Review

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Review

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Abstract

The use of botanical extracts derived from *Jatropha* spp. offers a sustainable alternative for controlling insect pests, thereby reducing the reliance on synthetic chemical insecticides. A systematic review and meta-analysis was conducted to summarize the published evidence on the insecticidal activity of these extracts. Electronic database searches were conducted to identify relevant studies evaluating Jatropha ssp. botanical extracts against insect pests, including mortality, antifeedant activity, time of development, oviposition inhibition, and repellency. A random-effects meta-analysis for continuous variables with 95% confidence intervals was employed to compare treated insects against a control group. The study encompassed 77 articles, which evaluated the extracts from various botanical parts of *J. curcas* and *J. gossypifolia* against insects from nine taxonomic orders. The results of the meta-analyses demonstrated that aqueous, ethanolic, and methanolic extracts from leaves and seeds were effective in increasing the mortality rate of treated insects. These extracts also affected the insects by prolonging development time, reducing weight gain in larvae and pupae, inhibiting oviposition, and increasing the percentage of repellency. Consequently, botanical extracts obtained from the leaves and seeds of *J. curcas* and *J. gossypifolia* should be considered a sustainable and agroecological alternative for pest management.

Keywords: Natural products; botanical extracts; insecticide; sustainable agriculture

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1. Introduction

The presence of insect pests poses a substantial threat to global agriculture systems. According to the Food and Agriculture Organization of the United Nations (FAO), insect pests are responsible for the annual loss of up to 40% of global crop, resulting in economic losses estimated at $220 billion (https://www.fao.org/plant-health-day/es accessed on 27 October 2025). In response to this menace, farmers frequently employ the intensive use of synthetic chemical insecticides, which offer rapid and effective protection against insect pests [1]. However, the indiscriminate use of synthetic chemical insecticides has resulted in significant ecological and toxicological consequences [2]. Among the most critical impacts are environmental pollution and the negative effects on non-target insects [3]. Concurrently, a high incidence of deaths resulting from self-inflicted poisoning has been documented among agricultural workers exposed during the application of these compounds [4]. Considering these circumstances, the employment of botanical extracts has emerged as a promising alternative for the sustainable management of insect pests, thereby reducing dependence on synthetic chemical insecticides [5]. Moreover, the accessibility of botanical extracts is expected to be both affordable and convenient, and their rapid biodegradability is anticipated to be environmentally friendly [6].

Botanical extracts contain active compounds that are effective against a wide range of agricultural pests, offering a functional and ecological alternative to the use of synthetic insecticides [7]. The constituents present in plant extracts have been demonstrated to function as repellents, attractants, feeding deterrents, and growth inhibitors, thus impacting diverse physiological processes in insect pests [8]. In this context, members of the genus Jatropha (family Euphorbiaceae) have exhibited bioinsecticidal potential [9]. This genus comprises approximately 170 species of drought-tolerant shrubs and trees adapted to low-fertility soils. A previous systematic review has compiled evidence on the efficacy of extracts obtained from different parts of *J. curcas*, which represents the most frequently used species [10]. The summary of the available evidence showed that methanolic, aqueous, petroleum ether, and essential oil extracts from both seeds and leaves have significant effects, as evidenced by the documented inhibition of development, oviposition, and adult emergence, along with an increase in mortality rates among a variety of insect pest species [10].

To date, no meta-analysis has been conducted to estimate the pooled effect of independent studies that assess botanical extracts from Jatropha, which is necessary to determine their efficacy against insect pests of important crops. Similarly, the available evidence concerning other species of the Jatropha genus [11,12] has not been analyzed. Therefore, the present study was conducted to address the following questions:

1) What is the insecticidal effect of the botanical extracts of Jatropha on controlling insect pests?

2) What effect do the botanical extracts of Jatropha have on the growth and development of larvae and pupae?

3) Which botanical extracts of Jatropha are most effective at controlling insect pests?

4) Which insect pests are the botanical extracts of Jatropha more effective against?

The present study aims to expand our knowledge on the effect of Jatropha botanical extracts, incorporating statistical meta-analysis tools, as well as published evidence on other species of the Jatropha genus that have demonstrated insecticidal activity against various species of insect pests. This approach will facilitate a more robust and quantitative integration of the available findings, with the objective of generating a more substantial and representative body of evidence that strengthens the scientific basis for decision-making. The results of this study will enhance our understanding of the bioinsecticide potential of this plant genus and its subsequent incorporation into sustainable integrated pest management strategies.

2. Materials and Methods

2.1. Protocol and Inclusion Criteria

The present study was conducted in accordance with an a priori protocol, which was developed following the PRISMA-P (Preferred Reporting Item for Systematic review and Meta-analysis Protocol) statement [13]. The protocol is available to the public on the Open Science Framework website (URL). The preparation and report of the study was performed in accordance with the Cochrane guidelines [14] and the updated PRISMA 2020 statement [15]. As outlined in **Table 1**, the PICOS approach was employed to select studies for inclusion in the systematic review and meta-analysis [15]. In summary, the present study exclusively incorporated primary research articles with experimental design that were published as full text in peer-reviewed journals. These articles reported the insecticidal effect of Jatropha spp. botanical extracts against a range of insect pests that impact crops and vegetable products of economic importances.

Table 1. Eligibility criteria based on the PICOS approach of the PRISMA statement.

Acronym	Definition
Population	We included studies that reported the effect of Jatropha spp. botanical extracts on insect pests of any taxonomic order affecting crops and vegetable products of agriculture and economic interest. Such crops may include one of several categories, including food crops (wheat, corn, rice, tomatoes, lettuce, legumes, potatoes); fruit crops (oranges, lemons, berries, mangoes, melons); fodder crops (barley, oats, sorghum, sugar beets, hay); timber crops, stored grain products; and oil crops (sunflower and olive)
Intervention	We considered studies that reported feeding or contact bioassays of at least one botanical extract obtained from the from fresh or dried vegetative parts of Jatropha spp., including leaves, stems, roots, bark, seeds, and fruits. We considered the following four treatment categories: • Botanical extracts, including hexane, acetonic, chloroform, ethyl acetate, petroleum ether, methanolic, and aqueous extracts • Powders or macerates • Botanical oils • Secondary metabolites
Comparator	The selected studies should include at least one of the following categories as comparison groups: • Studies that included a control group, which received no treatment or placebo, including any other inert substance, vehicle, solvent or water • Studies comparing the effect of any other plant species (including powders, extracts, macerates, or oils), chemical insecticides, commercial botanical insecticides or any other substance against Jatropha spp. • Studies that reported the use of two or more plant parts or fresh or dried parts of the plant, one of them will be used as a reference or control • Studies that reported two or more doses, one of them will be used as a reference or control
Outcome	The studies should report any of the following outcomes, without prioritization: • Insecticidal activity, defined as the percentage of mortality, including the number of insects or populations killed by the treatment, or the reduction of populations/colonies of pest insects with respect to a reference value or control • Effect on larval and pupal growth and development, defined as the anti-feeding effect, as evaluated by the reduction of larval and pupal weight. We also included any effect on the morphological development and the presence of malformations, changes in fecundity and fertility, anti-oviposition effect, reduction of egg hatching, and any other physiological change were also considered
Studies	We included primary studies with experimental design that reported feeding or contact bioassays under laboratory, greenhouse, or experimental plot conditions. The studies should be published in English, Spanish, or Portuguese as full text in peer-reviewed journals. No temporal or regional restrictions were applied, and unpublished studies (gray literature) were not considered into the analysis

2.2. Information Sources and Search Strategies

One reviewer (AVR) conducted a specialized search using the digital library system of the Metropolitan Autonomous University (https://bidi.uam.mx) to access the following electronic databases: Scopus, ScienceDirect, Web of Science, SciELO, CAB Direct, BioOne, PubMed, Virtual Health Library, and AGRIS. The searches were conducted from August 29 to September 2, 2023, with an update executed on January 14, 2026, to extend the search for additional relevant studies published between 2024 and 2025.

The search terms were defined as follows: "population" (Jatropha ssp OR Jatropha); "intervention" (extracts OR botanical OR hexanic OR acetonic OR methanolic OR aqueous); and "outcome" (insecticides OR insectistatic OR insect pest OR crop insect pest OR activity OR biocide). In each database, the available methodological filters were used to define the search process, with Boolean operators (AND and OR) being employed to extend the search command. A general search command was defined, with the searches being performed by title and abstract, when available, for example: Title-abs= (jatropha) AND (extracts OR botanical OR hexanic OR acetonic OR methanolic OR aqueous) AND (insecticides OR crop insect pest). **Supplementary Table 1** presents a comprehensive overview of the search strategy employed in the review, encompassing all databases that were included. Once the electronic searches were completed, all the bibliographic records were retrieved and downloaded as RIS/ENW file formats to construct an EndNote 21 library (Thomson Reuters, USA).

2.3. Study Selection Process, Information Collected, and Data Extraction

The selection process of the studies to be included in the narrative synthesis and the meta-analysis was conducted by a single reviewer (DD). The process began with the removal of the duplicates from the EndNote library, which were removed manually and automatically using the duplicate find tool included in the software. The reviewer subsequently screened the records to identify relevant studies that met the inclusion criteria based on the title and abstract. Following this step, the selected records were retrieved in full text to assess their eligibility for final inclusion. To address this, the reviewer employed a standardized questionnaire based on the inclusion criteria outlined in **Table 1**. Before being used with the entire library, the questionnaire underwent a pilot testing phase, using a random selection of 10% of the screened studies to identify and rectify any inconsistencies and ensuring its reliability. A second reviewer (AFM) meticulously reviewed the selected studies to ensure that they fulfilled the defined inclusion criteria. In cases where inconsistencies were identified, the two reviewers reached a consensus to resolve the discrepancy.

For each selected study, the main characteristics were extracted by a single reviewer (RFB) and recorded in an Excel spreadsheet, with a codebook being generated for the correct management of the information. The database enabled the reviewer to generate summary tables and data charts. The following items were extracted: study identification (author, language, and year of publication), study design, main objective of the study, a brief description of the methodology, and a summary of the results reported. The data items also included the name of the Jatropha spp. evaluated, the type of botanical extract, and how it was used to control the insect pests. Furthermore, the type of sample evaluated (eggs, larvae, pupae, or adult insects) and the insecticide effect of the Jatropha spp. botanical extract were also extracted. Finally, also any information regarding the identification of secondary metabolites and their bioactivity in the control of insect pests was extracted for the summary of evidence. Once the extraction was completed, another reviewer (DD) confirmed and corrected the extracted information for all the selected studies.

2.4. Risk of Bias Assessment

The risk of bias was assessed by one reviewer (MARL) using an adapted version of a previously published methodology [10]. The evaluation of each study was conducted by assigning a binary designation "Yes" (meets the defined criterion and is considered free of bias) or "No" (does not meet the criterion and there is risk of bias in the criterion evaluated). The evaluation criteria employed are outlined as follows: 1) Adequate definition of the population included in the study, 2) Clear specification of the method employed in the bioassays, 3) Consistency of reporting, with no discrepancies, 4) Outcomes must include an assessment of the insecticidal activity or the effects of the botanical extracts on larval and pupal growth and development, 5) The description of the method for obtaining extracts and treatments must be clear, and they must be compared to a control or reference

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group, 6) Results must not be selectively reported. The results of the risk of bias assessment were presented both individually for each study and also as a percentage summary for the whole set of studies reviewed.

2.5. Statistical Analysis of the Bioactivity of Jatropha spp. Botanical Extracts

In order to assess the bioactivity of Jatropha spp. botanical extracts against insect pests, the following outcomes were estimated: 1) Mortality, defined as the average percentage (±SD, standard deviation) of larvae, pupae, or adult insects killed by the treatment at any stage of development; 2) Antifeedant activity, defined as the average (±SD) weight of larvae, pupae, or adults at a given day during any stage of development; 3) Development time, defined as the average (±SD) number of days taken for a larva or pupa to complete their stage development; 4) Oviposition inhibition, defined as the average number (±SD) of eggs laid by the treated insects; and 5) Repellency activity, defined as the average percentage (±SD) of larvae, pupae, or adult individuals that stop feeding due to treatment exposure. In cases were a single publication reported the results for distinct Jatropha spp., botanical part, types of extracts, or insect species, each result was extracted and considered as an individual study for the meta-analysis.

All the outcomes were independently assessed through a meta-analysis for two-group comparison of continuous variables, employing the mean difference as the effect size. The model incorporated the sample size, the mean, and the standard deviation for the treatment and the control/reference groups, assuming unequal group variance. Given the anticipated heterogeneity across studies, the DerSimonian-Laird (D-L) random effects model was employed to generate the pooled estimates and 95% Confidence Intervals (95% CI) [16]. Moreover, complementary meta-analyses were constructed for each outcome, incorporating the Jatropha spp., the botanical structure, the type of extract, the insect species, and the stage of development, all of which were evaluated as methodological subgroups within the model.

As previously outlined [17], the z-test was utilized to ascertain a significant overall effect size, whereas the Cochran's Q test of homogeneity was employed to assess heterogeneity among publications, following the recommended level of $p = 0.1$. The Tau^2 statistic was employed as a measure of heterogeneity, with values greater than 1 being considered indicative of substantial heterogeneity [16]. Finally, the I^2 statistic was employed to assess the proportion of variation in effect estimates attributable to heterogeneity in true effects rather than to sampling error [18].

2.6. Secondary Analysis and Software

The heterogeneity of the studies was visually examined using Galbraith plots, which present a scatterplot of the z-score of the effect size on the y-axis plotted against the inverse standard error (precision) on the x-axis. A regression line that passes through the origin is fitted to represent the overall effect size with a parallel 95% CI region, with an additional reference line at y = 0 indicating "no effect" [16]. In the absence of heterogeneity, 95% of studies should be distributed across the region. Furthermore, as suggested for meta-analysis that include more that 12 studies, the publication bias was formally assessed using an Egger regression-based test to determine the presence of a small-study effect, defined as smaller studies reporting larger effect sizes [19]. The test performs a weighted linear regression on the effect sizes on their standard error, weighted by the precision, hypothesizing that there is a significant association between the effect sizes and the precision, with a zero-slope test confirming the small study effect.

Leave-one-out (sensitivity analysis) meta-analysis were conducted to identify possible studies in which exaggerated or distorted results may be present, while cumulative meta-analysis was used to identify trends in effect size, with the year of publication used as the ordering variable [20].

All the meta-analyses and secondary analyses, and graphs were performed in Stata 19 (StataCorp, TX, USA) using the "Meta-analysis tool" from the statistics menu. All additional graphs and maps were produced in Prism 11 (GraphPad Inc., CA, USA), DataWrapper

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(https://www.datawrapper.de) and SankeyMATIC (https://sankeymatic.com accessed on 15 December 2025). In all cases, a value of $p < 0.05$ was considered significant.

2.7. Use of Artificial Intelligence

The application Rubriq Premium from American Journal Experts (https://rubriq.com accessed on 5 January 2026) was used for translation of the original manuscript from Spanish to English, and DeepL Write Pro software was used to proofread and correct the English language.

3. Results

3.1. Selection of Studies

The comprehensive search in electronic databases yielded a total of 959 records, of which a substantial proportion was contributed by PubMed, Scopus, and CAB abstracts, accounting for 81.0% (777 records). In contrast, VHL, ScienceDirect, and SciELO had the lowest number of records with 13, 10, and 5 records, respectively. A total of 181 duplicates were eliminated, resulting in 778 records remaining for evaluation during the screening process. Following the application of the inclusion criteria to the title and abstract, 246 publications were selected that met the established inclusion criteria and were then retrieved in full text. Of these, 79 publications could not be located. After applying the eligibility format to the 167 full-text articles, 92 publications were excluded on the basis that they did not meet the inclusion criteria. The following reasons for exclusion were documented: 40.3% of the studies failed to include the defined outcomes, 22.5% did not present the population, 15.7% were not primary studies, 12.3% did not report the origin of the sample, and 10.1% were not the defined type of study. A detailed list of the excluded studies, accompanied by the primary reason for exclusion, is provided in **Supplementary Table 2**.

According to the PRISMA 2020 flow chart depicted in **Figure 1**, a total of 77 studies were included in the systematic review and meta-analysis, of which 70 studies included *J. curcas*, five studies reported results for *J. gossypifolia,* and two other studies included *J. dopharica*. The complete list of the 77 studies included is presented in **Supplementary Table 3**.

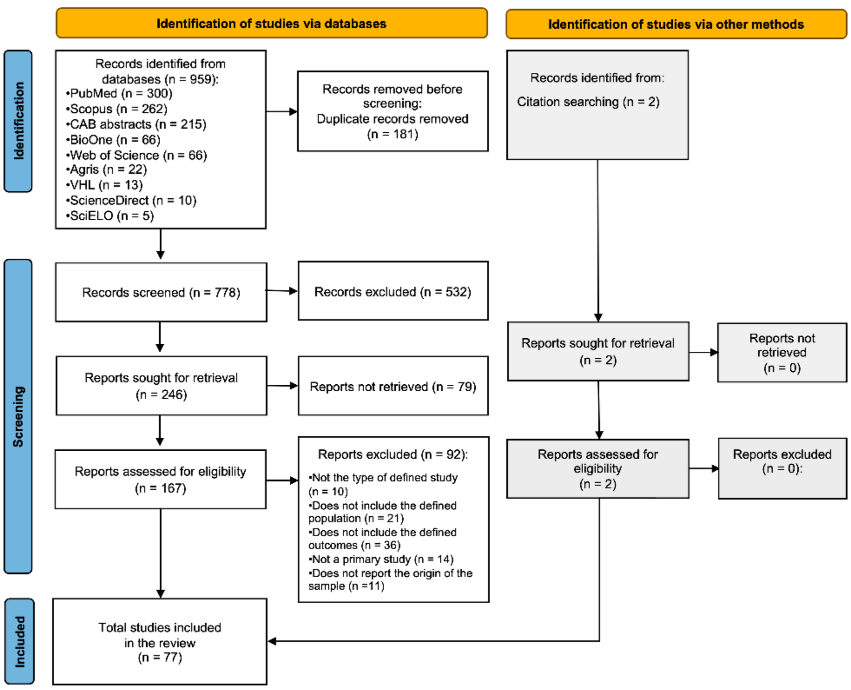

Figure 1. The PRISMA 2020 flow chart delineates the selection process of the 77 studies included in the narrative synthesis.

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3.2. General Characteristics of the Studies

The systematic review and meta-analysis included 77 studies that were published between 2002 and 2025. English was the predominant language in 92.2% (71/77) of the studies, followed by Portuguese and Spanish with three studies each. A total of 72.7% of the studies were published in countries from Africa and Asia (29 and 27, respectively), while the remaining 21 studies were conducted in countries from Latin America. All the publications included had an experimental design, being in vitro laboratory conditions the most frequent (82%, 65 studies), whereas the studies conducted under greenhouse and experimental plot conditions were less common (2 and 7 studies, respectively), with the remaining three studies assessing mixed conditions. With respect to the Jatropha ssp. vegetal parts from which botanical extracts were obtained, 57% and 16.8% employed seeds or seed oil, respectively (38 and 13 studies). The leaves were employed in 24.6% (19/77) of the studies, while five studies employed at least two distinct vegetal parts, and the remaining two studies reported the use of stem bark.

Among the 77 studies that were included in the systematic review, maceration was identified as the most frequently reported extraction method (53 studies), followed by Soxhlet and mechanical extraction (13 and 6, respectively). In two studies, filtration and hydrodistillation were used as the primary extraction methods, while in another study, boiling was reported as the extraction technique. The primary extracts obtained across the studies were predominantly aqueous (36 studies), acetonic (8), petroleum ether (8), methanolic (5), powders (5), hexanic (4), ethanolic (3), and eight studies that reported a mixture of extracts. Regarding the taxonomic order of the insect pests examined in each study, Coleoptera (29 studies) and Lepidoptera (25) were the most frequent, followed by Hemiptera (6) and Isoptera (6). Other five studies reported the effects of botanical extract against a mixture of insect pests from different orders, while the remaining six studies included insect pests from the orders Homoptera, Thysanoptera, and Orthoptera.

3.3. Risk of Bias of Individual Studies

The results of the risk of bias assessment conducted on the 77 studies included in the narrative synthesis are depicted in **Supplementary Figure 1**. In total, 100% of the studies were qualified as having a low risk of bias because they reported the plant species and the taxonomic order of the insect pests. Furthermore, 92.2% of the studies had a low risk of bias because they provided comprehensive and detailed descriptions of the botanical extraction method, the treatments evaluated, and their respective control groups. In the presentation of the variables, 98.7% of the studies included in the narrative synthesis presented a clear evaluation of the insecticidal activity, as well as 90.9% of the studies showed a clear specification of the application method (bioassay of ingestion or contact) and therefore were rated as having low risk of bias. With respect to consistency of reporting (absence of discrepancies) and the selective reporting of results, 28.6% and 20.7% of the studies, respectively, were rated as having an unclear risk of bias in these criteria.

3.4. Summary of Results of the 77 Individual Studies Included in the Systematic Review

A synthesis of the principal outcomes reported in each of the 77 studies included in the systematic review is presented in the **Appendix A1-A3**, with the results presented for each Jatropha spp. categorized according to the botanical part of the plant and the specific type of extract.

3.5. Meta-Analyses of the Mortality

Supplementary Table 4 presents a summary of the sub-group meta-analyses conducted to estimate the mortality of insect pests due to Jatropha spp. botanical extracts, whit the forest plots from each subgroup meta-analysis depicted in **Supplementary Figure 2** The pooled estimate of 57 individual studies reported in 23 publications demonstrated a significant increase in mortality of 54.56% (95% CI: 47.56 to 61.55) in insects treated with botanical extracts compared to the control group ($z = 15.30$, $p < 0.001$). The homogeneity test revealed substantial heterogeneity among the

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studies (Q = 26,785.73, $p < 0.001$), a finding that was confirmed by I^2 (99.79%) and Tau² (692.39) statistics, whose values indicated the existence of considerable disparity.

An analysis of the effect by species revealed that *Jatropha curcas* extracts exhibited a significant increase in insect mortality of 54.15% (48.24 to 60.07) in comparison to the control group, whereas *Jatropha gossypifolia* extracts had a pooled overall mortality of 58.47% (19.26 to 97.67) in treated insects. No significant difference in efficacy was detected between the two species (Qb = 0.05, $p = 0.831$), indicating that both species possess a comparable and high insecticidal effect.

With regard to the botanical part from which the extract was obtained, all the structures evaluated had a significant insecticidal effect, with the extracts derived from seeds having the highest efficacy, increasing mortality by 58.50%. Followed by extracts from the fruit (53.00%), stem/bark (48.45%), and leaves (47.88%). The test for differences between groups was not significant (Qb = 1.88, $p = 0.597$), indicating that the insecticidal activity of Jatropha remains consistent across the various botanical parts that were examined. On the contrary, the type of extract used was a determining factor in the mortality of the treated insects, as suggested by the significant differences found between groups (Qb = 559.26, $p < 0.001$). The most efficient extracts were found to be ethyl acetate (73.33%), hexanic (67.99%), acetonic (65.86%), and phorbol ester (63.34%). Aqueous extracts exhibited intermediate mortality, achieving 46.56%. In contrast, the lowest insecticidal activity was observed in petroleum ether and chloroform extracts, with mortality rates of 22.58% and 27.13%, respectively.

When analyzing the effect of the extracts according to the stage of development, mortality estimates differed between groups (Qb = 13.22, $p = 0.001$), with the treatment being most effective in the pupal stage, where mortality reached 70.47%. In the larval and adult stages, the estimates were 54.30% and 46.68%, respectively.

The meta-analysis encompassed a total of 16 insect pests, 12 of which were treated with extracfs of *J. curcas* and four with *J. gossypifolia* (**Table 2**). Except for two cases, the majority of insects pests exhibited increased mortality levels in response to the botanical extracts, which exerted a differential insecticidal activity. The top five species with the highest susceptibility were *Coptotermes vastator* (79.54%), *Busseola fusca* (70.63%), *Ostrinia nubilalis* (70.00%), *Zabrotes subfasciatus* (67.41%), *Nezara viridula* (66.36%), and *Spodoptera frugiperda* (66.48%). The species *Myzus persicae*, *Odontotermes wallonensis*, and *Brevicoryne brassicae* showed intermediate susceptibility, with mortality rates ranging from 53.70% to 58.09%. Finally, Jatropha spp. extracts exhibited low insecticidal activity against Rhyzopertha dominica (29.22%), Tribolium castaneum (27.38%), Spilarctia obliqua (21.16%), Sesamia nonagrioides (20.00%), and Rhynchophorus palmarum (2.30%).

Table 2. Summary of the D-L random-effects subgroup meta-analysis which included 57 individual studies reported in 23 publications that assessed the effect of Jatropha spp. botanical extracts on the mortality of insect pests.

Jatropha spp. Insect Species	Main Crop Affected	Mean Difference (95% CI)*	z (*p* Value)	Q (*p* Value) **	I^2
		Jatropha curcas			
Coptotermes vastator	Timber trees	79.54 (78.06 to 81.01)	105.89 (0.000)	-	-
Zabrotes subfasciatus	Stored grains	67.41 (54.55 to 80.27)	10.28 (0.000)	3.68 (0.055)	72.84
Spodoptera frugiperda	Corn	66.48 (60.88 to 72.09)	23.25 (0.000)	2944.54 (0.000)	99.39
Nezara viridula	Soybean	66.36 (60.09 to 72.63)	20.76 (0.000)	0.82 (0.366)	0.00
Myzus persicae	Cabbage	58.09 (45.62 to 70.56)	9.13 (0.000)	61.15 (0.000)	91.82
Odontotermes wallonensis	Wheat, peanuts, rice	58.06 (41.82 to 74.29)	7.01 (0.000)	17.99 (0.000)	88.88
Brevicoryne brassicae	Cabbage	53.70 (39.00 to 68.40)	7.16 (0.000)	154.16 (0.000)	97.41
Planococcus citri	Coffee	40.93 (29.50 to 52.36)	7.02 (0.000)	8.33 (0.080)	51.98
Spodoptera litura	Cabbage, asparagus	35.66 (33.43 to 37.88)	31.40 (0.000)	-	-
Rhyzopertha dominica	Stored grains	29.22 (17.41 to 41.03)	4.85 (0.000)	25.75 (0.000)	92.23
Tribolium castaneum	Stored grains	27.38 (24.19 to 30.57)	16.82 (0.000)	3.91 (0.142)	48.86

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Spilarctia obliqua	Sessame, mustard	21.16 (-0.72 to 43.05)	1.89 (0.058)	191.96 (0.000)	99.48
Sesamia nonagrioides	Sorghum	20.00 (-6.55 to 46.55)	1.48 (0.140)	-	-
Rhynchophorus palmarum	Palm fruit	2.30 (0.61 to 3.98)	2.67 (0.000)	-	-
		Jatropha gossypifolia			
Busseola fusca	Corn	70.63 (12.85 to 128.40)	2.40 (0.017)	26.05 (0.000)	96.16
Ostrinia nubilalis	Corn	70.00 (48.79 to 91.20)	6.47 (0.000)	-	-

* Effect size = mean difference (Treatment - Control). **Test for difference between groups: Q_b = Chi^2 (d.f. = 15) = 4891.11, Prob > Q_b = 0.000.

The secondary analyses for the mortality of insect pests are presented in **Supplementary Figure 3**. The Egger test indicated no evidence of publication bias, as the coefficient for the small study effect was not significant (β_1 = -0.14, *p* = 0.841). Furthermore, the Galbraith plot provided a visual confirmation of the substantial heterogeneity among the studies because there were several studies lying outside across the 95% CI region. The cumulative meta-analysis indicated that the direction of the effect (an increased mortality rate) was consistently established from the earliest publications from 2009, and as additional studies were incorporated, the effect size gradually stabilized. The sensitivity analysis demonstrated that the pooled estimate remained consistent within the overall confidence interval (47.66 to 61.55) after the iterative exclusion of each of the 57 individual studies. This finding indicates that no individual study had a disproportionate influence on the overall result.

3.6. Meta-Analyses of the Antifeedant Activity

As detailed in **Supplementary Table 5**, which presents the sub-group meta-analyses results, and **Supplementary Figure 4**, which presents the forest plots, the antifeedant activity was reported in seven publications that included 23 individual studies. All studies included in the meta-analysis evaluated *J. curcas* extracts obtained from seeds exclusively, avoiding the possibility of conducting comparisons between species or botanical parts. The pooled estimate demonstrated a significant reduction in weight gain of -20.50 mg (-29.80 to -11.20) in insects treated with botanical extracts in comparison to the control group (z = -4.32, *p* < 0.000), thus indicating a notable antifeedant activity of Jatropha spp. extracts. The homogeneity test indicated substantial heterogeneity among the studies (Q = 4533.07, *p* < 0.001), with considerable disparity as evidenced by the 99.51% of I^2 and 485.21 of Tau^2.

As depicted in **Figure 2**, with the exception of oil, all the extracts exhibited a significant decrease in weight gain, characterized by variations in the magnitude of the effect. Hexanic extracts showed the greatest reduction in weight gain, with a mean difference of -28.93 mg. This was followed by acetonic and aqueous extracts, which showed moderate reductions of -17.83 and -15.98 mg, respectively. Conversely, methanolic extracts had the lowest, although significant, reduction of -11.87 mg. Despite this variation, the test for differences between groups was not statistically significant (Qb = 4.53, *p* = 0.339), indicating that the antifeedant activity of *J. curcas* remains consistent across the various types of extract examined.

When analyzing the effect of the extracts according to the development stage of the insects pests, no significant differences in weight gain reduction were found between the groups evaluated (Qb = 0.09, *p* = 0.759). In the larval stage, the reduction was -21.45 mg (-36.66 to -6.24), while in the pupal stage, the reduction was -18.75 mg (-27.13 to -10.33). This findings indicate a comparabale effect on both stages.

The meta-analysis included four insect species that exhibited a differential effect on weight gain in response to the botanical extracts (Qb = 56.27, *p* < 0.001). The most susceptible species was *S. obliqua*, which showed a reduction in weight gain of -64.00 mg, followed by *S. frugiperda* with a moderate reduction of -22.39 mg. Finally, *J.* curcas extracts exhibited low antifeedant activity against *C. decolora*

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(-6.78 mg) and *S. litura* (-6.38 mg), whose reductions in weight gain were not statistically significant compared to the control group.

According to the results summary presented in **Supplementary Figure 5**, Egger's regression test did not detect significant evidence of small study effects ($\beta_1 = 2.07$, $p = 0.058$). However, the Galbraith plot indicated substantial heterogeneity among the studies, as evidenced by the dispersion of points above and below the regression line and the confidence region. As demonstrated in the cumulative meta-analysis, except for two studies at the beginning of the period, the estimates remained within the range of -25.5 to -8.40 mg throughout the entire period analyzed, thereby confirming the temporal consistency of the effect of *J. curcas* extracts on the weight gain of insect pests. This pattern suggests that the evidence accumulated to date is sufficiently stable and that the incorporation of future studies would have a limited impact on the direction and magnitude of the estimated effect. The findings of the sensitivity analysis indicated that the pooled estimate constently persisted within the overall 95% CI of -29.80 to -11.20, indicating that the estimates are and not determined by any specific study.

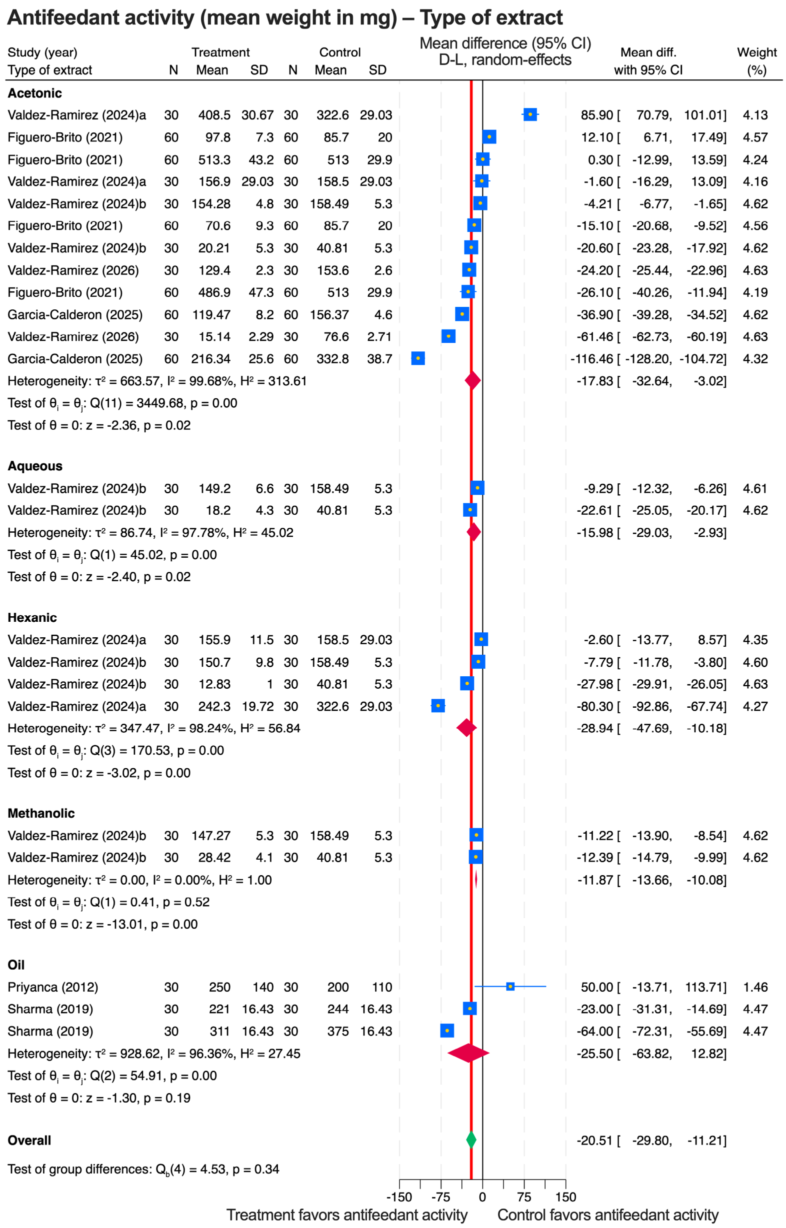

Figure 2. Forest plot of the D-L random-effects subgroup meta-analysis that included 23 individual studies reported in seven publications that assessed the effect of Jatropha spp. botanical extracts on the antifeedant activity against insect pests.

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3.7. Meta-Analyses of Development Time

Supplementary Table 6 presents a summary of the sub-group meta-analyses conducted to estimate the effect of Jatropha spp. botanical extracts on the ddevelopment time of the insect pests and **Supplementary Figure 6** presents the forest plots of the meta-analysis. The pooled estimate from 30 individual estudies included in 10 different publications demonstrated that in comparison to the control group, the insects treated with the botanical extracts from *J. curcas* showed a significant increase in their development time of 3.27 days (0.89 to 5.64; z = 2.70, $p = 0.007$). With a value of Q = 12,420.23, the homogeneity test indicated a significant heterogeneity among the studies ($p < 0.001$), a finding further confirmed by the I^2 (99.77%) and Tau² (43.03) heterogeneity statistics, whose values demonstrated the existence of substantial disparity. Given that all the studies evaluated exclusively *J. curcas*, it was not possible to conduct a comparison between species.

Seed-derived extracts significantly prolongued insect development time by 4.70 days (3.26 to 6.14), and contracry to the expectations, the extracts obtained from leaves had an accelerating effect because they reduced development time by -5.84 days (-6.73 to -4.95). As a consequence, there were significant differences observed between the botanical structures evaluated in the studies (Qb = 148.95, $p < 0.000$). The type of extract was also a determining factor in modifying the development time of the treated insects with contrasting effects observed depending on the solvent used. Hexanic (7.21 days), aqueous (5.98 days), acetonic (5.31 days), and oil (2.58) were the extracts that prolonged development time. In contrast, ethyl acetate and methanolic extracts reduced development time by -6.94 days and -0.88 days, respectively. This differential effect resulted in significant differences found between the groups (Qb = 320.47, $p < 0.001$). These results suggest that certain types of extract may have opposite effects on the duration of insect development, possibly due to differences in the bioactive compounds selectively extracted by each solvent.

The meta-analysis results indicated a differential activity of the extracts on the development time of the evaluated insect species (Qb = 33.18, $p < 0.001$). Insect species that experienced the greatest prolongations in their development time were *C. decolora* (5.54 days) and *Schistocerca gregaria* (4.95 days). They were followed by *S. frugiperda* (3.26 days) and S. obliqua (2.08 days). Finally, *J. curcas* extracts did not significantly alter the development time of S. litura, suggesting that this species is less susceptible to the effect of the extracts on this biological parameter.

As shown in **Figure 3**, when analyzing the effect of the extracts according to the development stage of the insect, there a differential effect of the botanical extract that depended on the stage assessed (Qb = 7.85, $p = 0.020$). With an increase of 4.97 days (3.82 to 6.12), the nymphal stage experienced the greatest prolongation in development time. Whereas in the larval stage the prolongation was 3.79 days (0.21 to 7.37) and 2.46 days (1.13 to 3.78) in the pupal stage.

According to the secondary analysis summarized in **Supplementary Figure 7**, there was no evidence of publication bias ($\beta_1 = -0.79$, $p = 0.583$) and the Galbraith plot suggested substantial heterogeneity across the individual studies, as the points were distributed mainly above the 95% confidence region. The cumulative meta-analysis revealed that although the direction of the effect size varied during the early years, the prolongation of development time consistently established from 2019, with the magnitude of the effect gradually stabilizing as additional studies were incorporated. Finally, the sensitivity analysis showed that the pooled estimate remained consistent after iterative exclusion of each of the 30 individual studies.

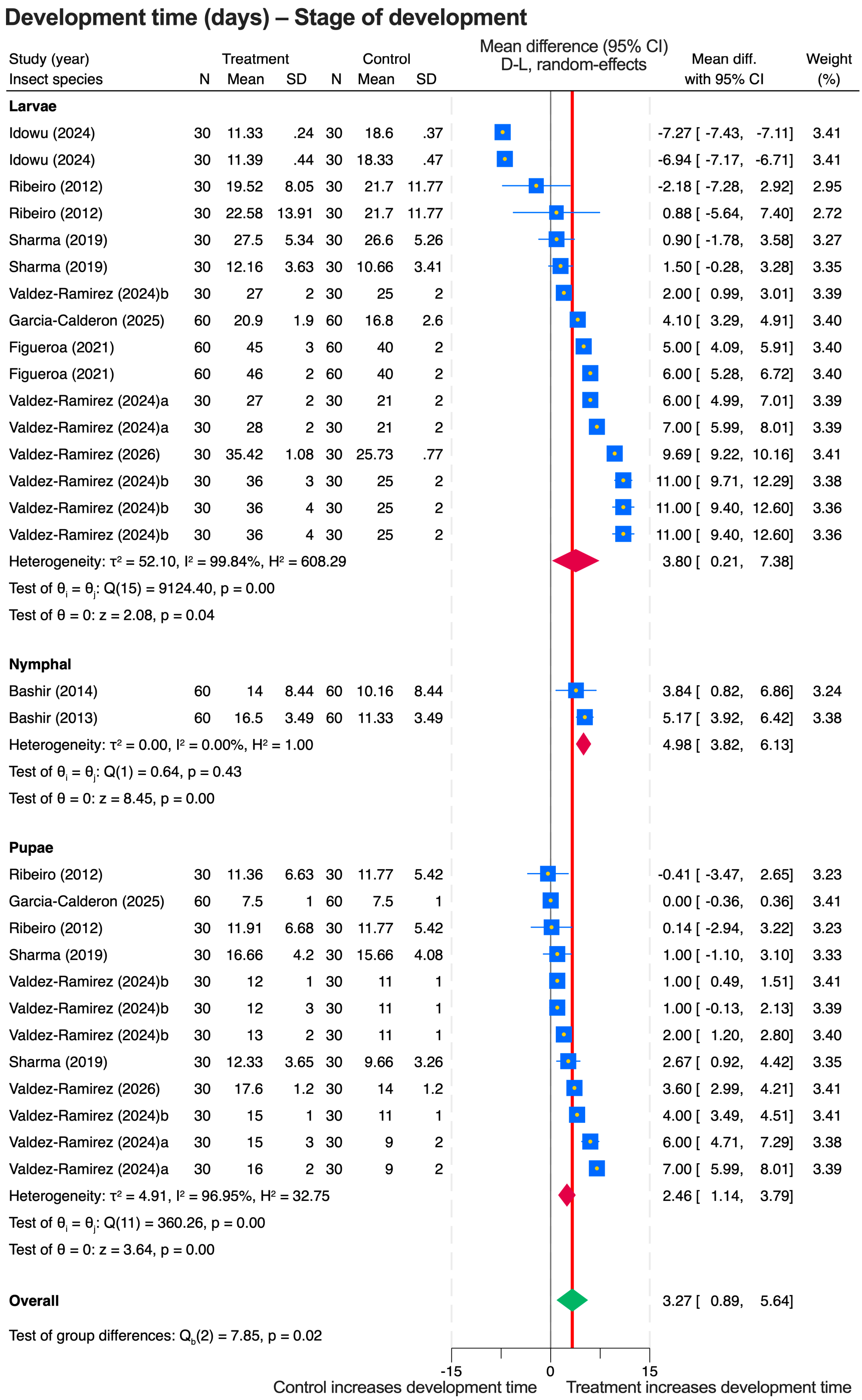

Figure 3. Forest plot of the D-L random-effects subgroup meta-analysis that included 30 individual studies reported in 10 publications that assessed the effect of Jatropha spp. botanical extracts on the development time of insect pests.

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3.8. Meta-Analysis of the Oviposition Inhibition

Supplementary Table 7 presents a summary of the sub-group meta-analyses conducted to estimate the mortality of insect pests due to Jatropha spp. botanical extracts. **Supplementary Figure 8** provides a visual representation of the forest plots from the meta-analysis. Eleven studies that were included in six publications showed that, in comparison to the control group, the pooled estimated from the treated insects had a significant reduction in oviposition of -20.53 eggs laid (-28.77 to -12.28; z =-4.88, $p < 0.001$). According to a value of Q = 23,789.02, the homogeneity test revealed substantial heterogeneity across the studies ($p < 0.001$), with the heterogeneity statistics I^2 (99.96%) and Tau² (184.31) confirming this disparity.

An analysis of the effect by Jatropha spp. revealed that *J. curcas* extracts exhibited a significant reduction in insect oviposition of -43.73 eggs laid (-60.74 to -26.73), while *J. gossypifolia* extracts showed a modest reduction of -3.60 eggs (-4.21 to -2.99) in treated insects. A significant difference in the efficacy of the two species was identified (Qb = 21.36, $p < 0.001$), suggesting that *J. curcas* has a substantially greater oviposition-inhibiting effect than *J. gossypifolia*. Regarding the botanical part from which the extract was obtained, significant differences in oviposition inhibition were observed between the structures evaluated (Qb = 5.65, $p = 0.017$). The seeds-derived extracts had the greatest efficacy, reducing oviposition by -46.90 egg laid, while in contrast, the extracts derived from the leaves did not demonstrate a significant effect on oviposition (-7.87%, $p = 0.124$).

The subgroup meta-analysis by type of extract revealed a differential effect on oviposition of the treated insects (Qb = 51.97, $p < 0.001$). Oil was identified as the most effective extract, achieving a reduction in oviposition of -46.90 eggs laid. This was followed by diethyl ether, ethanolic, and crude extracts, which showed intermediate but significant oviposition reduction, with a range of -10.85 to -2.75 eggs laid in comparison to the control ($p < 0.00$). In contrast, aqueous extracts had no significant effect on oviposition (-10.85, $p = 0.201$).

The meta-analysis included five insect species, among which Jatropha spp. extracts exerted a differential oviposition inhibitory activity depending on the specific insect evaluated (Qb = 2431.02, $p < 0.001$). The most susceptible species were *C. maculatus* (-58.74 eggs laid) and *S. zeamais* (-33.43 eggs laid), whereas *C. chinensis* showed moderate susceptibility, with a reduction in oviposition of -4.28. Finally, *Jatropha* spp. botanical extracts did not significantly inhibit the oviposition of *S. gregaria* or *T. castaneum* (p > 0.05). Due to the reduced number of studies included, no secondary analyses were conducted.

3.9. Meta-Analyses of the Repellency Activity

A summary of the sub-group meta-analyses conducted to estimate the repellency activity effect of Jatropha spp. extracts is presented in **Supplementary Table 8**, with their forest plots included in the **Supplementary Figure 9**. All the studies included in the meta-analysis evaluated exclusively extracts of *J. curcas*. The pooled estimate of the eight individual studies reported in three publications showed a significant increase in repellency of 33.37% (21.29 to 45.46) among the insects treated with the botanical extracts compared to the control group (z = 5.41, $p < 0.001$). The homogeneity test revealed substantial heterogeneity among the studies (Q = 173.98, $p < 0.001$), a finding that was confirmed by the heterogeneity statistics I^2 (95.98%) and Tau² (272.58), whose values indicated the existence of considerable disparity.

There were significant differentes in the repellency activity depending on the botanical part from which the extract was obtained (Qb = 11.83, $p = 0.001$). Seed extracts showed the highest efficacy, with an increase in repellency of 52.40% (33.46 to 71.35), while leaves-derived extracts also had a significant repellent effect, though to a lesser extent (17.05%, 9.11 to 24.99). Furthermore, the type of extract utilized was a determining factor in the repellent activity against the treated insects, as suggested by the significant differences found between the groups (Qb = 32.61, $p < 0.001$). The most efficient extracts were petroleum ether (45.52%), and oil extracts (43.20%). Methanolic and chloroform extracts showed intermediate efficacy, with repellency values of 26.75% and 21.27%, respectively, with the lowest repellent activity being observed in hexanic extracts (7.59%).

The meta-analysis included a total of three insect pest species, among which the botanical extracts from *J. curcas* resulted in a differential repellent activity on the evaluated species (Qb = 15.77, $p < 0.001$). *S. zeamais* was the most susceptible species, with a repellency of 65.01%, followed by *Rhynchophorus ferrugineus* (43.20) and *T. castaneum* (17.05%). Due to the reduced number of individual studies, no additional secondary anlyses were performed.

4. Discussion

This systematic review and meta-analysis identified a total of 77 publications documenting the insecticidal activity and developmental effects of extracts obtained from different botanical parts of Jatropha spp. for the control of insect pests. The geographical distribution of these studies was concentrated in tropical regions, primarily in East Africa, South Asia, and Latin America. This finding can be attributed to the ecological adaptation of the genus Jatropha (Euphorbiaceae), which includes approximately 186 species [21], and whose natural distribution is mainly restricted to tropical and subtropical areas. The lack of studies in regions such as Europe, North Asia, and North America may be attributed to climatic conditions that do not favor the growth and proliferation of these species, as well as to the limited presence of crops that are vulnerable to tropical insect pests. The predominance of research in Africa indicates a regional interest in the development of botanical alternatives for the management of insect pests, particularly those that affect stored grains and crops of economic importance. This approach responds to the need to reduce the use of synthetic insecticides, enhance food security, and promote sustainable agricultural practices.

With respect to the representativeness of Jatropha species, the majority of studies have focused on *J. curcas*, followed by *J. gossypifolia* and, to a lesser extent, *J. dopharica*. These results are consistent with previous research that has demonstrated the bioactivity of extracts from the seeds, leaves, and oil of *J. curcas* against insects of various taxonomic orders [10], consolidating its potential as a phytosanitary resource in the context of pest management. In addition, the sumary of evidence indicated that aqueous and powder extracts, primarily derived from leaves and seeds, exhibited insecticidal properties that included high mortality rates and disruptions in the development of insect pests. This finding is particularly relevant from an agroecological perspective, as these extracts can be produced in an accessible manner by local producers, without requiring complex or costly extraction processes. Consequently, the use of botanical extracts from Jatropha constitutes a viable and sustainable alternative for the control of insect pests, both within storage systems and in agricultural crops affected by polyphagous pests. The majority of publications in this study were in English, suggesting a potential barrier to the dissemination of knowledge from regions such as Africa and Latin America, where access to scientific literature in English may be limited. Consequently, the paucity of research on less extensively studied species of the Jatropha genus may be attributed to this phenomenon.

The findings of this study confirm that extracts from the leaves and seeds of *J. curcas* exhibit notable insecticidal activity and disrupt the development of insect pests associated with grain storage. These findings were also demonstrated in a previous study, which observed a significant increase in mortality and a reduction in insect populations, accompanied by physiological alterations, as well as a decrease in oviposition, inhibition of adult emergence, an increase in anti-feeding activity, and a high percentage of repellency [10]. The observed prolongation of larval and pupal development, in conjunction with the diminished oviposition, indicates a direct impact on the reproductive cycle of pests. This impact has the potential to result in a sustained population decline below the economic threshold, thus aiding in the prevention of substantial losses in crops and in the economy of producers in various regions. These effects would directly contribute to the protection of stored grains, including corn, wheat, rice, oats, cowpeas, beans, sorghum, barley, lentils, and chickpeas, and reinforce the potential of *J. curcas* as an agroecological alternative for post-harvest management of insect pests.

These findings reinforce the potential of *J. curcas* as an agroecological solution for managing insect pests affecting stored grains, including corn, wheat, rice, oats, cowpeas, beans, sorghum, barley, lentils, and chickpeas. Furthremore, the aqueous extract of *J. curcas* seeds has demonstrated efficacy against phytophagous insects, including *Aphis gossypii*, Cheilomenes spp., Dydercus spp., Nisotra spp., Podagrica spp., and *Zonocerus variegatus*, common pests in okra (Abelmoschus esculentus) crops in West Africa [22]. These results suggest that botanical extracts from *J. curcas* can be utilized in the cultivatio of regionally important crops. However, it would be appropriate to expand their evaluation under different agroecological conditions and against endemic insect pests in order to validate their effectiveness in diverse regional contexts.

When extracted using suitable solvents and combined with appropriate adjuvants, the botanical extracts from Jatropha spp. acquire pesticidal properties that enhance their effectiveness in the field [23]. In addition, it was observed that extracts of *J. curcas* exhibited bioactivity against polyphagous lepidoptera of the Noctuidae family, including *S. frugiperda*, *S. exigua*, and *H. armigera*. These lepidopterans are notorious for their abolity to damage a wide range of gricultural crops, including corn, sorghum, tomato, soybean, cabbage, tobacco, peanut, cotton, broccoli, cauliflower, lettuce, and spinach. The application of these extracts could contribute to the preservation of these crops, thereby reducing economic losses and enhancing food security. Moreover, Jatropha spp. botanical extracts could assist in decreasing the reliance on synthetic chemical insecticides, whose excessive use has had deleterious effects on the environment and human health [24].

Notable, seeds from local genotypes, such as *J. curcas* Atencingo, have been found to contain compounds such as oleic and linoleic acids, which have demonstrated bioactivity against S. frugiperda [25]. In this context, previous studies have associated these fatty acids with mechanisms of action that include the induction of apoptosis in neuronal cells of Helicoverpa zea [26] and transient uncoupling in SF-21 cells of S. frugiperda, affecting their respiratory metabolism [27]. The search for novel control strategies has prompted the investigations of synergies between extracts from different botanical species, as well as other organisms and microorganisms. For example, in comparison to the individual application, the combination of extracts from the leaves of *Lantana camara* and *J. curcas* has shown higher larval mortality and lower egg hatching in *Diparopsis castanea*, a cotton pest in Central Africa [28]. Similarly, a synergistic interaction has been demonstrated between the botanical extract of *J. curcas* and the enzymatic extract of *Serratia marcescens* in the control of *S. frugiperda* [29]. This finding provides a novel framework for the development of combined formulations that integrate lytic enzymes and plant metabolites, with the potential to improve their effectiveness of insect pest control. Furthermore, the utilization of mixtures with different mechanisms of action has the potential to diminish the probability of resistance development in insect pests populations, thus strengthening sustainable control strategies.

This study identified a limited amount of research reporting the bioinsecticidal activity of *J. gossypiifolia* against insect pests. This scarcity of evidence for this species could be attributed to its nature as a regional shrub, predominantly distributed in southern Africa, where climatic conditions favor its growth [30]. However, the findings reveal that leaf extracts of *J. gossypiifolia* exhibit insecticidal activity against *S. exigua* and **S. frugiperda**, which are two insect species that affect economically important crops such as broccoli and corn, respectively. Likewise, an effect was observed on the development of stored grain pests, including *C. chinensis* and *T. castaneum*. It is important to note that most of the studies documenting this activity have been conducted in countries such as Thailand, Bangladesh, and Colombia, suggesting that these species have been evaluated within specific local contexts. The evidence summarized suggests a growing interest in exploring alternative control measures that are derived from endemic plant resources and are adaptable to the agroecological characteristics of each region.

J. gossypiifolia has been demonstrated to possess several mechanisms of action that contribute to the protection of local agricultural crops, thereby reinforcing its potential as an agroecological control agent. The use of plant species that possess bioactive properties, such as J. gossypiifolia, constitutes a promising strategy for the management of insect pests, particularly within agricultural systems that aspire to reduce dependence on synthetic chemical insecticides and promote integrated management practices which are adapted to regional particularities. This phenomenon is corroborated by complementary studies conducted with other species belonging to the Euphorbiaceae family. For instance, aqueous extracts of *Euphorbia thymifolia* have shown notable feeding deterrent and repellent properties against *Rhyzopertha dominica [31],* while the latex of *Euphorbia tirucalli* has inhibited the oviposition of *Callosobruchus maculatus* [32]. These results demonstrate the value of exploring and applying plant extracts in the agroecological context for the control of insect pests. Earlier research has documented the insecticidal prperties and the impact on the development of *S. frugiperda* when hexanic, methanolic, and ethyl acetate extracts obtained from *Ricinus communis* seeds were employed [32]. These findings serve to reinforce the notion that various species of Euphorbiaceae possess bioactive compounds with the potential to be incorporated into integrated pest management strategies, both in food crops and in stored grain systems.

Finally, methanolic and ethanolic extracts from J. dopharica leaves exhibited limited insecticidal activity, with effects observed solely against *C. chinensis*. The inclusion of only two studies in this systematic review and meta-analysis on *J. dopharica* precludes the generation of conclusive evidence to recommend its use as an alternative for insect pest control. However, other studies have reported that extracts from the leaves and seeds of *J. dopharica* increase the mortality of *Bemisia tabaci* whitefly nymphs on tomato plants (*Solanum lycopersicum*) [33]. The divergent outcomes and the paucity of studies may be attributable to the restricted geographical distribution and the limited accessibility in the field. Nonetheless, these preliminary results suggest that *J. dopharica* could have specific applications in the regional management of certain insect pests. This approach would facilitate a more precise estimation of its potential as a tool in sustainable control strategies.

5. Conclusions

The objective of our research was achieved by synthesizing the body of evidence for the different species, demonstrating a greater amount of research on *J. curcas* but with a well-documented effect, while *J. gossypiifolia* and *J. dopharica* showed lower efficacy but promising results as viable alternatives in the integrated management of insect pests, both in agricultural crops and in storage systems. The accessibility of aqueous and powdered extracts, in conjunction with their established efficacy, renders then as promising alternatives for producers in tropical regions seeking sustainable and cost-effective solutions for insect pest management. However, further research is necessary to conduct toxicity tests and ascertain that they do not pose a threat to non-target insects and human health.

The results obtained confirmed the potential of the Jatropha spp. as a viable agroecological alternative for the biological control of insect pests belonging to different taxonomic orders. As suggested by Dalavayi Haritha et al. [7] the integration of botanical extracts from these species into organic farming systems, in conjunction with alternative integrated pest management strategies holds promise as a highly effective approach. The implementation of such integration would allow producers to utilize these extracts as a preventive measure, thereby contributing to the mitigation of insect pests outbreaks that have the potential to compromise crop productivity. However, further research is needed to identify and characterize a greater number of metabolites with bioinsecticidal activity present in Jatropha extracts, with the aim of advancing toward their commercial-scale production. Consequently, it is recommended that bioassays be conducted under greenhouse and field conditions to evaluate the performance of these extracts in real-world scenarios and to determine the environmental and agronomic variables that may influence their effectiveness. These studies will contribute to the optimization of their formulation and application, thus strengthening their role as an agroecological alternative in pest control.

6. Limitations

This study has several limitations that should be considered when interpreting the results. First, the studies included were published exclusively in English, Portuguese, and Spanish, which may have excluded relevant research available in other languages or in non-peer-reviewed journals, thus limiting the comprehensiveness of the analysis. Second, the studies employed a variety of methodologies and experimental designs, which complicates the direct comparison between them difficult and limits the possibility of generalizing the findings. Finally, substantial variability was observed in the content of active ingredients present in the different plant parts of Jatropha used, attributable to geographical differences. This variability represents a significant challenge for the standardization and production of extracts with a consistent chemical composition. In this regard, the present research constitutes a first effort to systematically synthesize the available information by employing robust statistical methodologies that facilitate the integration of results from studies with disparate approaches and experimental conditions. Despite the heterogeneity among the studies analyzed, it was possible to generate estimates of the insecticidal potential as well as the effects on the development of insect pests, providing quantitative evidence of their bioactive potential. However, this heterogeneity must be carefully considered when interpreting the results, as it may influence the reproducibility and applicability of the recommendations in different agroecological contexts.

Supplementary Materials: The following supporting information can be downloaded at: Preprints.org, Supplementary Table 1: Detailed strategy of the search in electronic databases; Supplementary Table 2: Excluded studies and their main reasons; Supplementary Table 3: List of the 77 studies included in the systematic review and meta-analysis by the Jatropha spp.; Supplementary Figure 1: Risk of bias assessment of individual studies; Supplementary Table 4: Summary of the subgroup meta-analyses to estimate mortality; Supplementary Figure 2: Forest plots of the meta-analysis to estimate mortality; Supplementary Figure 3: Secondary analysis of the meta-analysis to estimate mortality; Supplementary Table 5: Summary of the subgroup meta-analyses to estimate antifeedant activity; Supplementary Figure 4: Forest plots of the meta-analysis to estimate antifeedant activity; Supplementary Figure 5: Secondary analysis of the meta-analysis to estimate antifeedant activity; Supplementary Table 6: Summary of the subgroup meta-analyses to estimate development time; Supplementary Figure 6: Forest plots of the meta-analysis to estimate development time; Supplementary Figure 7: Secondary analysis of the meta-analysis to estimate development time; Supplementary Table 7: Summary of the subgroup meta-analyses to estimate oviposition inhibition; Supplementary Figure 8: Forest plots of the meta-analysis to estimate oviposition inhibition; Supplementary Table 8: Summary of the subgroup meta-analyses to estimate repellency activity; Supplementary Figure 9: Forest plots of the meta-analysis to estimate repellency activity.

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Appendix A

Appendix A.1. Jatropha curcas (70 studies)

1. *J. curcas* - Seed extract (32 studies)

- Aqueous extract

In total, 15 studies assessed the effect of aqueous extract from seeds of *J. curcas*. Adabie-Gomez et al. [34] evaluated an aqueous extract and seed powder at 0-20% (w/v) via ingestion bioassays against *Sitophilus zeamais* and *Callosobruchus maculatus*, finding that the highest concentration resulted in 58% and 68.1% repellency, respectively. Another study evaluated 0.25 and 0.5% (v/v) of an aqueous extract using contact bioassays on *Nezara viridula*, observing mortality rates between 80 and 100% [35]. Babarinde et al. [36] administered an aqueous extract through fumigation (50 to 200 µL/L) and contact bioassays (0.30 to 1.50 µL/cm²) against *S. zeamais*, observing a 84.6% mortality rate at 200 µL/L. In another study, Botti-Holtz et al. [37] documented a 60% mortality rate of *Brevicoryne brassicae* after applying 0 to 3.0% (v/v) of an aqueous extract via ingestion bioassay. In a study conducted by Diabate-Gnago et al. [38], 50 and 80 (g/L) of an aqueous extract in an ingestion bioassay was administered, the results showed that the highest concentration decreased the number of *Bemisia tabaci* as well as the number of *Helicoverpa armigera* larvae. Holtz et al. [39] reported a mortality rate of 71% for *Myzus persicae* after treatment with 2.5% (w/v) of an aqueous extract obtained from the dried fruits of *J. curcas.* After applying a 3% (v/v) of an aqueous extract via contact bioassay on *Diatraea saccharalis*, Oliveira et al. [40] reported a 40% decrease in egg hatching and an increase in embryonic development of 7.1 days. Another study administered an aqueous extract at 10% (w/v) in a contact bioassay on *Podagrica uniforma* and *Podagrica sjostedti*, which reduced their populations by 64% compared to the control [41].

In a study by Orozco-Santos et al. [42], an aqueous extract at 1 and 4% (v/v) was applied to nymphs of *Diaphorina citri*, resulting in a 92.5% reduction in the number of nymphs at the highest concentration. Pant-Dubey et al. [43] determined the effect of an aqueous extract enriched with eucalyptus oil nanoemulsion and karanja (300-1500 ppm) on *Tribolium castaneum*, finding that the highest concentration resulted in mortality rates of 100%. A study was conducted to evaluate the effect of an aqueous extract at 3% (w/v) in contact application against *Rhynchophorus palmarum*, resulting in 100% repellency achieved [44]. Silva-Faroni et al. [45] demonstrated that an aqueous extract at 10% (w/v) resulted in mortality rates of 75, 100, 60, and 90% of *S. zeamais*, *Rhyzopertha dominica*, *T. castaneum*, and *Oryzaephilus surimanensis*, respectively. After administering 1.5 to 2.5% (w/v) of an aqueous extract via an ingestion bioassay on *C. maculatus*, Uddin & Abdulazeez [46] showed that the highest concentration increased the mortality in adult insects and decreased adult emergence compared to the control group. In a separate study, Ugwu [47] utilized 75 and 100% (w/v) of an aqueous extract in contact and residual bioassays on *Phytolyma fusca*, finding an increase of the mortality rate of adult insects at 100% (w/v). In the study by Ukpai-Ibediungha et al. [48], concentrations ranging from 2.5 to 10.0 (w/v) of an aqueous extract applied on *S. zeamais* resulted in an increased mortality rate of adult insects exposed to the highest concentration.

- Petroleum ether

In total, five studies assessed the effect of petroleum ether extract from seeds of *J. curcas*. Petroleum ether extract from seeds at concentrations ranging from 0.5 to 2% (v/w) was administered to *C. maculatus*, resulting in the complete inhibition of adult emergence and a reduction in oviposition [49]. In their study, Khani-Awang et al. [50] examined the effect of petroleum ether extract via ingestion (2-10 µL/g) and contact bioassays (4-20 µL/g) on the larvae and eggs of *Corcyra cephalonica*, the findings revealed an anti-feeding activity of 48.1% at 6 (µL/g) and a 58% reduction in egg hatchability at 2 (µL/mL). Kona-Taha et al. [51] utilized petroleum ether extract in contact (62.5-1000 mg/L) and ingestion bioassays (2000-8000 mg/L) on *Tuta absoluta*, finding that a 25% mortality rate in eggs was achieved at 125 mg/L, while 8000 mg/L resulted in 100% larval mortality. Another study evaluated petroleum ether extract in ingestion (1-5% w/v) and contact bioassays (2-10 µl/g) against *Sitophilus oryzae*, with results indicating a 66% mortality rate at 10 (µl/g) and 69.6% repellency at 5% (w/v) [52]. Ugwu determined the effect of petroleum ether extract at a concentration of 10 (mL/L) in an ingestion bioassay on the populations of *Megalurothrips sjostedi* and *Maruca vitrata*, observing a 52.0% and 59.1% reduction in their numbers, respectively [53].

- Acetonic extract

Four studies determined the effect of acetonic extract from seeds of *J. curcas*. Following the application of acetone extract at concentrations between 0.5% and 20% (v/v) via immersion against *S. zeamais,* a 100% mortality was achieved at the highest concentration, while the progeny emergence was diminished by 45.80% [54]. García-Calderón et al. [55] evaluated concentrations of 1000, 2300, and 5000 ppm of acetone extract via ingestion bioassay on *Spodoptera frugiperda*, their results showed that 5000 ppm caused a larval mortality rate of 73%. In the study by Valdez-Ramírez et al. [29], acetone extract (100 to 2500 ppm) was administered via an ingestion bioassay on *S. frugiperda*, the authors found that a concentration of 2500 ppm resulted in 86.67% larval mortality and a delay in larval development by 4-10 days. In another study, where 0-2500 ppm of an acetone extract was administered against *S. frugiperda*, the authors reported that the highest concentration resulted in a 51.5% reduction in the percentage of damage to corn plants [56].

- Methanolic, ethanolic, or hexanic extract

In total, six studies assessed the effect of methanolic, ethanolic, or hexanic extracts from seeds of *J. curcas*. Baideng et al. [57] reported the use of methanolic extract (10,000 to 60,000 ppm) by ingestion on *Crocidolomia binotalis*, finding that at 50,000 (ppm), 90% larval mortality was achieved. Another study evaluated the ethanolic extract (10, 20, 30, 40, and 50%, v/v) in contact and ingestion bioassays on *Rhynchophorus ferrugineus*, reporting that the highest dose resulted in 100% mortality 24 h post-treatment [58]. The hexane seed extract, used in bioassays at 5 to 20% (v/v), and ingestion at 10% (v/v) against nymphs of *Schistocerca gregaria* exhibited a mortality of 59.2% at a concentration of 20%, while ingestion of the extract led to a reduction in egg hatching and a delay in nymphal development by five days [59]. A subsequent study reported that ingestion and contact bioassays using 5% (v/v) hexane extract on *S. gregaria* produced an anti-feeding effect of 78.92%, whereas 10% (v/v) showed a nymph mortality of 43.39% and reduced fertility when compared to the control group [60].

- Mixture of extracts

Four studies assessed the effect of a mixture of extract from seeds of *J. curcas*. In a series of studies, Figueroa-Brito et al. [61,62] evaluated the effects of aqueous and acetone extracts on *Copitarsia decolora* under laboratory and greenhouse conditions, finding that a concentration of 5% (v/v) aqueous extract reduced larval viability by 46% compared to the control, whereas the acetone extract at 500 ppm resulted in 60% deformities in adults and 50% cumulative mortality. The study conducted by Valdez-Ramírez et al. [63] used hexane and acetone extracts at concentrations ranging from 0 to 5000 ppm against *S. frugiperda*, the authors showed that 5000 ppm caused 100% larval mortality. In a separate study, Valdez-Ramírez et al. [25] administered hexane, acetone, methanol, and aqueous extracts from seeds of different genotypes at concentrations ranging from 0 to 5000 ppm via ingestion bioassay on *S. frugiperda*, with their results showing that the Ahuehuetzingo genotype resulted in 100% larval and pupal mortality at the highest concentration.

2. *J. curcas* - Seed oil (14 studies)

Acda [64] found that applying seed oil at concentrations ranging from 20% (w/w) on *Coptotermes vastator* resulted in a mortality rate of 93.5%. Agboka-Mawufe et al. [65] reported that seed oil at a low concentration of 5% (v/v) against *Mussidia nigrivenella* increased the oviposition deterrence and reduced larvae in 49.2% in the field when compared to the control group. Another study reported that the use of seed oil at 5, 10, and 30 (mg/mL) was toxic and reduced the survival rate of *Atta sexdens* to less than 25% [66]. In the study by Verma-Pradhan et al. [67], phorbol esters from seed oil (0.005 to

0.5 g/mL) were utilized against *Odontotermes obesus*, resulting in a 100% mortality rate at the highest concentration. Priyanka & Srivastaya [68] treated *Spodoptera litura* larvae with 1 or 2% (v/v) seed oil in contact and ingestion bioassays and found that a concentration of 2% caused 73.3% larval mortality. Another study administered seed oil at 0.5-3% (v/w) on *C. maculatus* and *Callosobruchus chinensis,* with the results showing that all concentrations caused a cumulative mortality ranging from 66.9 to 73.1% [69]. Bessike-Ndiwe et al. [70] found that seed oil at 1,000 (mL) in a contact bioassay on *Macrotermes bellicosus* resulted in a reduced mortality rate of 13.3%.

Devappa et al. [71] investigated the effect of a seed oil enriched with phorbol esters on *S. frugiperda* using contact and ingestion bioassays, they reported that 0.25 (mg/mL) resulted in a 33% reduction in food consumption and a 42% reduction in larval growth, with 20 (mg/mL) causing 80% larval mortality. Holtz-Stingue et al. [72] showed that the administration of 3% (v/v) of seed oil resulted in a mortality rate of 76.9% of *B. brassicae*. Katoune-Lafia et al. [73] evaluated the effects of seed oil at concentrations ranging 2.5-10% (v/v) on the infestation of *M. sjostedti*, *Clavigralla tomentosicollis*, and *Aphis craccivora*, the authors observed that at a concentration of 10%, infestation levels were reduced in comparison to the control group. Prabowo [74] administered 5 to 40 (mL/L) of seed oil from the Wangi and Nut IP2A varieties via ingestion bioassays on *H. armigera*, showing that the highest concentration resulted in 65.3% inhibition of pupal weight and a 98.4% reduction in egg hatchability. Ratnadass-Togola et al. [75] administered seed oil (0.35 to 12.2, g/mL) in contact and ingestion bioassays against *H. armigera*, finding that 0.35 g/mL led to a 68.7% reduction in hatching rate, while pupal weight decreased 35.5% at a concentration of 3.5 g/mL. Sharma-Verma et al. [76] employed a contact bioassay with seed oil enriched with phorbol esters in both cold and hot water applications at concentrations ranging from 1.25 to 6.25% (v/v) on *O. obesus,* the authors found that a higher concentration of the oil in cold water resulted in an 83.3% mortality rate. In a separate study, Sharma & Gaur [77] applied 2.5 to 10% (v/v) seed oil in an ingestion bioassay on *S. litura* and *Spilarctia obliqua*, finding that at 10% (v/v) the larval period increased by 13.3 and 28.3 days, respectively, while mortality was 56.6 and 53.3%.

3. *J. curcas* - Seed powder (5 studies)

Andargae-Tagele et al. [78] reported that 5% (w/w) seed powder administered in an ingestion bioassay on *C. maculatus* significantly reduced the emergence of progeny. In another study conducted on the same insect, with the application of seed powder at 15, 20, and 25% (w/w) the authors observed that the intermediate concentration of 20% resulted in a repellency rate of 53.3% and 60% mortality, with no offspring produced [79]. Araya & Getu [80] administered 5-15% (w/w) seed powder to *Zabrotes subfasciatus* in an ingestion bioassay and observed a reduction in the emerging offspring at the lowest dose of 5%. Bayih-Tamiru et al. [81] evaluated the effect of seed powder (1 and 2%, w/w) on *Z. subfasciatus*, finding an increased mortality of 74.1% at a concentration of 2%. Ohazurike-Omuh et al. [82] evaluated 0.1-0.4 (g) seed powder in an ingestion bioassay on *S. zeamais* and found that 0.3 and 0.4 g led to an increase in the mortality rate when compared to the control.

4. *J. curcas* - Leaf extract (16 studies)

- Aqueous extract

In total, 11 studies examined the effect of aqueous extract from leaves of *J. curcas*. Addisu-Mohamed et al. [83] reported that 20 to 35% (w/v) of an aqueous extract resulted in 100% mortality of *Macrotermes ssp. in a contact bioassay.* Another study reported an 88.6% mortality and increased anti-feeding activity after applying an aqueous extract of 10% (w/v) in an ingestion bioassay on *Odontotermes wallonensis* [84]. Opuba-Adetimehin et al. [85] reported a high mortality of 98% and an 81% reduction in oviposition rate after exposing *C. maculatus* in an ingestion bioassay with an aqueous extract at 1.0% (w/v). Silva-Souza et al. [86] evaluated a 10% (w/v) aqueous extract in an ingestion bioassay on *Ceratitis capitata*, finding a 95.6% mortality rate. Conversely, two additional studies reported a decreased mortality following the administration of aqueous extract. Ohoueu-Bouet et al. [87] found that concentrations ranging from 100 to 400 (mg/mL) administered via an ingestion bioassay on *Hypothenemus nampie* resulted in all concentrations causing 50% mortality.

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Another study found a low mortality rate of 10.1% after applying a 2% (w/v) aqueous extract on *S. obliqua* larvae [88].

Amoabeng-Gur et al. [89] evaluated a 3% (w/v) aqueous extract in an ingestion bioassay against larvae of *Plutella xylostella* and *B. brassicae* aphids, finding an increased larval mortality rate and reduced aphid infestation. Chudasama-Sagarka et al. [90] determined that 5% (w/v) of an aqueous extract resulted in 64.1% deterrence of oviposition and 62.0% reduction in adult emergence of *C. maculatus*. In a separate study, aqueous extracts (range, 1.0-3.0%, w/v) administered to *M. persicae* resulted in high mortality rates ranging from 86 to 96% [91]. Jide-Ojoa et al. [92] demonstrated that an aqueous extract at 100% (w/v) inhibited oviposition by 76.4% and suppressed progeny of *S. zeamais*. In a subsequent study, these researchers employed aqueous extracts (0-100 ppm) through topical applications on the same insect, observing that the highest concentration inhibited oviposition by 90%, reduced adult emergence by 92.3%, and caused 90% mortality [93].

- Methanolic or acetonic extract

Three studies assessed the effect of methanolic or acetonic extract from leaves of *J. curcas*. Ribeiro-Silva et al. [94] determined the effect of a methanolic extract from fresh or dry leaves (1000 mg/kg) in an ingestion bioassay against *S. frugiperda*, documenting a larval mortality between 56.6 and 60%. Another study evaluated ethyl acetate and methanolic extract at concentrations ranging from 25 to 100% (v/v) in contact and ingestion bioassays against *S. frugiperda*, with the highest concentration resulting in 100% contact toxicity after 96 h post-treatment, while ingestion of the extracts caused 100% larval mortality [95]. In an ingestion bioassay against *S. obliqua*, acetone extract at 5.0 (v/v) caused a larval mortality rate of 33.3%, while at 1.25 (v/v) it reduced pupation by 26.6% compared to the control [96].

- Mixture of extracts

Two studies reported the effect of a mixture of extract from leaves of *J. curcas*. Habib ur et al. [97] utilized methanolic, chloroform, and n-hexane extracts at concentrations ranging 5-15% (v/v) in an ingestion bioassay on *T. castaneum* and *R. dominica*, with their findings indicating that the highest dose caused a mortality of 37.3 and 49.1%, respectively. Rehman-Mirza et al. [98] applied 15% (w/v) methanolic, chloroform, petroleum ether, and n-hexane extracts via contact application on *T. castaneum* and reported that the highest dose resulted in an increased repellency of 63.3% when compared to the control.

5. *J. curcas* - Stem (3 studies)

Guerra-Árevalo et al. [99] evaluated an aqueous extract at 10-40% (v/v) in an ingestion bioassay against *Hypsipyla grandella*, where the highest administered dose resulted in a 67% mortality. In a separate study, aqueous extracts (0.0-3.0%, w/v) were assessed in an ingestion bioassay on *P. citri*, with the two highest concentrations of 2.0 and 3.0% causing 91.6% mortality of the insects [100]. In an ingestion bioassay against *P. xylostella* and *B. brassicae*, 25-50% (v/v) aqueous extracts reduced both the infestation levels of *B. brassicae* and the number of larvae [101].

Appendix A.2. Jatropha Gossypifolia (5 Studies)

1. *J. gossypifolia* - Leaf extract (4 studies)

Bullangpoti-Khumrugsee et al. [102] utilized 1000 to 9000 (ppm) ethyl acetate extracts in an ingestion bioassay on *Spodoptera exigua* larvae, with the extract showing a LC_{50} value of 8644 ppm at 24 h post-exposure. In a separate study, the authors evaluated the ethanolic extract in ingestion bioassays at 400 to 40,000 (mg/L) and contact bioassays at 4 (mg/L) on *S. frugiperda* larvae, where they documented 100% mortality at the highest dose [103]. Hina & Meera [104] employed an aqueous, crude, suspension, ethanolic, and diethyl ether extracts (range 1-25%, w/v) in an ingestion bioassay on *C. chinensis*. The authors showed that 25% (w/v) ether extract significantly reduced the oviposition of the insect. Another study evaluated 400 to 1200 (ppm) of an aqueous extract in an ingestion bioassay against *T. castaneum*, whose oviposition percentage was lower than the control at 800 ppm [105].

2. *J. gossypifolia* - Leaves powder (1 study)

Valencia et al. [106] used 0.01 to 100 (mg/mL) leaves powder in an ingestion bioassay on larvae of *Busseola fusca*, *Ostrinia nubilalis*, and *Sesamia nonagrioides*, with the highest dose causing 100% mortality in *B. fusca* and *O. nubilalis*.

Appendix A.3. Jatropha dopharica (2 studies)

1. *J. dopharica* - Leaf extract (2 studies)

Al-Lawati et al. [107] evaluated 1% (v/v) methanolic and ethanolic extracts in a contact bioassay on *C. chinensis* and observed a mortality of 70%. In a subsequent study, a higher concentration of 2% caused 80% mortality compared to the control [108].

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