North America. However, the test for regional differences was not statistically significant (Q between groups = 0.48, *P* = 0.9236), suggesting that the effect did not differ meaningfully across regions. When stratified by income level, AGPs were associated with an increase of 30 g/day in upper-middle-income countries and 20 g/day in high-income countries. Again, subgroup differences were not statistically significant (Q between groups = 0.42, *p* = 0.5165), indicating no meaningful variation across income groups.

Regarding antimicrobial importance, AGPs classified as Highly Important showed a mean effect of 50 g/day, while those not used in human medicine had a smaller effect of 10 g/day. Despite these differences, the test for subgroup variation was not statistically significant (Q between groups = 1.41, *p* = 0.2355), implying that categorical classification alone did not explain observed differences in ADG.

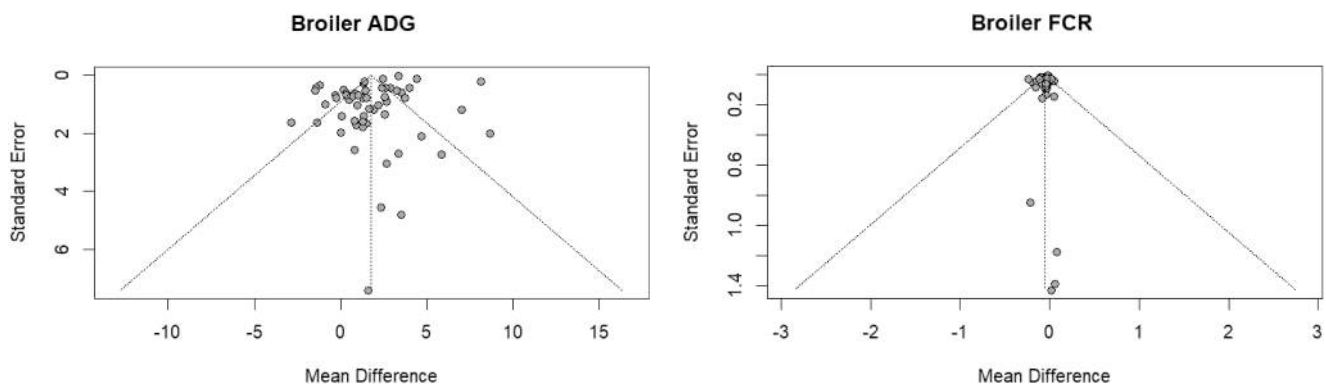


Fig. 3. (a). Funnel plot showing the distribution of studies (points) on the effect of AGPs on ADG and their standard errors in broilers. (b). Funnel plot showing the distribution of studies (points) on the effect of AGPs on FCR and their standard errors in broilers.

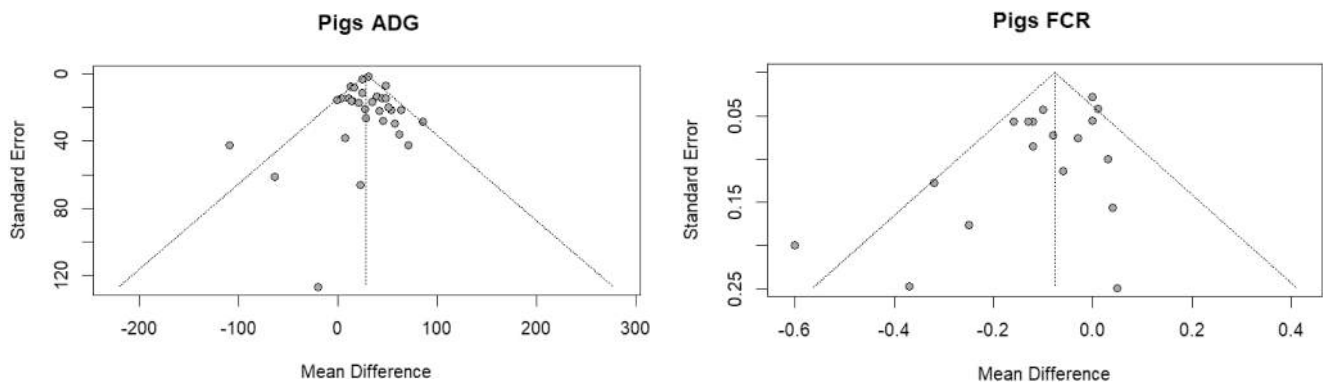


Fig. 4. a. Funnel plot showing the distribution of studies (points) on the effect of AGPs on ADG and their standard errors in pigs. (b). Funnel plot showing the distribution of studies (points) on the effect of AGPs on FCR and their standard errors in pigs.

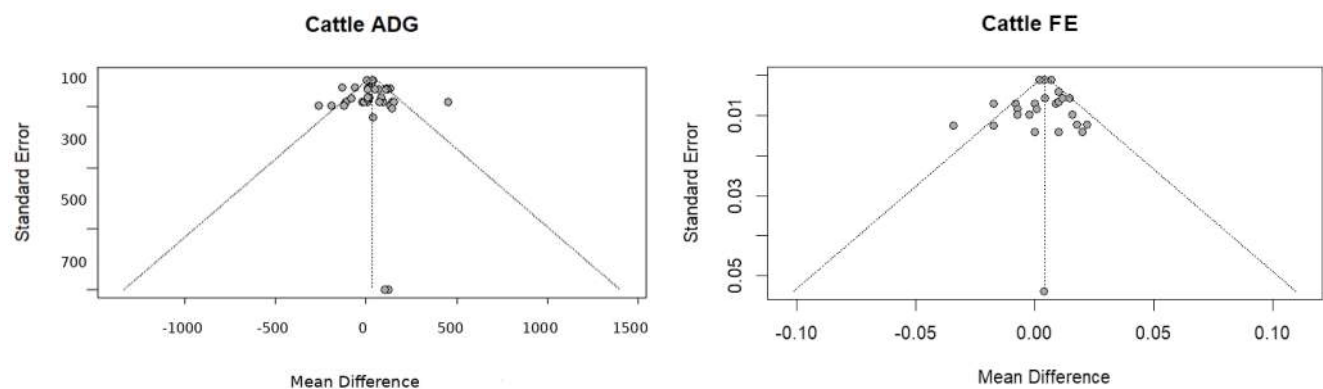


Fig. 5. (a). Funnel plot showing the distribution of studies (points) on the effect of AGPs on ADG and their standard errors in cattle. (b). Funnel plot showing the distribution of studies (points) on the effect of AGPs on FE and their standard errors in cattle.

Analysis by AGPs type revealed that Virginiamycin was associated with the largest gain, whereas Monensin had an effect close to zero. Other AGPs such as Narasin, Salinomycin, Lasalocid, and Tylosin were evaluated, albeit in a smaller number of studies. The test for subgroup differences by AGPs type was not statistically significant (Q between groups = 3.03, $p = 0.6947$), suggesting that individual molecule effects did not differ systematically across the limited sample.

The meta-analysis based on 49 observations for broiler (Table 4) demonstrated a statistically significant overall effect of AGPs use on FCR ($MD = -0.05$). Substantial heterogeneity was observed, indicating considerable variability in AGPs responses across different settings. The test for regional differences was statistical significant (Q between groups = 46.90, $p < 0.0001$), region-specific estimates showed a small but significant reduction in FCR in Latin America and Caribbean, Asia Pacific, and Europe and Central Asia. In Sub-Saharan Africa, a large significant reduction was observed, accompanied by low heterogeneity. These findings suggest a generally consistent direction of AGPs effects on FCR across regions, though the magnitude of the effect varies.

Subgroup analysis by income level did not yield statistically significant differences (Q between groups = 0.02, $p = 0.9914$). Nonetheless, within-income groups, small but significant reductions were observed in upper-middle-income countries and high-income countries. In contrast, differences by antimicrobial importance were statistically significant (Q between groups = 17.51, $p = 0.0006$), suggesting that AGPs effectiveness may vary with antimicrobial classification. A moderate reduction in FCR was observed for CIAs, along with significant but small reductions

for Highly Important antibiotics, and agents not used in human medicine.

Subgroup analysis by AGPs type also revealed statistically significant variation (Q between groups = 33.76, $p = 0.0007$). Colistin and Avilamycin were associated with moderate reductions in FCR, while Enramycin and Flavomycin showed smaller but still significant effects. Finally, no statistically significant differences were found based on housing system (Q between groups = 0.90, $p = 0.3429$).

The meta-analysis based on 18 observations for pigs (Table 5) showed a significant overall effect of AGPs use on FCR ($MD = -0.09$). Moderate heterogeneity was observed, indicating substantial variability in AGPs effects across different contexts. It is worth noting that many studies reported the gain-to-feed ratio rather than FCR (feed-to-gain), limiting the inclusion of some available data.

The test for regional differences revealed statistically significant variation in AGPs effects on FCR (Q between groups = 7.25, $p = 0.0466$). Regional analyses showed a small reduction in Asia Pacific and Latin America and Caribbean, both associated with low heterogeneity. In Europe and Central Asia, a larger reduction was also observed, although accompanied by high heterogeneity. In contrast, subgroup analysis based on income level was not statistically significant (Q between groups = 3.59, $p = 0.0582$). Within income categories, small reductions in FCR were noted in upper-middle-income countries and high-income countries.

The effect of AGPs according to its classification for human health showed no statistically significant variation (Q between groups = 5.37,

Table 1
Summary of the meta-analysis of the effect of AGPs on broiler daily weight gain (ADG; g/day).

| Sample ADG | N ¹ | Effect (g/day) | C. I. ² [95 %] | C.I. [95 %] | I ² * (%) | Q ³ (p-value) |
|-----------------------------|----------------|----------------|---------------------------|-------------|----------------------|--------------------------|
| Global | 56 | 1.78 | 1.18 | 2.38 | 96.5 | 1574.84 (<0.001) |
| Latin America and Caribbean | 13 | 1.18 | 0.38 | 1.98 | 82.4 | |
| North America | 9 | 1.84 | -0.05 | 3.74 | 97.8 | |
| Sub-Saharan Africa | 3 | 6.37 | 4.39 | 8.35 | 0.0 | |
| Near East and North Africa | 5 | 3.62 | 1.52 | 5.72 | 70.8 | |
| Asia Pacific | 18 | 1.73 | 0.79 | 2.66 | 95.1 | |
| Europe and Central Asia | 8 | 0.44 | -0.81 | 1.69 | 71.1 | |
| Lower-middle income | 12 | 2.30 | 0.79 | 3.81 | 94.1 | |
| Upper-middle income | 29 | 1.65 | 1.07 | 2.22 | 94.6 | |
| High income | 15 | 1.78 | 0.15 | 3.41 | 98.0 | |
| Critically important | 7 | 2.59 | 1.69 | 3.49 | 68.8 | |
| Highly important | 19 | 2.48 | 1.23 | 3.72 | 98.1 | |
| Important | 15 | 1.38 | 0.57 | 2.18 | 87.0 | |
| Not used in humans | 15 | 0.81 | -0.33 | 1.94 | 97.0 | |
| Bacitracin | 8 | 0.41 | -0.27 | 1.08 | 11.0 | |
| Colistin | 7 | 2.59 | 1.69 | 3.49 | 68.8 | |
| Enramycin | 5 | 1.77 | 0.75 | 2.80 | 69.8 | |
| Flavomycin | 7 | 2.18 | 1.13 | 3.23 | 78.6 | |
| Virginiamycin | 5 | 1.85 | 0.53 | 3.16 | 83.7 | |
| Cage | 41 | 1.64 | 0.91 | 2.37 | 96.9 | |
| Pen | 15 | 2.14 | 1.15 | 3.14 | 90.0 | |

Note: All effects refer to weight gain (grams per day) in the Total rearing period (1–42 days). ¹N: Total number of effect sizes included in the meta-analysis for each subgroup. ²C.I. [95 %]: Lower and upper bounds of the 95 % confidence interval for the mean difference. ³Q (p-value): Result of the Q test for total heterogeneity, with the corresponding p-value. ⁴I² (%): Percentage of total variation due to heterogeneity (I-squared statistic).

Table 2
Summary of the meta-analysis of the effect of AGPs on pigs daily weight gain (ADG; g/day).

| Sample ADG | N ¹ | Effect (g/day) | C. I. ² [95 %] | C.I. [95 %] | I ² * (%) | Q ³ (p-value) |
|-----------------------------|----------------|----------------|---------------------------|-------------|----------------------|--------------------------|
| Global | 32 | 28.15 | 21.52 | 34.77 | 47.3 | 58.87 (<0.001) |
| Weaned | 25 | 27.43 | 20.64 | 34.22 | 50.9 | |
| Grow and Finishing | 7 | 37.54 | 12.42 | 62.65 | 39.7 | |
| Latin America and Caribbean | 6 | 21.56 | -11.92 | 55.04 | 66.9 | |
| North America | 7 | 20.70 | 7.23 | 34.17 | 42.4 | |
| Asia Pacific | 16 | 33.69 | 24.11 | 42.28 | 33.2 | |
| Europe and Central Asia | 3 | 30.77 | 28.41 | 33.12 | 36.7 | |
| Upper-middle income | 17 | 29.01 | 16.89 | 41.12 | 41.0 | |
| High income | 15 | 28.07 | 19.90 | 36.25 | 53.6 | |
| Critically important | 10 | 31.54 | 16.47 | 46.62 | 32.0 | |
| Highly important | 10 | 27.22 | 8.10 | 46.33 | 68.5 | |
| Important | 4 | 17.89 | 4.49 | 31.29 | 9.3 | |
| Not used in humans | 8 | 27.83 | 22.43 | 33.23 | 18.4 | |
| Colistin | 7 | 28.52 | 9.85 | 47.19 | 12.0 | |
| Tylosin | 4 | 29.53 | 8.35 | 50.71 | 52.5 | |
| Avilamycin | 4 | 28.16 | 21.78 | 34.53 | 57.0 | |

¹N: Total number of effect sizes included in the meta-analysis for each subgroup. ²C.I. [95 %]: Lower and upper bounds of the 95 % confidence interval for the mean difference. ³Q (p-value): Result of the Q test for total heterogeneity, with the corresponding p-value. ⁴I² (%): Percentage of total variation due to heterogeneity (I-squared statistic).

Table 3
Summary of the meta-analysis of the effect of AGPs on cattle daily weight gain (ADG; g/day).

| Sample ADG | N ¹ | Effect (g/day) | C. I. ² [95 %] | C.I. [95 %] | I ² * (%) | Q ³ (p-value) |
|-----------------------------|----------------|----------------|---------------------------|-------------|----------------------|--------------------------|
| Global | 40 | 30.00 | 0.00 | 60.00 | 61.9 | 102.25 (<0.001) |
| North America | 9 | 20.00 | 0.00 | 40.00 | 0.0 | |
| Latin America and Caribbean | 29 | 30.00 | -10.00 | 80.00 | 71.4 | |
| Upper-middle income | 31 | 30.00 | 0.00 | 70.00 | 69.4 | |
| High income | 9 | 20.00 | 0.00 | 40.00 | 4.10 | |
| Important | 16 | 50.00 | 20.00 | 80.00 | 44.8 | |
| Not used in humans | 24 | 10.00 | -40.00 | 60.00 | 67.3 | |
| Monensin | 19 | 0.00 | -60.00 | 70.00 | 71.1 | |
| Virginiamycin | 15 | 50.00 | 20.00 | 80.00 | 47.9 | |

Note: All effects refer to weight gain (g per day) in the grow and finishing phases. ¹N: Total number of effect sizes included in the meta-analysis for each subgroup. ²C.I. [95 %]: Lower and upper bounds of the 95 % confidence interval for the mean difference. ³Q (p-value): Result of the Q test for heterogeneity, with the corresponding p-value. ⁴I² (%): Percentage of total variation due to heterogeneity (I-squared statistic).

Table 4
Summary of the meta-analysis on the effect of AGPs on broiler FCR (FCR; g:g).

| Sample FCR | N ¹ | Effect (g:g) | C. I. ² [95 %] | C.I. [95 %] | I ² * (%) | Q ³ (p-value) |
|-----------------------------|----------------|--------------|---------------------------|-------------|----------------------|--------------------------|
| Global | 49 | -0.050 | -0.06 | -0.03 | 77.0 | 208.73 (<0.001) |
| Latin America and Caribbean | 13 | -0.04 | -0.06 | -0.02 | 58.8 | |
| North America | 4 | -0.03 | -0.08 | -0.00 | 80.9 | |
| Sub-Saharan Africa | 3 | -0.24 | -0.30 | -0.18 | 0.00 | |
| Near East and North Africa | 4 | -0.05 | -0.09 | -0.01 | 77.9 | |
| Asia Pacific | 18 | -0.04 | -0.07 | -0.02 | 61.1 | |
| Europe and Central Asia | 7 | -0.06 | -0.12 | -0.02 | 74.0 | |
| Lower-middle income | 11 | -0.04 | -0.11 | 0.01 | 82.7 | |
| Upper-middle income | 29 | -0.04 | -0.06 | -0.03 | 72.1 | |
| High income | 9 | -0.04 | -0.08 | -0.02 | 79.8 | |
| Critically important | 7 | -0.06 | -0.09 | -0.04 | 73.3 | |
| Highly important | 16 | -0.05 | -0.09 | -0.01 | 86.3 | |
| Important | 12 | -0.01 | -0.03 | -0.00 | 23.7 | |
| Not used in humans | 14 | -0.06 | -0.08 | -0.04 | 0.00 | |
| Bacitracin | 5 | -0.01 | -0.04 | 0.00 | 22.8 | |
| Colistin | 7 | -0.06 | -0.09 | -0.04 | 73.3 | |
| Enramycin | 5 | -0.03 | -0.07 | -0.00 | 78.0 | |
| Flavomycin | 7 | -0.03 | -0.05 | 0.02 | 34.3 | |
| Virginiamycin | 4 | -0.01 | -0.05 | 0.02 | 0.00 | |
| Avilamycin | 10 | -0.06 | -0.09 | -0.04 | 0.00 | |
| Cage | 15 | -0.04 | -0.06 | -0.02 | 70.0 | |
| Pen | 34 | -0.05 | -0.08 | -0.03 | 79.6 | |

Note: All effects refer to FCR in the total rearing period (1–42 days). ¹N: Total number of effect sizes included in the meta-analysis for each subgroup. ²C.I. [95 %]: Lower and upper bounds of the 95 % confidence interval for the mean difference. ³Q (p-value): Result of the Q test for total heterogeneity, with the corresponding p-value. ⁴I² (%): Percentage of total variation due to heterogeneity (I-squared statistic).

p = 0.1467). Small reductions in FCR were reported for CIA, Highly Important, and Not used in human medicine antibiotics. Among specific AGPs, Colistin and Avilamycin were associated with reductions in FCR. It's necessary to note that the number of observations for individual molecules is low, and more studies are needed to improve the statistical

Table 5
Summary of the meta-analysis on the effect of AGPs on pigs FCR (FCR; g:g).

| Sample | N ¹ | Effect (g:g) | C. I. ² [95 %] | C.I. [95 %] | I ² * (%) | Q ³ (p-value) |
|-----------------------------|----------------|--------------|---------------------------|-------------|----------------------|--------------------------|
| Global | 18 | -0.09 | -0.12 | -0.03 | 45.5 | 21.20 (0.0189) |
| Asia Pacific | 9 | -0.07 | -0.12 | -0.01 | 16.6 | |
| Europe and Central Asia | 3 | -0.024 | -0.61 | 0.12 | 76.6 | |
| Latin America and Caribbean | 4 | -0.12 | -0.20 | -0.04 | 34.4 | |
| Upper-middle income | 11 | -0.10 | -0.15 | -0.04 | 41.1 | |
| High income | 7 | -0.02 | -0.08 | 0.03 | 49.4 | |
| Critically important | 5 | -0.11 | -0.17 | -0.06 | 0.0 | |
| Highly important | 3 | -0.03 | -0.12 | 0.05 | 0.0 | |
| Important | 4 | -0.03 | -0.12 | 0.05 | 58.7 | |
| Not used in humans | 6 | -0.21 | -0.39 | -0.02 | 62.8 | |
| Colistin | 4 | -0.11 | -0.17 | -0.05 | 0.0 | |
| Avilamycin | 3 | -0.24 | -0.60 | 0.12 | 76.6 | |

¹N: Total number of effect sizes included in the meta-analysis for each subgroup. ²C.I. [95 %]: Lower and upper bounds of the 95 % confidence interval for the mean difference. ³Q (p-value): Result of the Q test for heterogeneity, with the corresponding p-value. *I² (%): Percentage of total variation due to heterogeneity (I-squared statistic).

Table 6
Summary of the meta-analysis on the effect of AGPs on cattle FE (FE; g:g).

| Sample FE | N ¹ | Effect (g:g) | C. I. ² [95 %] | C.I. [95 %] | I ² * (%) | Q ³ (p-value) |
|-----------------------------|----------------|--------------|---------------------------|-------------|----------------------|--------------------------|
| Global | 26 | 0.0043 | 0.0020 | 0.0065 | 52.9 | 53.06 (<0.001) |
| Latin America and Caribbean | 18 | 0.0008 | -0.0050 | 0.0066 | 53.3 | |
| North America | 7 | 0.0052 | 0.0025 | 0.0079 | 57.8 | |
| Upper-middle income | 19 | 0.0014 | -0.0041 | 0.0069 | 52.4 | |
| High income | 7 | 0.0052 | 0.0025 | 0.0079 | 57.8 | |
| Highly Important | 10 | 0.0056 | 0.0030 | 0.0082 | 50.4 | |
| Not used in humans | 16 | 0.0027 | -0.0025 | 0.0079 | 47.9 | |
| Monensin | 13 | 0.0010 | -0.0045 | 0.0065 | 37.8 | |
| Virginiamycin | 9 | 0.0052 | 0.0024 | 0.0079 | 52.8 | |

Note: All effects refer to the FE (g of gain/g of feed intake) in the grow and finishing phases. ¹N: Total number of effect sizes included in the meta-analysis for each subgroup. ²C.I. [95 %]: Lower and upper bounds of the 95 % confidence interval for the mean difference. ³Q (p-value): Result of the Q test for heterogeneity, with the corresponding p-value. *I² (%): Percentage of total variation due to heterogeneity (I-squared statistic).

precision of the results.

The meta-analysis based on 26 observations for cattle (Table 6) revealed a significant overall effect of AGPs use on FE (MD = 0.0043), where FE is defined as the ratio of weight gain to feed intake. Moderate heterogeneity was observed across studies.

The test for regional differences did not reach statistical significance (Q between groups = 2.56, p = 0.2777). Nonetheless, region-specific analyses indicated a very small positive effect in Latin America and Caribbean and a small positive effect in North America, although with high heterogeneity. Similarly, subgroup analysis by income level showed no statistically significant differences (Q between groups = 1.46, p = 0.2262). Within income groups, a small positive effect was

Table 7
Meta-regression results related to study characteristics on AGPs efficiency in weight gain - Broilers and Pigs - g/day; Cattle - g/day.

| | Broilers | Pigs | Cattle |
|-----------------------------|---------------|-----------------|----------------|
| Intercept | 2.34** (0.80) | 36.06*** (7.41) | 70.00 (80.00) |
| Europe and Central Asia | -0.75 (1.02) | 4.47 (10.76) | - |
| Near East and North Africa | 0.07 (0.90) | - | - |
| Latin America and Caribbean | - | -13.3 (9.73) | -10.00 (80.00) |
| North America | 1.75 (1.18) | -19.24* (9.13) | -30.00 (80.00) |
| Sub-Saharan Africa | 4.25* (1.72) | - | 10.00 (170.00) |
| Highly Important | -0.61 (1.02) | 7.88 (9.68) | - |
| Important | -1.03 (1.12) | -4.19 (12.06) | - |
| Not Used in Human Medicine | -1.46 (1.14) | -9.55 (9.47) | -47.00 (30.00) |
| R squared | 10.6 % | 27.5 % | 3.0 % |
| N | 56 | 32 | 40 |

Note: Marginal effects are reported, with standard errors in parentheses. *, **, and *** denote significance at the 0.10, 0.05, and 0.01 levels, respectively.

observed in upper-middle-income and high-income countries.

The classification of antibiotic importance did not significantly explain the variability in AGPs effects on FE (Q between groups = 0.93, p = 0.3351). However, small positive effects on FE were noted for antimicrobials classified as Highly Important and for those not used in human medicine. Among specific AGPs, Monensin and Virginiamycin were associated with small improvements in FE.

3.4. Meta-regression analysis

Meta-regression analyses were performed to evaluate the contribution of geographical region and antimicrobial importance to the heterogeneity in AGPs effects across broilers, pigs, and cattle (Table 7).

For broilers (N = 56), the model showed a significant positive overall effect of AGPs on weight gain (Intercept: 2.35, p = 0.0032). The only statistically significant moderating variable was the Sub-Saharan Africa region, indicating a substantial increase in AGP efficacy in that area. Despite this, the set of moderators explains only 10.57 % of the total observed heterogeneity. The model retains very high and significant residual heterogeneity (I² = 91.6 %, p < 0.0001).

For pigs (N = 32), the model showed a highly significant positive overall effect of AGPs on weight gain (Intercept: 36.06, p < 0.0001). The only statistically significant moderating variable was the North America region, indicating a substantial effect on AGP efficacy in that area, compared to the reference region (Asia Pacific). The set of tested moderators (Region and Antimicrobial Importance) explained 27.51 % of the total observed heterogeneity. Despite this, the model retained moderate and significant residual heterogeneity.

For cattle (N = 40), the model showed no statistically significant overall effect of AGPs on weight gain (Intercept: 70, p = 0.3599). The test of moderators was also not statistically significant. Consequently, no individual moderating variable (Region or Antimicrobial Importance) was statistically significant in explaining the variability of AGPs effects. The set of tested moderators explained 3.0 % of the total observed heterogeneity.

4. Discussion

This study offers a globally representative quantitative assessment of the effects of AGPs on livestock productivity. Through a systematic meta-analysis of 95 studies, we estimate the impact of AGPs on ADG, FCR, and FE in broilers, pigs, and cattle. Beyond estimating average effects, we explore how AGPs efficacy varies across geographic regions, income levels, and production systems, and examine whether antimicrobial classification, as defined by the WHO, influences productivity outcomes across species.

The meta-analysis encompasses 128 trial observations, with 43.8 % observations from broilers, 25.0 % from pigs, and 31.2 % from cattle. A large proportion of studies were conducted in Asia Pacific and Latin America and Caribbean, with fewer contributions from Near East and North Africa and Sub-Saharan Africa. Over half of the studies originated in upper-middle-income countries. Among the 22 AGPs evaluated, the most frequently studied compounds were Virginiamycin, Avilamycin, Monensin, Bacitracin, and Colistin. According to WHO classification, 34.3 % of AGPs were not used in human medicine, while 65.7 % were deemed CIAs.

Across species, AGPs use was consistently associated with improvements in productivity, although effect sizes varied by context. In broilers, AGPs increased ADG by 1.78 g/day and improved FCR by 0.05 units, with stronger responses observed in Sub-Saharan Africa. In pigs, AGPs improved ADG by 28.15 g/day and FCR by 0.09, with especially strong effects from CIAs such as Colistin and Tylosin. In cattle, AGPs improved ADG by 30 g/day and FE by 0.004.

Despite the robustness of the dataset, considerable heterogeneity was evident for broiler ADG, likely reflecting variability in climatic conditions, production systems, breeds, feed quality, and experimental protocols. For instance, in tropical grazing systems, seasonal shifts in forage quality can substantially affect the response to AGPs (Detmann et al., 2014; Lazzarini et al., 2016). Furthermore, El-Fateh et al. (2024) documented breed-dependent variations in FCR response to AGPs, highlighting the role of genetic and microbial factors in modulating efficacy.

The underlying physiological mechanisms support these findings. Sub-therapeutic AGPs are known to enhance gut health, reduce inflammation, and improve nutrient absorption (Dibner and Richards, 2005; Niewold, 2007). In broilers, such mechanisms are linked to improvements in gut morphology and immune function (Yazdi et al., 2014; Moses et al., 2017). However, several trials reported limited or even negative effects, underscoring the importance of host-specific factors such as microbiota composition and health status.

In pigs, the largest mean ADG effect was observed in the grower-finisher phase, compared to the weaning phase. However, the test for differences between these production stages was not statistically significant, indicating similar effects across these groups. The weaning phase is a period characterized by high metabolic and immunological stress (Heo et al., 2015). AGPs likely help buffer these stressors by suppressing pro-inflammatory responses and pathogenic metabolites (Cardinal et al., 2021).

Efficacy also varied by region and income level. Broiler productivity gains were highest in Sub-Saharan Africa, likely due to lower baseline performance and more limited access to veterinary inputs. Such regional variation may stem from differences in regulatory frameworks, farm management, feed quality, and availability of alternatives (El-Fateh et al., 2024). For pigs, productivity improvements were more consistent across regions, possibly reflecting more uniform genetics and feeding strategies. Broilers in high-income countries had higher ADG responses (1.78 g/day) than those in upper-middle-income countries (1.65 g/day), suggesting a link between AGPs efficacy and factors like biosecurity, infrastructure, and feed quality (Teillant and Laxminarayan, 2015).

The effects of AGPs also varied by compound. In broilers, Colistin was associated with the highest weight gain, followed by Flavomycin. Virginiamycin also showed a positive and significant effect. In pigs, Tylosin, Avilamycin and Colistin were among the most effective. In cattle, Virginiamycin was associated with modest performance improvements, while Monensin had limited impact despite its widespread use. These results likely reflect differences in molecular structure, spectrum of activity, and mode of action (Giguère, 2013; Labro, 2000).

However, limited data for individual compounds—particularly in pigs and cattle—restricted our ability to detect more nuanced differences. Sample size limitations remain a key constraint, and future studies are needed to better isolate compound-specific effects. Additionally, dosage emerged as an important variable: higher AGPs doses were linked to diminished FCR efficiency in some cases (El-Fateh et al., 2024), pointing to the existence of optimal dosing thresholds.

The interplay between AGPs efficacy and AMR introduces a critical policy challenge. Although CIAs often deliver the greatest productivity gains, their use is strongly associated with increased resistance to key human antibiotics, including ciprofloxacin and ceftiofur (Etienne et al., 2025). These findings reinforce WHO recommendations to phase out the use of CIAs in livestock to preserve their effectiveness for human medicine and to curb AMR.

In parallel, several studies have identified promising non-antimicrobial alternatives—such as essential oils, phytobiotics, and organic acids—that may replicate some benefits of AGPs (Goodarzi et al., 2013; Liu et al., 2017). However, evidence on their cost-effectiveness and scalability in diverse production settings remains limited. Rigorous field trials and economic assessments are needed to validate their viability as sustainable substitutes.

5. Policy implications

The results of this meta-analysis offer critical empirical inputs for economic models assessing the consequences of reducing or banning AGPs use in livestock production systems. In economic policy modelling, whether based on computable general equilibrium (CGE), or partial equilibrium frameworks, productivity parameters such as ADG are essential determinants of output levels, and ultimately sectoral and macroeconomic outcomes. By providing species-specific and regionally differentiated estimates of AGPs effects on ADG, FCR, and FE, this study improves the accuracy and contextual relevance of such models. For instance, the observed ADG gain of 1.78 g/day for broilers, 28.15 g/day in pigs, and 30 g/day in cattle attributable to AGPs use can be directly translated into shifts in production functions, enabling more precise estimation of output changes and associated welfare effects under AGPs-reduction scenarios.

Importantly, the findings underscore that the magnitude of productivity loss, and therefore economic cost, associated with AGP bans is not homogeneous. The results suggest that systems in LMICs, where baseline productivity is lower and health infrastructure is weaker, are more likely to experience significant output shocks from AGPs withdrawal. Conversely, HICs, where alternative practices are already widely adopted, may face minimal productivity disruptions. These distinctions are essential for designing tailored mitigation policies. Moreover, the analysis reveals that AGPs classified by the WHO as CIA for human medicine yield some of the largest productivity effects, particularly in pigs. This introduces a complex policy dilemma, while AGPs can close productivity gaps and support food security, their continued use increases the risk of AMR. Economic models that integrate this trade-off can inform balanced, One Health-aligned policy decisions that weigh productivity losses against long-term societal benefits.

Notwithstanding these contributions, important data gaps persist across species, regions, and compounds. These gaps constrain fully

developed economic modelling because key parameters — such as long-run productivity trajectories under AGP withdrawal, cost structures for alternative interventions, and context-specific moderators — can only be partially derived from this study. Our estimates should therefore be used as calibrated inputs for baseline scenarios rather than as a complete basis for cost–benefit appraisal, pending new experimental evidence and systematic data collection to populate these missing parameters.

6. Conclusion

This meta-analysis provides a systematic and geographically diverse assessment of the effects of AGPs on livestock productivity, based on 95 studies encompassing 128 trial observations. Across species, AGPs use was generally associated with improved performance, including ADG increases of 1.78 g/day in broilers, 28.15 g/day in pigs, and 30 g/day in cattle, as well as modest improvements in feed conversion and efficiency. However, the magnitude and consistency of these effects varied widely depending on species, production conditions, and antimicrobial class.

While the findings support the view that AGPs contribute to growth performance, they also highlight the uneven distribution of these benefits and the particular reliance on CIAs in lower-mid to low income countries. These insights may help improve the accuracy and contextual relevance of economic models that simulate the potential impacts of AGPs reduction. Given the growing pressure to phase out medically important antimicrobials in livestock, these results underscore the importance of context-sensitive transition strategies, balancing productivity needs with public health goals under a One Health framework. As with any synthesis of experimental data, the estimates presented here should be interpreted in light of the underlying study conditions, and

Annex 1. Syntax for paper search

The syntax used for the main search on Scopus is:

TITLE-ABS-KEY ("antibiotic growth promoter*" OR "antimicrobial growth promoter*" OR "sub-therapeutic antibiotic*" AND "swine*" OR "pig*" OR "hog*" OR "broiler*" OR "chicken*" OR "cattle" OR "bovine*" OR "ruminant*") AND PUBYEAR > 2000

For the Spanish and French search, we used the same syntax as in English and refined the search by language (English, French and Spanish). The following keywords were used:

- Spanish: "Promotor de crecimiento antimicrobiano", "antimicrobianos promotores del crecimiento", "antibióticos subterapéuticos" in addition to "porcino", "cerdo", "cerdos destetados", "pollos de engorde", "pollos", "vacuno", "bovino" or "rumiante".
- French: "Stimulateur de croissance antibiotique", "Stimulateurs de croissance antimicrobiens" in combination with "porcs", "poulet", "bovine".

This approach ensured that relevant studies in all the three languages were captured systematically.

Annex 2. Full reference list of papers used in the meta-analysis

| Full reference list (1) | Animal (2) |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
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| de Souza, O. F., Vecchi, B., Gumina, E., Matté, F., Gazoni, F. L., Hernandez-Velasco, X., et al. Development and Evaluation of a Commercial Direct-Fed Microbial (Zymospore®) on the Fecal Microbiome and Growth Performance of Broiler Chickens under Experimental Challenge Conditions. <i>Animals</i> . 2022. 12(11), 1436. | Broiler |
| Sánchez, E. R., Barrera, E. M., & González, E. Á. Evaluación de promotores de crecimiento en pollos de engorda, en un sistema de alimentación restringida ya libre acceso. <i>Veterinaria México</i> . 2000. 31(1), 1–9. | Broiler |
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(continued on next page)

further field-based research will be important to refine them under real-world settings.

Mandated accession codes

No data with mandated deposition.

CRediT authorship contribution statement

Alejandro Acosta: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Cardinal Katia Maria:** Writing – review & editing, Methodology. **Francesco Nicolli:** Writing – original draft, Methodology, Investigation, Formal analysis. **Fabiola Onofrio:** Visualization, Formal analysis, Data curation. **Junxia Song:** Writing – review & editing, Writing – original draft, Supervision.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT for language editing purposes. After, using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

(continued)

| Full reference list (1) | Animal (2) |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| Liu, Y., Yang, X., Xin, H., Chen, S., Yang, C., Duan, Y., et al. Effects of a protected inclusion of organic acids and essential oils as antibiotic growth promoter alternative on growth performance, intestinal morphology and gut microflora in broilers. <i>Animal Science Journal</i> , 2017; 88(9), 1414–1424. https://doi.org/10.1111/asj.12782 | Broiler |
| Goodarzi, M., Landy, N., & Nanekarani, S. Effect of onion (<i>Allium cepa</i> L.) as an antibiotic growth promoter substitution on performance, immune responses and serum biochemical parameters in broiler chicks. <i>Health</i> . 2013; 5(8), 1210. | Broiler |
| Kidane, Z., Mengistu, A., & Singh, H. Effect of different mixture levels of oyster mushroom, garlic and ginger powder as substitutes for antibiotic growth promoter on carcass traits of broilers. <i>Adv. Biol. Res.</i> 2017; 11(4), 183–189. | Broiler |
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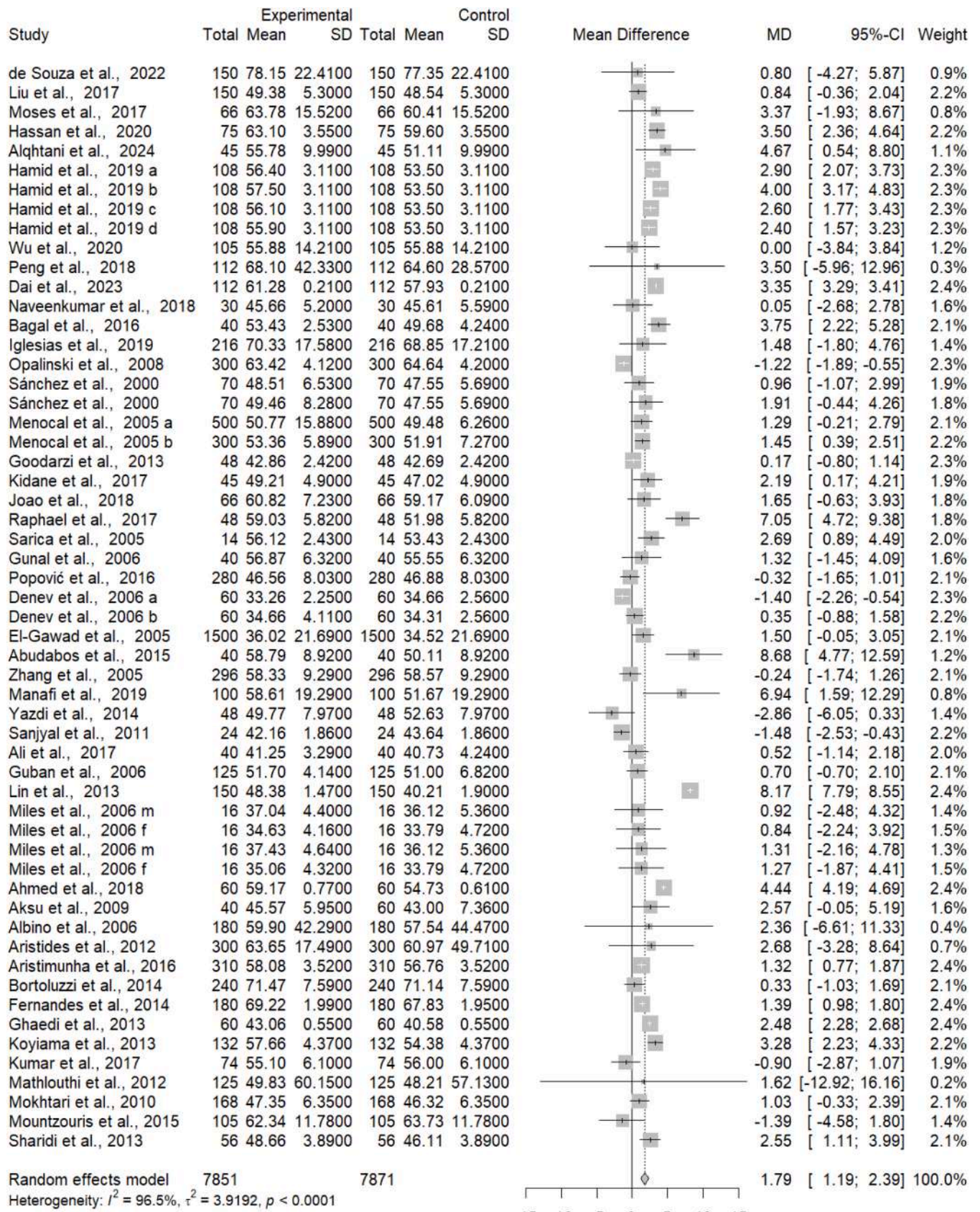
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Annex 3. Antimicrobial growth promoter reported in individual studies for each species

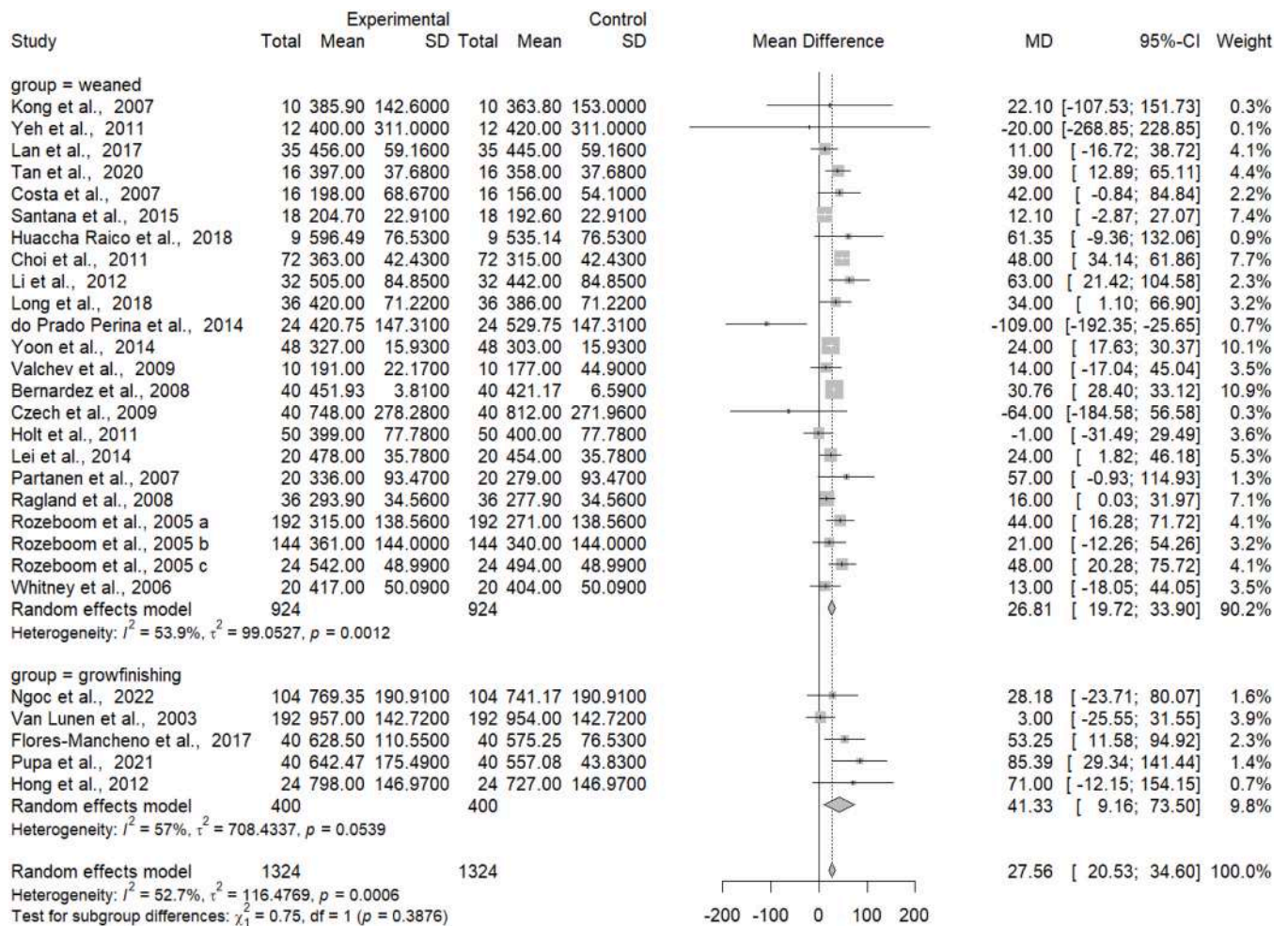
| Broiler | Pigs | Cattle |
|-------------------|-----------------------|---------------|
| Avilamycin | Amoxiciclin | Lasalocid |
| Avoparcin | Apramycin | Monensin |
| Bacitracin | Aureomycin | Narasin |
| Chlortetracycline | Avilamycin | Salinomycin |
| Colistin | Bacitracin | Tylosin |
| Doxycycline | Chlorhydroxyquinoline | Virginiamycin |
| Enramycin | Chlortetracycline | |
| Flavomycin | Colistin | |
| Flavophospholipol | Flavomycin | |
| Lincomycin | Flavophospholipol | |
| Oxytetracycline | Tiamulin | |
| Salinomycin | Tylosin | |
| Tylosin | Virginiamycin | |
| Virginiamycin | | |

Substances considered AGPs should be administered in low, continuous doses that are subtherapeutic (i.e., below the doses used to treat diseases). The main goal isn't to cure a specific infection, but rather to improve the animals' zootechnical performance.

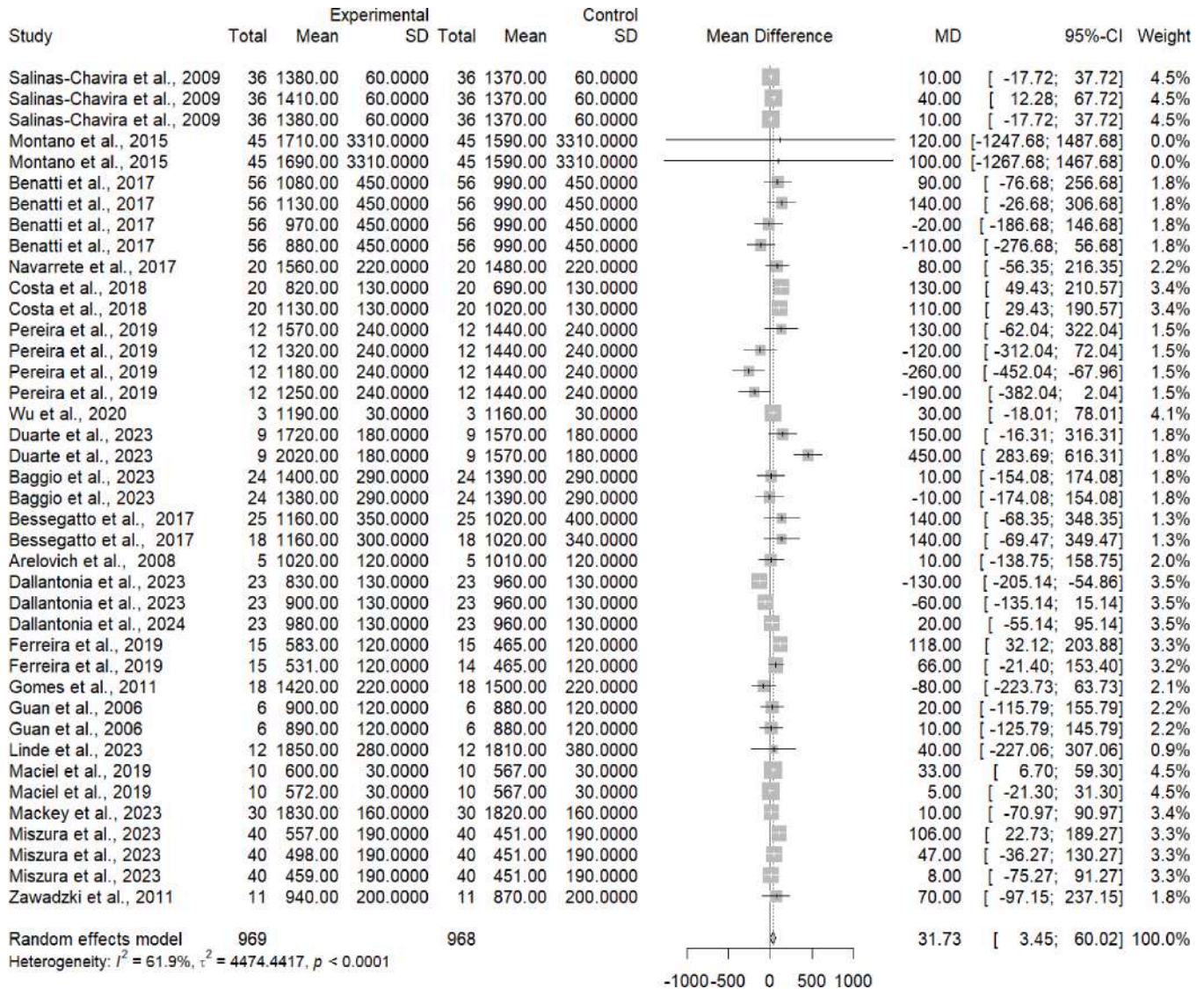
Annex 4. Forest plots by production system



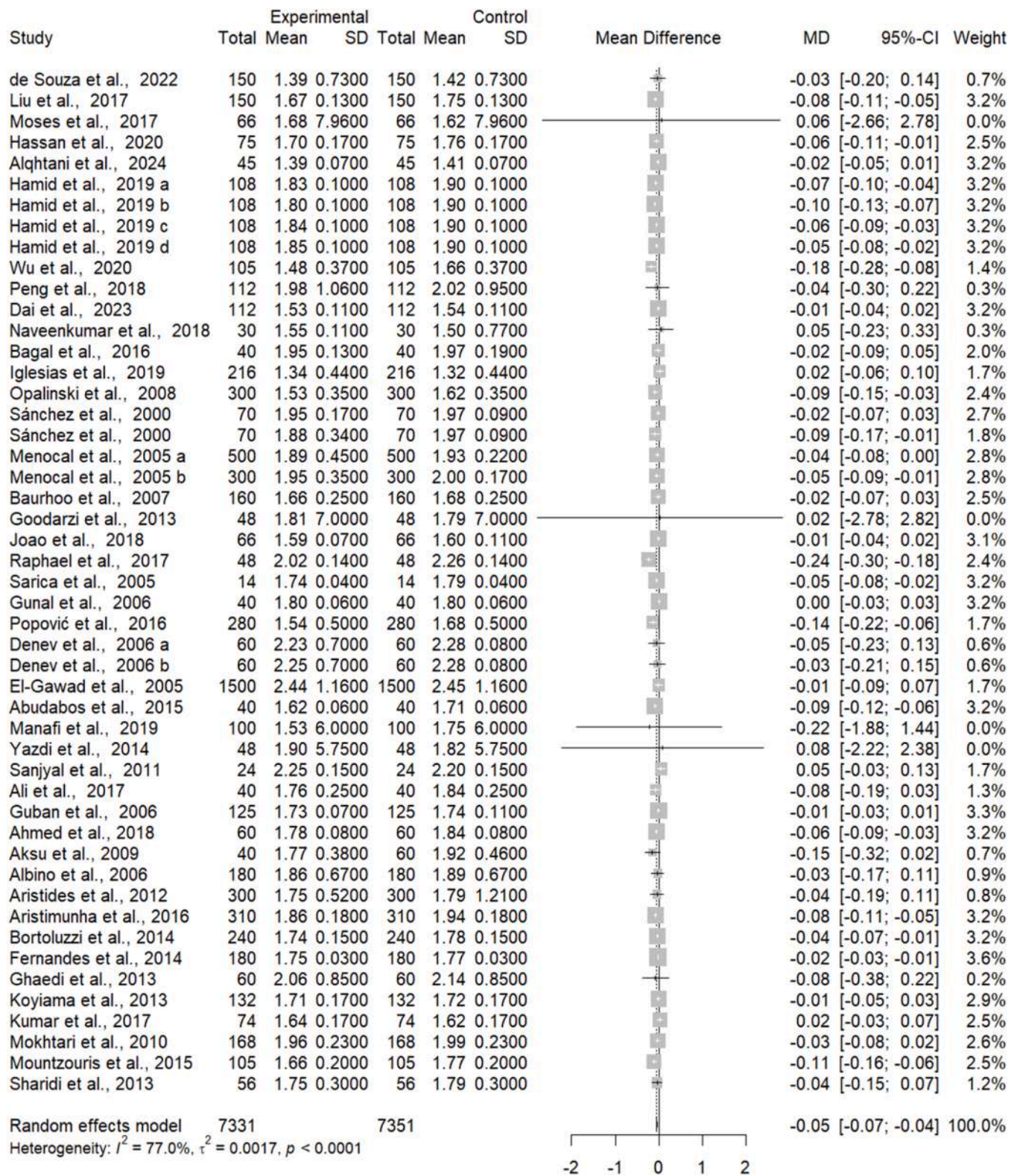
Forest plot of Broiler Daily Weight Gain (g/day) in the total period of rearing.



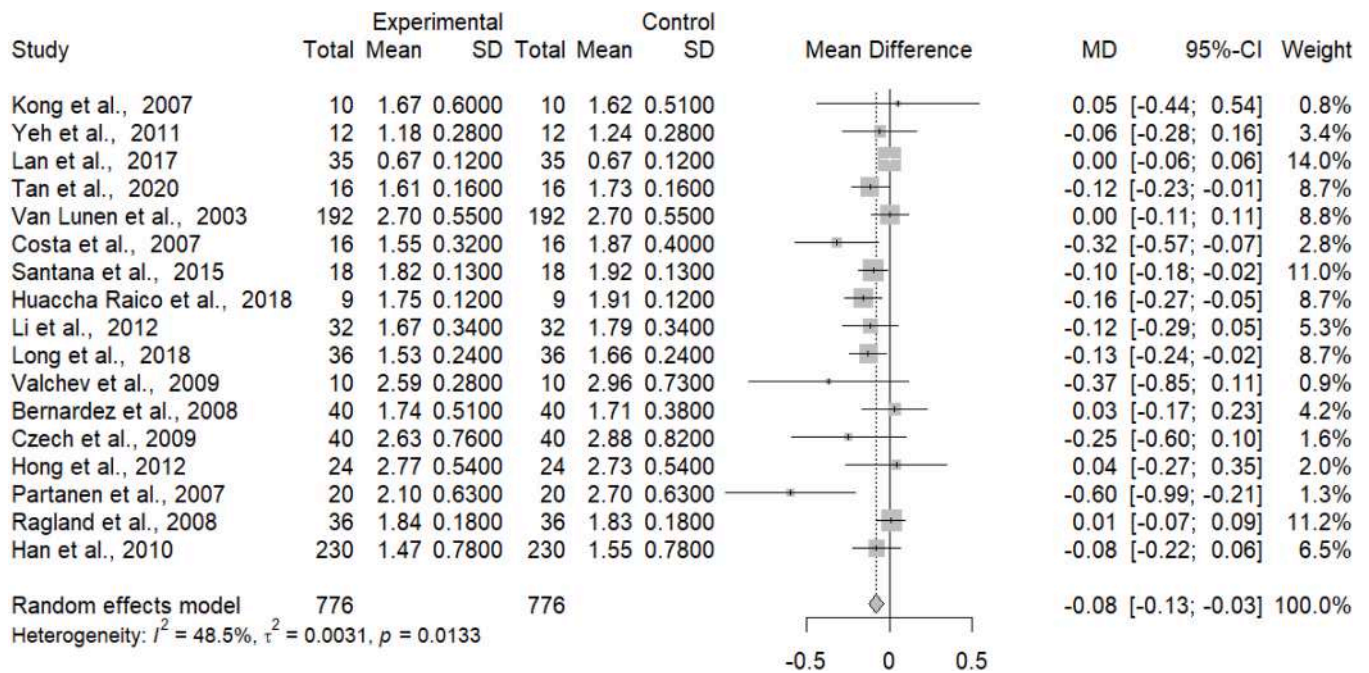
Forest plot of Pigs Daily Weight Gain (g/day) in Weaned Pigs and Grower-Finisher Phase.



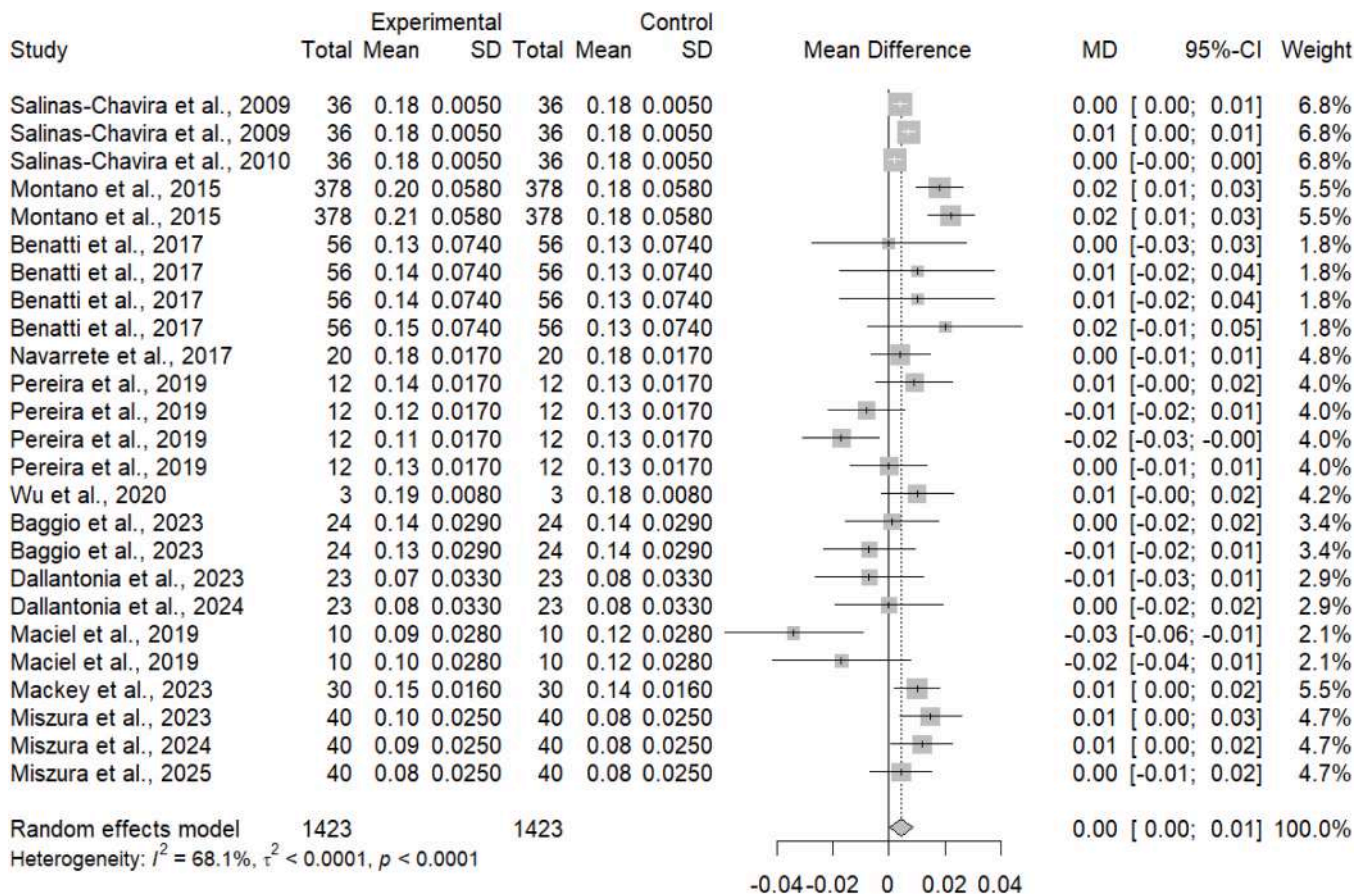
Forest plot of Cattle Daily Weight Gain (g/day) in Grow and Finishing periods.



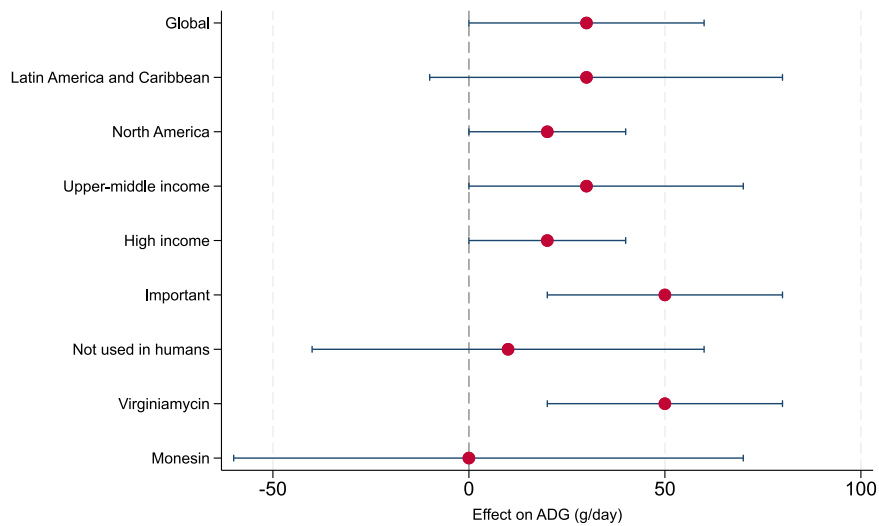
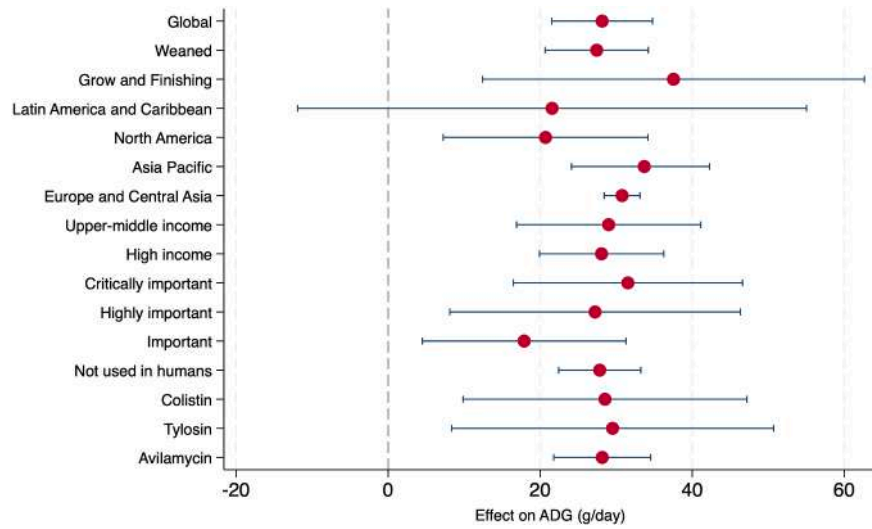
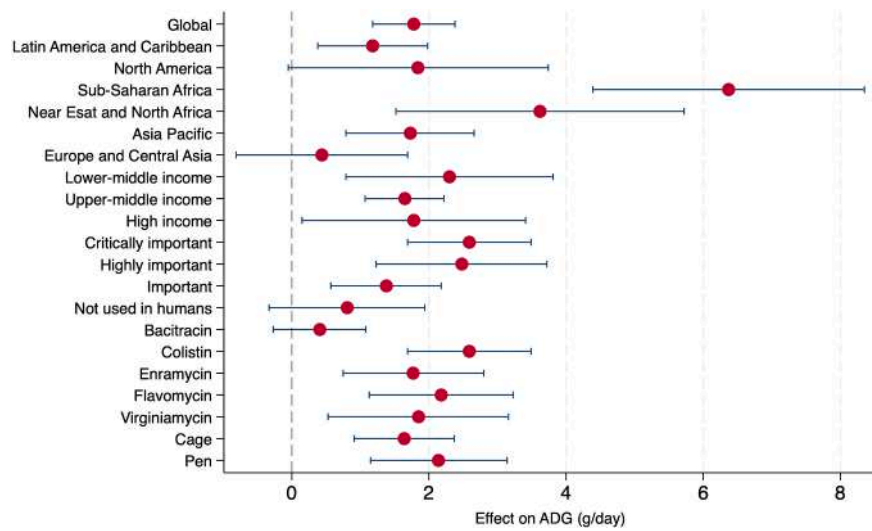
Forest plot of Broiler FCR (g:g) in the total period of rearing.

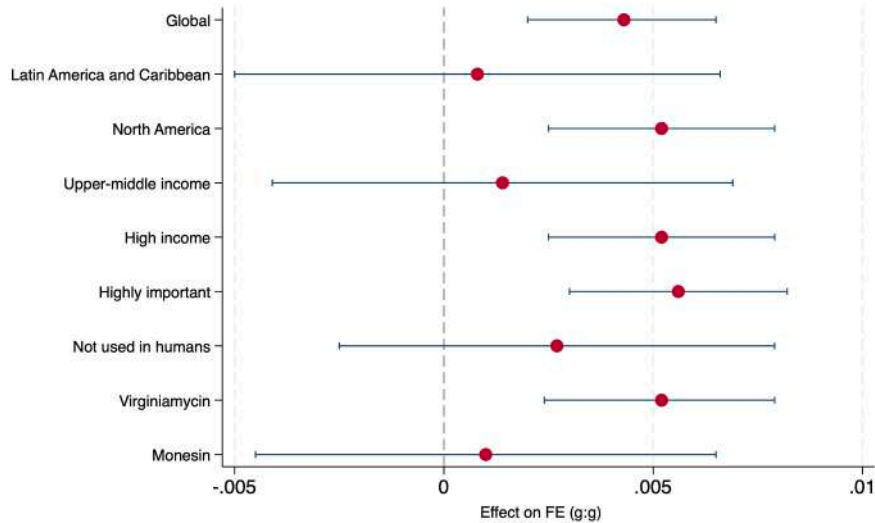
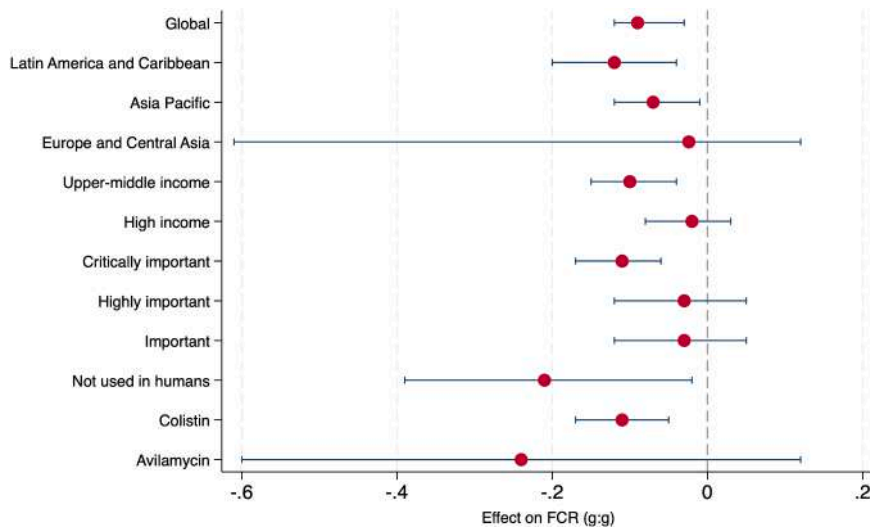
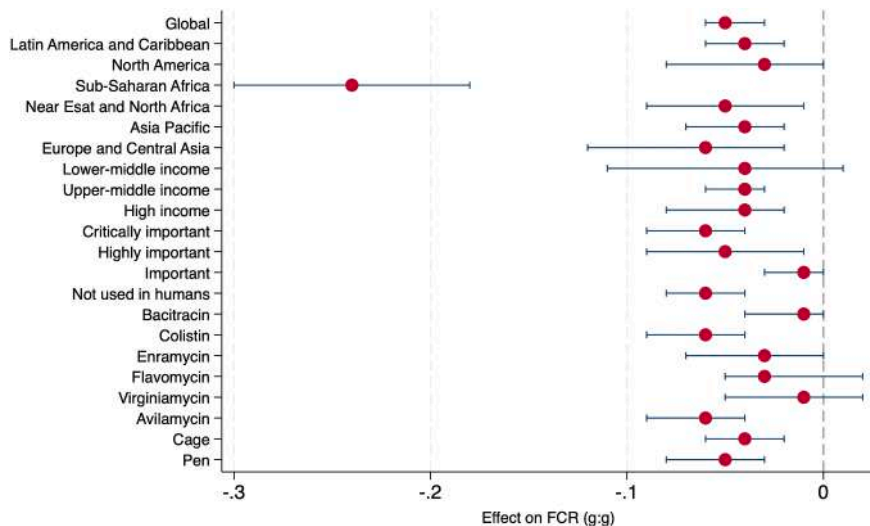


Forest plot of Pigs FCR (g:g) considering Weaned Pigs and Grower-Finisher phase



Forest plot of Cattle FE (gain/feed consumption – g/g) considering Grow Finishing period





Visual representation of the results in Tables 1–6

Annex 5. Summary of Findings

| Certainty assessment | | | | | | | N ^o of observations | Effect | | Certainty | Importance |
|------------------------------|-------------------|--------------|---------------|--------------|-------------|----------------------|--------------------------------|-----------------------------|--------------------------------------------------------------|-----------|------------|
| N ^o of studies | Study design | Risk of bias | Inconsistency | Indirectness | Imprecision | Other considerations | | Total number of observation | Relative (95 % CI) | | |
| Broiler | | | | | | | | | | | |
| 52 | randomised trials | not serious | not serious | not serious | not serious | none | 16162 | - | MD 1.70 g higher (0.90 higher to 2.50 higher) ^a | ⊕⊕⊕⊕ High | CRITICAL |
| Weaned pigs | | | | | | | | | | | |
| 21 | randomised trials | not serious | not serious | not serious | not serious | none | 1848 | - | MD 26.81 g higher (19.72 lower to 33.90 higher) ^a | ⊕⊕⊕⊕ High | CRITICAL |
| Grower-finisher phase | | | | | | | | | | | |
| 5 | randomised trials | not serious | not serious | not serious | not serious | none | 800 | - | MD 41.33 g higher (9.16 lower to 73.50 higher) ^a | ⊕⊕⊕⊕ High | CRITICAL |
| Cattle | | | | | | | | | | | |
| 20 | randomised trials | not serious | not serious | not serious | not serious | none | 3223 | - | MD 30 g higher (0.00 higher to 60 higher) | ⊕⊕⊕⊕ High | CRITICAL |

Data availability

No new data were created or analyzed in this study.

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