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Comparing the sensitivity of aquatic organisms relative to *Daphnia* sp. toward essential oils and crude extracts: A meta-analysis

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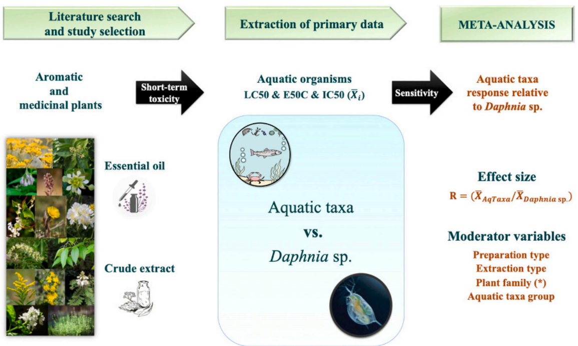
HIGHLIGHTS

- Plant-based crude extracts-CE and essential oils-EO may pose aquatic organisms at risk.
- A meta-analysis was used for sensitivity comparisons of aquatic taxa and *Daphnia* sp. to CE and EO.
- Plant family strongly influenced the magnitude of the toxic effects of CE and EO.
- *Daphnia* sp., *Danio rerio* and *Thamnocephalus platyurus* are potential model organisms.
- *Artemia* sp. can be a relevant tool for a preliminary screening of CE and EO.

GRAPHICAL ABSTRACT



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ABSTRACT

Interest on aromatic and medicinal plants (AMP)-based products, especially crude extracts (CE) and essential oils (EO), has increased over recent years due to their bioactive and biopesticide properties, though a variety of these compounds is environmentally damaging. Aquatic organisms can easily be exposed to the toxicological risks of AMP-based products, but research exploring existing ecotoxicity data to non-target organisms is limited. The present study aimed to, for the first time, systematically review published evidence on the acute/short-term toxicity (LC50, EC50 or IC50) of CE and EO from AMP, comparing sensitivity of aquatic organisms. Eleven studies that reported the sensitivity of aquatic taxa and *Daphnia* sp. to CE and/or EO, were included in the review, contributing with 27 effect sizes, calculated as the response ratio R ($\mathrm{Ecotoxicity}_{\mathrm{AquatTaxa}}/\mathrm{Ecotoxicity}_{Daphnia}$). Meta-analytic technics were used to estimate the overall sensitivity of aquatic taxa relative to *Daphnia* sp. while identifying moderators [plant preparation (CE or EO), extraction type, plant part, plant family, and aquatic taxa identity] potentially affecting relative sensitivities. The overall effect size R was 1.51 (95 % CI = 0.97 to 2.34, *N* = 27), indicating a non-significant difference in the toxicity of CE and EO to aquatic taxa relative to *Daphnia* sp. However, the high heterogeneity among individual effect sizes (I^2 = 99 %) suggested opposing responses of aquatic taxa relative to *Daphnia* sp. The magnitude of effects (R) was strongly influenced only by plant family. *Daphnia* sp. arose as a potential model organism for assessing the ecotoxicity of CE and EO, along with the fish

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Danio rerio and the crustacean *Thamnocephalus platyurus*, while *Artemia* sp. seems a relevant alternative for a preliminary screening. Likewise, the current study sheds light on the (underestimated) toxicity of CE and EO to aquatic ecosystems and that much remains to be uncovered, providing insights and recommendations for future research.

1. Introduction

Interest on crude extracts (CE) and essential oils (EO) from aromatic and medicinal plants (AMP) has increased over recent years due to their bioactive and biopesticide properties (da Silva Sá et al., 2022; Ebani and Mancianti, 2020; Masetti, 2016). Plant products are generally thought to be safe, though plants can produce and accumulate a variety of compounds with potential environmental toxic effects (Ifeoma and Oluwakanyinsol, 2013; Ofosu et al., 2020). Various factors, including genetics, taxonomy, plant part, geographical region, production methods, and analytical methods for extracting and quantifying plant compounds, can influence their toxicity (Choudhary and Sekhon, 2011; Thangaleela et al., 2022). Another significant concern is plant prior contamination by pollutants such as metals or pesticides, which raises additional safety issues and can impact the potential benefits of plant preparations (Iordache et al., 2022). Furthermore, the high complexity and variability in composition and properties of plant formulations poses a significant challenge not only to standardize the various specific commercial purposes but also to categorize the potential adverse environmental effects (Choudhary and Sekhon, 2011).

Extraction is the first crucial step for obtaining the target compounds from plant materials (Brusotti et al., 2014). It involves the separation of compounds by selective and well-established methods, including conventional techniques such as solid–liquid extraction (solvent extraction) and hydrodistillation, or advanced techniques such as supercritical fluid extraction and solvent-free techniques (Brusotti et al., 2014; Bubalo et al., 2018; Chemat et al., 2019). When solvents are employed for CE or EO extraction, solvent selection is primarily determined by the solubility characteristics of the target compounds (Abubakar and Haque, 2020; Gupta et al., 2012; Sasidharan et al., 2011). The plant part used in the extraction process of CE or EO also significantly impacts the quality of the extracted compounds (Lezoul et al., 2020). Plant extractions can be prepared from the whole plant or from its various parts, viz. flowers, buds, seeds, leaves, twigs, bark, wood, fruits, and roots (Gupta et al., 2012; Thangaleela et al., 2022). The accumulation of bioactive compounds from secondary metabolism in specific organs is part of plants defensive strategies, resulting in high variation in compound composition and concentration among plant organs (Falkowski et al., 2020). Furthermore, the plant family serves as an important taxonomic classification level for identifying the usefulness and potential toxicity of plant species (Huai et al., 2010). Families such as Apocynaceae, Araceae, Aristolochiaceae, Asteraceae, Euphorbiaceae, and Fabaceae, are commonly associated with plants that produce toxic compounds (Griffiths et al., 2020; Huai et al., 2010). For instance, alkaloid quinolizidines and flavonoid rotenoids are toxic compounds that are mostly found in the Fabaceae family (Falkowski et al., 2020; Griffiths et al., 2020).

Research findings on the environmental toxic effects of plant products are not consensual, although some studies indicate short- and long-term toxic effects (Ifeoma and Oluwakanyinsol, 2013; Ofosu et al., 2020; Yap et al., 2021). Most studies assessing the potential toxicity of plant CE and EO focus on the organisms to be targeted and employ in vitro toxicity tests (da Silva Sá et al., 2022; Ivanescu et al., 2021; Yap et al., 2021). Studies including toxicity assessments on non-target organisms are less common, and among these, the majority focuses on aquatic biota (Ferraz et al., 2022; Luz et al., 2020; Yap et al., 2021). Aquatic organisms are among those that can be exposed to the toxicological risks posed by plant-based products through contamination of aquatic ecosystems by agricultural, urban, and industrial activities (Amoatey and Baawain, 2019), due to the use of CE and EO in food and cosmetics, as biopesticides, and for medicinal and veterinary purposes (Ebani and Mancianti, 2020; Ivanescu et al., 2021; Thangaleela et al., 2022). These products are continuously released into the environment, primarily through the discharge of effluents from wastewater treatment plants, but also directly into natural aquatic systems (e.g., rivers, lakes, surface and groundwater) by runoff or leaching (Caliman and Gavrilescu, 2009; Margot et al., 2015; Musee et al., 2023). The increasing commercial demand for these products across most economic activities (Jugreet et al., 2020) will likely lead to higher concentrations in the environment, though there is limited information on environmental levels for CE and EO or even their constituents. In a recent review, Musee et al. (2023) identified several aromatic compounds, some derived from plants, present in sanitizers and disinfection products, occurring in various aquatic systems (lakes, rivers, groundwaters), with data indicating concentrations ranging from low (< 1 ng L^{-1}) to high (> 100 μg L^{-1}) levels. Apart from the concentrations at which these products can be found in the environment, the adverse effects on aquatic organisms will be also influenced by their persistence, transport by water, and transformations caused by degradative processes occurring at different stages (Caliman and Gavrilescu, 2009; Margot et al., 2015).

As with other chemical products, the sensitivity of aquatic organisms to the potential toxicity of these products may differ among taxonomic and functional groups (Kovalakova et al., 2020; Wu and Seebacher, 2020). *Daphnia magna* and fish toxicity tests are the most frequently used to evaluate the toxicity of CE and EO (Ferraz et al., 2022). Although some authors suggest the use of *Artemia* sp. (Ntungwe et al., 2020) or zebrafish embryos (Jayasinghe and Jayawardena, 2019) for screening the ecotoxicity of plant-based products, they are still not demonstrated as being the most sensitive. In effect, there is a lack of debate on the differences in sensitivity of aquatic biota to the toxicity of a panoply of CE and EO, from which model test organism(s) to evaluate the toxicity of these products could be singled out. Accordingly, despite the growing interest in the use of plant-based products, few studies have explored the data already published on CE and EO ecotoxicity to aquatic species using a systematic review (but see Ferraz et al., 2022), and none using a quantitative approach such as meta-analysis. Moreover, meta-analysis, a powerful statistical tool to synthesize data taking into account their precision (Gurevitch et al., 2018), is rarely used in the ecotoxicological field.

Therefore, in the present study we carried out a quantitative systematic review of published evidence on the acute/short-term toxicity of CE and EO to aquatic taxa, including a meta-analysis to assess the sensitivity of aquatic taxa relative to *Daphnia* sp. and to identify the variables (moderators) that may affect that response. Moderators included plant preparation type (CE or EO), extraction type, plant part, plant family, and aquatic taxa identity. The questions addressed and hypotheses tested in this meta-analysis are listed in Table 1. *Daphnia magna* was selected to estimate relative sensitivities because it is one of the most worldwide recommended organisms for regulatory ecotoxicity screening of chemicals and substances in aquatic systems (e.g., EMEA, 2018; EU, 2006, 2009; OECD, 2004). Moreover, *Daphnia* species, particularly *D. magna*, have shown high sensitivity to a wide range of chemicals compared to other aquatic organisms (Blinova, 2004; Boudreau et al., 2003; Daam and Rico, 2018; Martins et al., 2007; Teodorovic et al., 2009), and has been frequently used to assess the ecotoxicity of CE and EO (e.g., Ferraz et al., 2022). What is more, since *Daphnia* sp. is a standard species, research with this organism was expected to most adequately meet the criteria for inclusion in the meta-analysis, allowing for the comparison of sensitivities with other organisms, thus with

Table 1
Questions and hypotheses addressed in the meta-analysis.

Questions	Hypotheses
Q1. Do CE and EO from AMP distinctly affect aquatic taxa relative to *Daphnia* sp.?	H1. CE and EO from AMP affect lesser aquatic taxa relative to *Daphnia* sp. that is considered the standard test species.
Q2. Are the effects (direction and magnitude) of CE and EO from AMP on aquatic taxa relative to *Daphnia* sp. affected by experimental choices…	
Q2a. … such as the type of preparation?	H2a. The effects are affected by the type of preparation (i.e., CE or EO) due to the different compounds and the proportion in which they are extracted in each method.
Q2b. … such as the type of extraction?	H2b. The effects are affected by the type of extraction (e.g., hydrodistillation, solvent extraction, or supercritical fluid extraction) that differ in the solvent that can be used, the compounds that can be extracted, and the extraction procedure.
Q2c. … such as the solvent?	H2c. The effects are affected by the type of solvent (e.g., aqueous, hydroalcoholic, ethanol, methanol, or carbon dioxide) due to the different polarity and toxicity of the chosen solvents.
Q2d. … such as the plant part?	H2d. The effects are affected by the plant part (e.g., aerial or underground) used in the preparation due to different patterns of accumulation of (toxic) compounds among plant organs.
Q2e. … such as the plant family?	H2e. The effects are affected by the plant family (e.g., Asteraceae, Lamiaceae, Piperaceae, etc.), considering that some are known for producing toxic bioactive compounds.
Q2f. … such as the contrast aquatic taxa group?	H2f. The effects are affected by the contrast aquatic taxa group (e.g., bacteria, algae, plants, etc.), since some traits common to each functional group may influence the organism's response to toxicity.
Q2g. … such as the contrast aquatic taxa family?	H2g. The effects are affected by the contrast aquatic taxa family, considering that families may differ in their sensitivity?

CE = crude extracts; EO = essential oils; AMP = aromatic and medicinal plants.

Table 2
Strings used on the online literature search. Search strings were applied to the field 'Topic', which includes title, abstract, keywords (both those defined in the study and those chosen for indexing purposes).

Data base	Search string
Web of Science Core Collection (Science Citation Index Expanded; Social Sciences Citation Index; Arts & Humanities Citation Index; Conference Proceedings Citation Index – Science / Social Science & Humanities; Emerging Sources Citation Index; Current Chemical Reactions; Index Chemicus)	((aquatic OR marine OR freshwater OR saltwater OR invertebrate* OR cladocera* OR Daphnia OR Artemia OR Thamnocephalus OR anostraca* OR vertebrate OR fish OR microalgae OR alga* OR macrophyte OR "aquatic plant*" OR zooplankton OR phytoplankton OR plankton OR insect* OR dipteran OR Chironomus OR amphibian* OR mollusc* OR crustace* OR decapod* OR annelid* OR bacteria OR protozoa OR fungi OR "aquatic hyphomycete*") AND ("essential oil*" OR "plant extract*" OR "aromatic plant*" OR "medicinal plant*") AND ("toxicity test*" OR "ecotoxicity test*" OR ecotoxic* OR "aquatic test*" OR "aquatic toxicolog*" OR toxicolog* OR EC50 OR LD50 OR LC50 OR IC50 OR acute OR *lethal* OR chronic))
Web of Science SciELO Citation Index	((aquatic OR marine OR freshwater OR saltwater OR invertebrate* OR cladocera* OR Daphnia OR Artemia OR Thamnocephalus OR anostraca* OR vertebrate OR fish OR microalgae OR alga* OR macrophyte OR "aquatic plant*" OR zooplankton OR phytoplankton OR plankton OR insect* OR dipteran OR Chironomus OR amphibian* OR mollusc* OR crustace* OR decapod* OR annelid* OR bacteria OR protozoa OR fungi OR "aquatic hyphomycete*") AND ("essential oil*" OR "plant extract*" OR "aromatic plant*" OR "medicinal plant*") AND ("toxicity test*" OR "ecotoxicity test*" OR ecotoxic* OR "aquatic test*" OR "aquatic toxicolog*" OR toxicolog* OR EC50 OR LD50 OR LC50 OR IC50 OR CE50 OR DL50 OR CL50 OR CI50 OR acute OR *lethal* OR chronic))

potential to screen the toxicity of CE and EO in aquatic ecosystems. Finally, the approach of assessing the relative sensitivity among different species was used before in ecotoxicological studies (Arena and Sgolastra, 2014; Pelosi et al., 2013). Hence, the methodological approach used intents to provide new and relevant information, namely to contribute to establish a battery of model test organisms representative of aquatic systems biodiversity and sensitivity for evaluating the effects of a variety of commercialized CE and EO from AMP on the aquatic environment.

2. Materials and methods

2.1. Literature search and study selection

Empirical studies that have addressed the toxicity of CE and EO from AMP to *Daphnia* sp. and other aquatic taxa were searched. Studies in English and Portuguese, published until November 7th, 2022, were located using Web of Science (WoS) (databases: Core Collection and SciELO Citation Index), personal literature databases, and reference lists in primary studies and in key review papers. Strings used to search for studies in the WoS databases are detailed in Table 2. The literature search produced 7084 unique records subjected to the screening process detailed below and summarized in Fig. 1.

Screening was performed in two stages (Foo et al., 2021) and reported according to the preferred reporting items for systematic reviews and meta-analysis (PRISMA) guidelines (O'Dea et al., 2021). Firstly, titles and abstracts were screened, and studies were selected if they addressed (i) the toxicity of CE and/or EO from AMP to *Daphnia* sp. and at least one other aquatic taxa (contrast aquatic taxa, henceforward), if the species names were mentioned, and (ii) reported acute/short-term toxic effects (i.e., survival, luminescence, growth) as median lethal concentration (LC50), median effective concentration (EC50) or median inhibition concentration (IC50), as all these are estimations of a 50 % adverse effect on an acute/short-term measured response. After title and abstract screening and the exclusion of clearly irrelevant studies 26 records were kept, i.e., those either clearly relevant or of uncertain relevance (Fig. 1). Secondly, the full text of the pre-selected 26 studies was screened and studies were selected for inclusion in the matrix if they met criteria (i) and (ii) mentioned above, and reported standard deviation (SD) associated with the LC50, EC50 and IC50 estimates, or enough information to allow its calculation, i.e., they reported any other variation measure and the sample size (the number of tested CE or EO concentrations) for both *Daphnia* sp. and each contrast aquatic taxa.

Some studies reported multiple LC50, EC50 or IC50 values for the same taxa. When multiple estimates referred to different exposure periods, only the value estimated for the standard exposure period or for the exposure period closest to the standard was extracted (e.g., Huang et al., 2014). If multiple estimates referred to different exposure conditions (e.g., temperature), only data obtained in the same conditions as for *Daphnia* sp. was extracted (e.g., Seremet et al., 2018). For studies addressing the effects of CE, extracts obtained from the extraction and isolation of specific constituents were not considered (e.g., Jiang et al., 2018). Missing information was requested from authors before a decision to exclude the study was made. The final matrix thus included 11

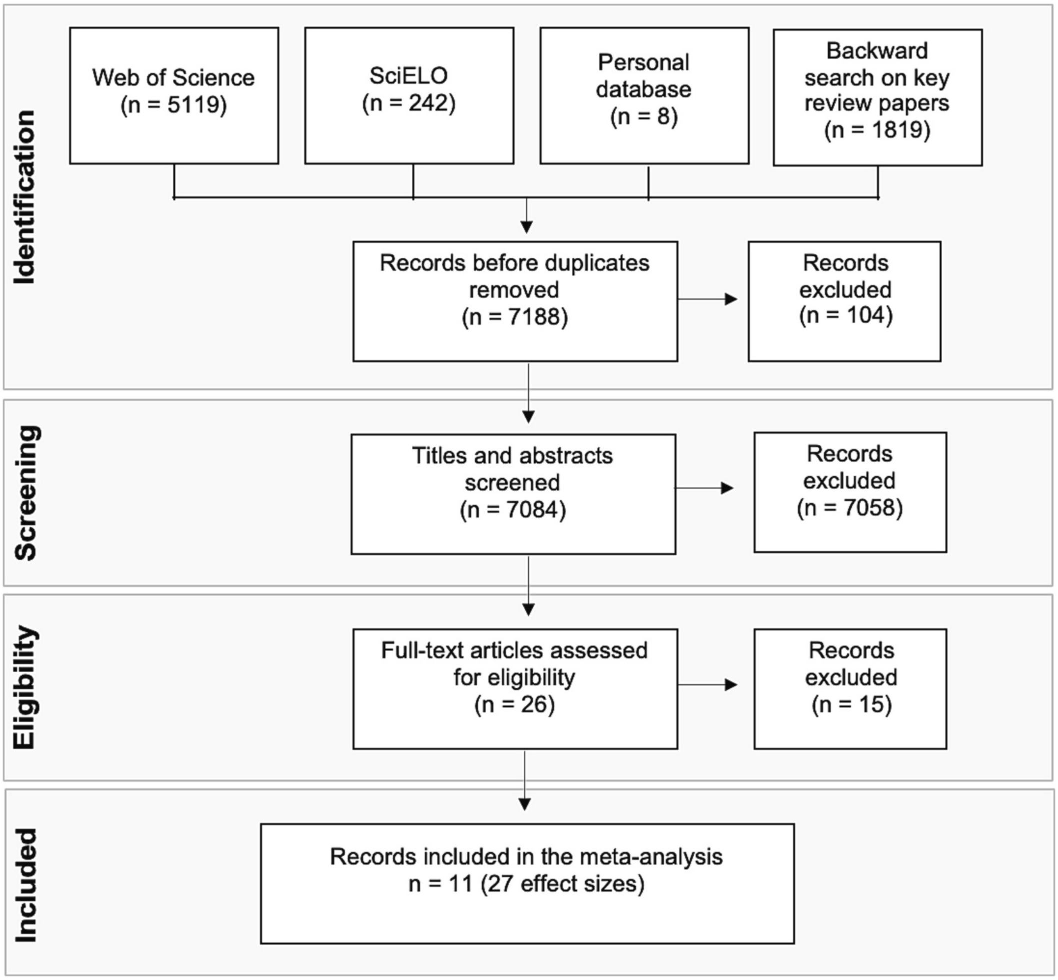

Fig. 1. PRISMA diagram showing the literature search and study selection procedure.

studies (Fig. 1, Tables S1, S2 and S3).

2.2. Extraction of primary data

From the selected studies, the following primary data were extracted for *Daphnia* sp. and the contrast aquatic taxa, i.e., a non-target organisms for the tested CE or EO: (i) acute/short-term toxicity, which included survival of invertebrates and fish (estimated as mortality or immobilization), luminescence of bacteria and growth of microalgae (estimated from cell densities or photosynthetic yield) reported in terms of toxicity parameters as LC50, EC50 or IC50 values expressed in mass/volume (i.e., mg/L, μg/mL, ppm, or %); (ii) sample size (n = number of tested CE or EO concentrations) for each toxicity parameter; and (iii) variability measure (i.e., SD, standard error (SE) or 95 % confidence interval (CI)) for each toxicity parameter determined (Table S2). LC50, EC50 or IC50 estimates (or information that allowed their calculation (only for LC50 values in Olaru et al. (2015), using the software PriProbit 1.63, http://ars.usda.gov/Services/docs.htm?docid=11284), associated variation measures, and sample sizes that were reported in the text or in tables were extracted directly, while information reported in graphs was extracted using WebPlotDigitizer (https://automeris.io/WebPlotDigitizer/), and missing information was requested from the authors by e-mail messages.

Variation measures were extracted as provided in the studies or by the authors after request (i.e., SD or 95 % CI). SD values were used directly for estimating the variance associated with the effect size (see below), while 95 % CIs were first converted into SD (for all studies except Huang et al. (2014) that provided SD measures). In one case, the missing SD value (associated with the LC estimate for *D. magna* exposed to extracts from *Fallopia dumetorum*; Olaru et al., 2015) was imputed from the other cases in the matrix following Lajeunesse et al. (2013):

$$SD_j = \overline{X}_j \times \left(\frac{\sum_i^K SD_i}{\sum\limits_i^K \overline{X}_i} \right),$$

where SD_j is the missing SD value, $\overline{X}_j$ is the LC value for which SD is missing, K is the number of studies i for which there is information on LC or EC ($\overline{X}_i$) and associated variation (SD_i).

2.3. Extraction of moderators

Moderators are experimental factors that may affect the magnitude and direction of the toxicity of CE and EO from AMP to aquatic taxa relative to *Daphnia* sp. Information on several potential moderators was extracted according to the hypotheses listed on Table 1: preparation type (CE or EO), extraction type (hydrodistillation, solvent extraction or supercritical fluid extraction), solvent (aqueous, carbon dioxide, ethanol, hydroethanolic or methanol), plant part (aerial or underground), plant family (several), contrast aquatic taxa group (several), and contrast aquatic taxa family (several) (Table S4).

2.4. Effect size

The toxicity of CE and EO from AMP to aquatic taxa relative to *Daphnia* sp. (effect size) was estimated as the response ratio R, given by the ratio between the EC50, LC50 or IC50 estimate for the contrast aquatic taxa ($\overline{X}_{AqTaxa}$) relative to the estimate for *Daphnia* sp. ($\overline{X}_{Daphnia}$): $R = \overline{X}_{AqTaxa}/\overline{X}_{Daphnia}$; analyses were performed on lnR (Hedges et al., 1999). $R = 1$ (lnR = 0) indicates similar responses in contrast aquatic taxa and *Daphnia* sp., $R > 1$ (lnR > 0) indicates higher EC50, LC50 or IC50 values (higher tolerance, i.e., lower sensitivity) in the contrast aquatic taxa than in *Daphnia* sp., and $R < 1$ (lnR < 0) indicates lower EC50, LC50 or IC50 values (lower tolerance, i.e., higher sensitivity) in contrast aquatic taxa than in *Daphnia* sp.

The variance associated with lnR (V_{lnR}) was calculated following Hedges et al. (1999):

$$V_{lnR} = SD^2_{pooled} \times \left(\frac{1}{N_{AqTaxa} \times \left(\overline{X}_{Aqtaxa}\right)^2} + \frac{1}{N_{Daphnia} \times \left(\overline{X}_{Daphnia}\right)^2} \right),$$

$$SD^2_{pooled} = \frac{\left(N_{AqTaxa} - 1\right) \times SD^2_{AqTaxa} + \left(N_{Daphnia} - 1\right) \times SD^2_{Daphnia}}{N_{AqTaxa} + N_{Daphnia} - 2},$$

where $\overline{X}$ is the EC50, LC50 or IC50 estimate, *SD* is the associated standard deviation and *N* is sample size for contrast aquatic taxa and *Daphnia* sp. The variance V_{lnR} was used to determine the weight of each effect size in the analysis so that effect sizes with lower variance, and therefore more precise, contribute more than effect sizes with higher variance to the overall effect size. The variance V_{lnR} was also used to estimate the 95 % CI associated with each effect size, which can be used to assess significance of the effect sizes: lnR values with 95 % CI that do not include 0 (or R values with 95 % CI that do not include 1) are significant. Effect sizes and associated variance were estimated using OpenMEE (Wallace et al., 2017).

Empirical studies contributed with up to 5 effect sizes to the matrix as a result from including, e.g., different plant families or aquatic taxa. Thus, the 11 studies included in the matrix contributed with 27 effect sizes (Tables S1 and S2). These multiple effect sizes per study might affect results due to non-independence of effect sizes, but not considering them would have resulted in a low number of effect sizes ($N = 11$), which would have limited the analysis. Still, we have carried out a sensitivity analysis to assess if the results were affected by the non-independence of effect sizes (see below).

2.5. Statistical analysis

2.5.1. Overall effect size

The overall effect size was determined using the random-effects model of meta-analysis, which considers two sources of variance associated with effect sizes: within-study variance (V_{lnR}) and between-study variance (estimated by the restricted maximum likelihood (REML) method) (Borenstein et al., 2009). Individual effect sizes were weighed by the inverse of their variance, and the overall effect size was considered significant if its 95 % CI did not include 0 (in the case of lnR) or 1 (in the case of R). The percentage contribution of between-study variation to total variation among effect sizes (I^2) was also determined (Borenstein et al., 2009).

2.5.2. Subgroup analyses

The effects of moderators on the magnitude and direction of the toxicity of CE and EO from AMP to aquatic taxa relative to *Daphnia* sp. were assessed for the entire matrix or data subsets, considering only data subsets robust to publication bias (assessed by Rosenberg's fail-safe number, see below) and moderator levels with at least three effect sizes; solvent, plant part, and contrast aquatic taxa family did not comply with these criteria and were not used. Subgroup analysis was used to estimate mean effect sizes for moderator levels (subgroups), using the random-effects model of meta-analysis (with the REML method for estimating between-study variance) (Borenstein et al., 2009). Heterogeneity was assessed within and between (Q_M) subgroups to determine the significance of each subgroup and moderator, respectively. Mean effect sizes (R) for subgroups were significant if their 95 % CI did not include 1, and two subgroups significantly differed when their 95 % CI did not overlap (Borenstein et al., 2009).

2.5.3. Sensitivity analyses

Seven studies gave 2 to 5 effect sizes to the matrix, thus contributing to the non-independence of effect sizes. Therefore, the potential effects of the non-independence of effect sizes on the toxicity of CE and EO from AMP to aquatic taxa relative to *Daphnia* sp. were assessed by repeating the analyses, to the extent possible, considering a single effect size per study (i.e., independent effect sizes); multiple effects sizes from a single study were combined into a single effect size by subgroup analysis, with 'study reference' as the moderator and each study as a subgroup. Non-independence of effect sizes would be a problem if the interpretation of the results based on independent effect sizes ($N = 11$) differ from those obtained using the full matrix ($N = 27$).

2.5.4. Publication bias

Robustness of the entire matrix and data subsets used in subgroup analyses to publication bias was assessed by the Rosenberg's fail-safe number (N_{fs}). N_{fs} gives the number of missing effect sizes showing an insignificant effect that would be needed to nullify the mean effect size, with $N_{fs} > 5 \times N + 10$ (N = number of effect sizes) indicating that the matrix can be considered robust to publication bias.

All statistical analyses (i.e., overall effect size, subgroup analyses, and publication bias analyses) were done using OpenMEE (Wallace et al., 2017), and procedures and results were reported following PRISMA guidelines (O'Dea et al., 2021).

3. Results

3.1. Matrix description

The toxicity of CE and EO to aquatic taxa relative to *Daphnia* sp. was assessed mostly using CE (74 %). Solvent extraction (71 %) was the most often used extraction type, followed by hydrodistillation (21 %) and supercritical fluid extraction (8 %), with five solvent types: aqueous (56 %), methanol (16 %), hydroethanolic (12 %), and carbon dioxide and ethanol (8 % each) (Table S1). CE and EO were most often recovered from aerial (75 %) than from underground (25 %) plant parts, derived from 10 plant families (19 species). Contrast aquatic taxa (18 species) were most often crustaceans (56 %), followed by fish (22 %), algae (7 %), and bacteria, echinoderm, insects and aquatic plants (4 % each) (Table S1).

3.2. Overall effect size

The overall effect size lnR was 0.41, with 95 % CI of – 0.03 to 0.85 (*R* = 1.51, 95 % CI = 0.97 to 2.34, N = 27) (Fig. 2), indicating a non-significant difference in the toxicity of CE and EO to aquatic taxa relative to *Daphnia* sp. However, there was high heterogeneity among individual effect sizes ($I^2 = 99$ %), and therefore the overall effect size needs to be interpreted carefully as it results more from contrasting individual effect sizes (some strongly positive and others strongly negative) than from the absence of significant effect sizes (Fig. 2). These results are not affected by the non-independency of effect sizes since, when considering a single effect size per study, the overall effect size R was 1.72, with 95 % CI of 0.74 to 4.16 (N = 11), which is similar in terms of direction and significance to the result obtained with the entire matrix. The matrices (the full matrix with N = 27 and the matrix considering a single effect size per study with N = 11) were robust to

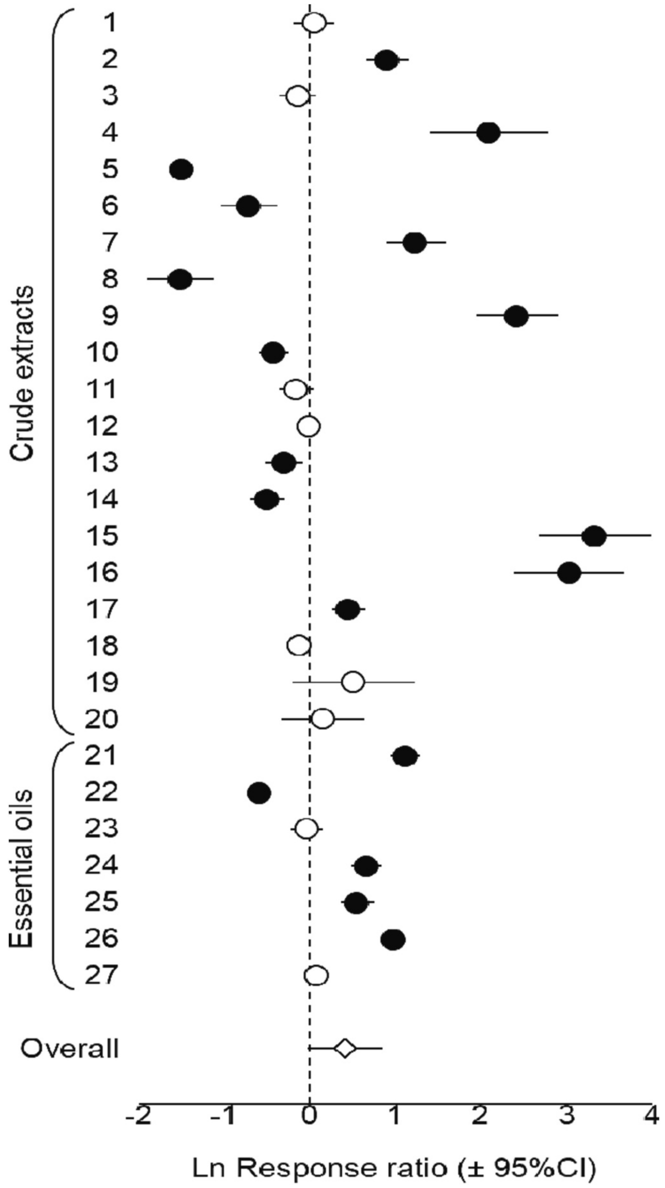

Fig. 2. Response of aquatic taxa relative to *Daphnia* sp. to effects of crude extracts and essential oils from aromatic and medicinal plants (lnR) in the 27 cases included in this review (see Table S1); overall response ($N = 27$) is also given. $\ln R = 0$ (dashed line) indicates similar responses in contrast aquatic taxa and *Daphnia* sp., $\ln R > 0$ indicates higher lnR values (higher tolerance, i.e., lower sensitivity) in the contrast aquatic taxa than in *Daphnia* sp., and $\ln R < 0$ indicates lower lnR values (lower tolerance, i.e., higher sensitivity) in contrast aquatic taxa than in *Daphnia* sp. lnR values are significant when the 95 % CI does not include 0 (black symbols).

publication bias as the Rosenberg fail safe numbers ($N_{fs} = 172$ and 740, respectively) were above the threshold for considering the matrix robust ($5 \times N + 10 = 145$ and 65, respectively).

3.3. *Moderator effects*

The toxicity of CE and EO to aquatic taxa relative to *Daphnia* sp. was not affected by the preparation type or extraction type, being the effect on aquatic taxa relative to *Daphnia* sp. non-significant in all subgroups for each moderator (Table 3, Fig. 3), but again there was high heterogeneity among effect sizes (Fig. 2). Plant family exerted a significant effect on the toxicity of CE and EO to aquatic taxa relative to *Daphnia* sp. (Table 3), with contrast aquatic taxa being less sensitive than *Daphnia* sp. to CE and EO from Lamiaceae ($R = 4.70$, 95 % CI = 1.25 to 17.57), more sensitive than *Daphnia* sp. to CE from Polygonaceae ($R = 0.77$, 95 % CI = 0.64 to 0.92), and as sensitive as *Daphnia* sp. to CE and EO from Zingiberaceae and Asteraceae (Fig. 3); other plant families did not have enough sample size to be tested. Toxicity of CE and EO to aquatic taxa relative to *Daphnia* sp. did not depend on the contrast aquatic taxa group, being the effect on crustaceans and fish relative to *Daphnia* sp. non-significant (Table 3, Fig. 3); other aquatic taxa groups did not have enough sample size to be tested. Although effects were similar on fish and *Daphnia* sp. (Fig. 3), Cyprinidae fish were more sensitive than *Daphnia* sp. to CE ($R = 0.29$, 95 % CI = 0.17 to 0.48, $N = 3$, $N_{fs} = 813$).

Table 3
Moderators tested in subgroup analyses with number of levels within moderators, total sample size (N), Rosenberg fail safe number (N_{fs}), Q_B statistics, degrees of freedom (df) and *p*-values (levels within moderators significantly differ if $p < 0.050$).

Moderator	No. levels	N	N_{fs}	Q_B	df	p-value
Preparation type	2	27	172	0.001	1	0.971
Extraction type (without supercritical fluid extraction as $N < 3$)	2	22	586	0.130	1	0.719
Plant family (without Lauraceae, Quilijaceae, Fabaceae, Piperaceae, and Boraginaceae as $N < 3$)	4	20	406	10.544	3	0.014
Contrast aquatic taxa group (without Algae, Insect, Plant, and Echinoderm as $N < 3$)	2	21	350	0.105	1	0.746

4. Discussion

The meta-analysis conducted in the present study shows that, overall, the contrast aquatic taxa exhibited similar sensitivity to CE and EO from AMP relative to *Daphnia* sp. However, the high heterogeneity among individual effect sizes ($I^2 = 99$ %) suggests that, rather than the lack of a significant difference, there were opposing responses of contrast aquatic organisms relative to *Daphnia* sp., with some taxa being more sensitive and others less sensitive than *Daphnia* sp. The magnitude of the effects was influenced by the plant family and did not depend on the preparation type, extraction type, or contrast aquatic taxa group. However, from the studies that examined the toxicity effects of CE and EO on *Daphnia* sp. and other aquatic organisms, only 11 studies were selected for meta-analysis and therefore the findings need to be interpreted with caution. Despite the limited number of effect sizes (27) obtained from the selected studies, the statistical analyses indicated that the matrix and datasets used were robust to publication bias.

Overall, the type of preparation, whether CE or EO, did not have a significant influence on the effect of AMP preparations on contrast aquatic taxa relative to *Daphnia* sp. Regarding the toxicity of CE ($N = 20$), the effect sizes varied in opposite directions, contributing to an overall non-significant effect. Several contrast aquatic taxa showed significant lower sensitivity to CE than *Daphnia* sp., namely the bacteria *Aliivibrio fischer*, the echinoderm *Paracentrotus lividus*, the fish *Oreochromis niloticus*, and the plant *Lemna minor* (Costa et al., 2021; Li et al., 2015; Pastorino et al., 2022). Among the major compounds identified in these studies as potentially inducers of toxicity are: Coronarin D and Coronarin D Ethyl Ether, both diterpenes, known for their cytotoxic activity (Costa et al., 2021); rotenone, an alkaloid, used as pesticide and fish toxin, known to be highly toxic to fish and *Daphnia* sp. (Li et al., 2015; Zubairi et al., 2016); and eugenol, a phenol, used as fish anesthetic, also reported to be highly toxic to *D. magna* (Gueretz et al., 2017; Pastorino et al., 2022). These compounds have different known modes of action, including the suppression of a factor regulating gene expression control (Coronarin D and Coronarin D Ethyl Ether), modulation of octopaminergic system (eugenol), and inactivation of the respiratory

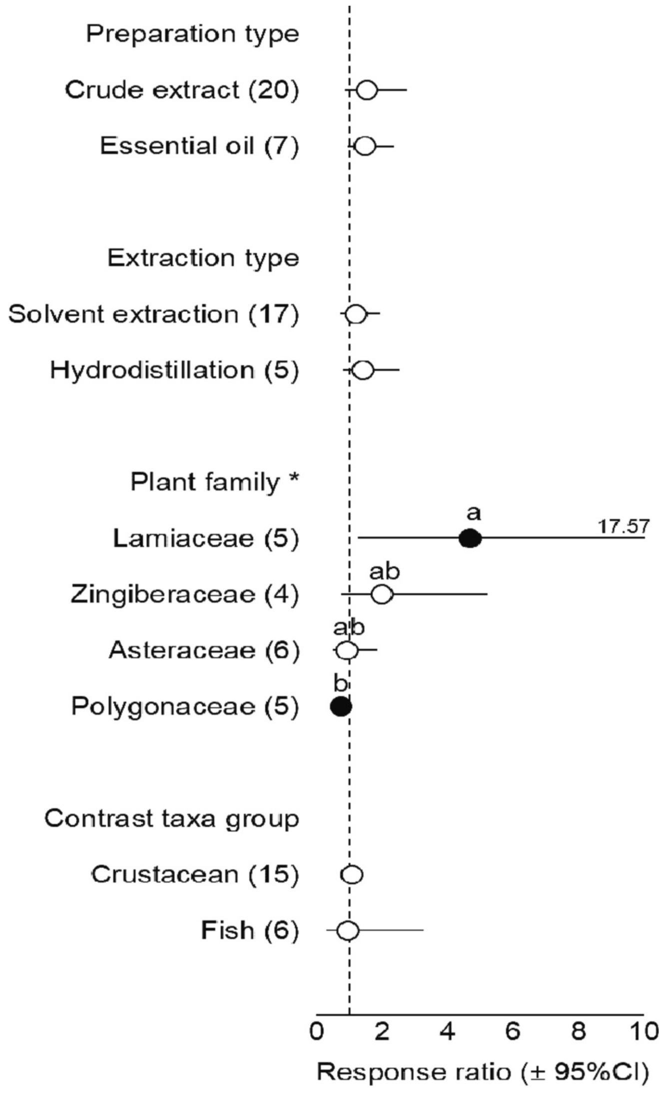

Fig. 3. Responses of aquatic taxa relative to *Daphnia* sp. (R) to effects of crude extracts and essential oils from aromatic and medicinal plants as a function of the preparation type, extraction type, plant family, and contrast aquatic taxa group. R = 1 (dashed line) indicates similar responses in contrast aquatic taxa and *Daphnia* sp., R > 1 indicates higher R values (higher tolerance, i.e., lower sensitivity) in the contrast aquatic taxa than in *Daphnia* sp., and R < 1 indicates lower R values (lower tolerance, i.e., higher sensitivity) in contrast aquatic taxa than in *Daphnia* sp. R values are significant when the 95 % CI does not include 1 (black symbols). Significant moderators are indicated with an asterisk, and levels significantly differ if their 95 % CI do not overlap (different letter). Values in brackets are sample sizes.

enzyme among other actions (rotenone) (Costa et al., 2021; Pavela and Benelli, 2016; Zubairi et al., 2016). Species sensitivities are commonly linked to the mode of action of chemicals, but species biological traits can also influence the sensitivity response (Rico and Van den Brink, 2015; Rubach et al., 2012). Among the mentioned organisms, *Daphnia* sp. is the only one that undergoes periodical molt to renew its exoskeleton. This process affects its sensitivity, since the new cuticle is more vulnerable in its early soft condition (Rowley, 2016). Besides, some chemicals are able to induce toxicity by interfering with exoskeleton formation and the molting process (Schmid et al., 2023), which may have been the case. In opposition to the trend described above, the fish species *Danio rerio* and *Pimephales promelas* showed significantly higher sensitivity than *D. magna* to CE (Huang et al., 2014; Jiang et al., 2018; Lambert et al., 1991). In this case, all plant species used in the CE have in common the presence of saponins in their composition. It is known that saponins in water are highly toxic to fish, acting like detergents damaging the respiratory system (Hajra et al., 2013), which may account for the higher toxicity found to fish. The crustaceans *Ceriodaphnia silvestrii* and *Artemia salina*, as well as the insect *Chironomus sancticaroli*, exhibited similar sensitivity to CE compared to *Daphnia* sp. (Costa et al., 2021; Olaru et al., 2015; Seremet et al., 2018). Crustaceans and insects are closely related taxa and share common biological traits, including periodic molting (Bentov et al., 2016), which may explain such similar responses.

Regarding the toxicity of EO ($N = 7$), *Artemia* sp. showed lower sensitivity than *D. magna* (Miura et al., 2021; Nogueira, 2021), and the fish *Oryzias latipes* exhibited either lower or similar sensitivity than *D. magna* (You et al., 2011). The response of the crustacean *Thamnocephalus platyurus* varied as well, either showing significant higher sensitivity to EO from *Helichrysum italicum* (Asteraceae) or similar response to EO from *Thymus mastichina* (Lamiaceae) (Nogueira, 2021), compared to *Daphnia* sp.

These findings suggest a higher variability in the response of contrast aquatic taxa to the toxicity of CE compared to *Daphnia* sp., with a tendency for some species, particularly *D. rerio*, to be more sensitive, *Artemia* sp. to be equally sensitive, and several taxa groups to be less sensitive. These results also seem to indicate a slightly higher sensitivity of *Daphnia* sp. to EO in comparison to other aquatic taxa, particularly *Artemia* sp. Ferraz et al. (2022), in the review of the relative toxicity of EO or plant extracts to *D. magna* also found a great variability in responses, with a tendency for EO to cause effects at lower concentrations than plant extracts. Moreover, they found it difficult to establish a link between the toxicity and the responsible compounds. Among the studies mentioned, only Miura et al. (2021) provided information on the main components of EO, indicating dillapiole as the major compound. Dillapiole is known for its ability to induce toxicity by inhibiting P450 cytochrome enzyme (Pavela and Benelli, 2016). This detoxifying enzyme is present in aquatic invertebrates, but variation in its activity among species, as observed by Gottardi et al. (2016), may have contributed to the variability found in organism responses. Moreover, the complex mixture of compounds in EO can act synergistically, inducing toxicity by multiple modes of action, such as inhibition of detoxifying enzymes activity, modification of membrane protein functions, or enhancing cuticular penetration (Tak and Isman, 2017). The differences in physiological traits among aquatic organisms, such as the degree of exoskeleton sclerotization, size, and respiration type, also play a significant role in species sensitivity responses (Rico and Van den Brink, 2015; Rubach et al., 2012).

The type of extraction also did not influence the overall effect of AMP preparations on contrast aquatic taxa relative to *Daphnia* sp. When comparing preparation obtained by solvent extraction and hydrodistillation, the response of contrast aquatic taxa relative to that of *Daphnia* sp. was similar for both preparation types. In the studies included in the analysis, solvent extraction was used to obtain CE and hydrodistillation was used to obtain EO and, therefore, effects of preparation type may be confounded by extract type. Although opposite responses of contrast aquatic taxa relative to *Daphnia* sp. were observed, these differences were reported mainly to CE obtained by solvent extraction, suggesting that the divergences in the response were not due to the type of extraction. Hydrodistillation and solvent extraction both employ extraction solvents. The efficacy of the extraction method can be influenced by the choice of solvents, and different solvents may contribute differently to the toxicity of plant preparation (Hutchinson et al., 2006; Ofosu et al., 2020). Due to the small number of cases (< 3), the hypothesis that the type of solvent could influence both the magnitude and direction of the response of aquatic taxa could not be evaluated. However, aqueous solvent was the most employed in the cases included in the analysis (56 % of total effect sizes). EO were all extracted using aqueous solvent, whereas CE included other solvents such as methanol (16 %), hydroethanol (12 %), and ethanol (8 %). These solvents are all polar and are commonly employed to extract a variety of polar compounds. Depending on the polarity of the solvent and the extraction conditions, different solvents, even the same solvent, can extract different compounds and/or concentrations of the same compound (Bubalo et al., 2018; Chemat et al., 2019; Lezoul et al., 2020). The varying responses of contrast aquatic taxa relative to *Daphnia* sp. to the toxicity of CE may have been influenced by the solvents. The case of supercritical fluid extraction (SFE) with carbon dioxide (CO_2) as the solvent (Pastorino et al., 2022), could not be included in the subgroup analysis. SFE is a recent green technology, often performed with the non-toxic solvent CO_2. SFE shows promise potential for increasing utilization, particularly for industrial purpose, despite its high investment cost (Bubalo et al., 2018). Interestingly, CE extracted using SFE exhibited high toxicity values for both contrast aquatic taxa and *Daphnia* sp. (EC50 < 1 mg/L), with contrast aquatic taxa markedly less sensitive (Pastorino et al., 2022), which may be related to other factors such as the plant family.

The effects of CE and EO from AMP on contrast aquatic taxa relative to *Daphnia* sp. were influenced by the plant family, namely Lamiaceae, Polygonaceae, Zingiberaceae, and Asteraceae. Among these families, Lamiaceae had the greatest influence ($R = 4.70$), with contrast aquatic taxa being significantly less sensitive to CE and EO derived from Lamiaceae species compared to *Daphnia* sp. Within the Lamiaceae species, CE from *Ocimum basilicum* showed high toxicity to *D. magna* (EC50 < 1 mg/L), which was considerably more sensitive than contrast aquatic taxa (Pastorino et al., 2022). Similar sensitivity of contrast aquatic taxa relative to *D. magna* was found to the EO of *T. mastichina* (Lamiaceae), displaying high toxicity for both taxa (Nogueira, 2021). It is known that plant species from the Lamiaceae family produce bioactive compounds such as monoterpenes, which can be toxic to several organisms, including aquatic ones (Wojtunik-Kulesza, 2022). Polyphenols and volatile compounds were identified in the CE and EO of the Lamiaceae species evaluated in these studies (Nogueira, 2021; Pastorino et al., 2022). Polyphenols, besides their beneficial properties, are known to have both short- and long-term toxic effects on human and animals (Ofosu et al., 2020). Among the volatile compounds identified, the monoterpenes linalool and 1,8-cineole were the major compounds found in *O. basilicum* CE and *T. mastichina* EO, respectively (Nogueira, 2021; Pastorino et al., 2022). According to Bullangpoti et al. (2018), the volatile compound 1,8-cineole was moderately toxic to the non-target fish *Poecilia reticulata*. The toxicity of CE from species belonging to the Polygonaceae family appears to have contributed to a higher sensitivity response of contrast aquatic taxa relative to *Daphnia* sp. However, the differences in the sensitivity response were not significant ($R = 0.77$), and the CE did not exhibit toxic levels either to contrast aquatic taxa or *Daphnia* sp. (LC50 > 1000 mg/L). This may be attributed to the major compounds identified in the CE, namely quercetin glycosides, which have been found to be safe in in vivo testing (Batiha et al., 2020). Regarding the Zingiberaceae and Asteraceae families, the toxic response of contrast aquatic taxa to CE and EO from plant species belonging to these families was overall similar to that of *Daphnia* sp. However, the sensitivity of contrast aquatic taxa to *Daphnia* sp. varied more within the Asteraceae family.

Although some scientific data is available on the toxic effects of CE and EO compounds, it is not enough to clarify the relationship between the toxicity found and the sensitivity of species. Other factors that can influence the toxicity of plant preparation, such as its previous contamination with pollutants, should also be considered. Certain plants, including Lamiaceae species, can exhibit high metal accumulation patterns, leading to contamination of their EO (Boularbah et al., 2006; Iordache et al., 2022). Iordache et al. (2022) evaluated several EO samples from various origins and found EO with high metal levels, likely caused by agricultural soil contamination. However, Boularbah et al. (2006) stated that plant accumulation patterns depend on plant species, as plant species from different families (including Lamiaceae) growing in soil with high metal contamination showed to be hypertolerant but not hyperaccumulators of metals (Boularbah et al., 2006). Therefore, several hypotheses need to be considered to understand the underlying roots of toxicity and their relationship to organism sensitive responses.

The magnitude of the toxicity of CE and EO was not dependent on the contrast aquatic taxa group, namely crustacean and fish, which were included in the subgroup analysis. The crustacean taxa group comprised mostly *Artemia* sp. species, as well as the species *T. platyurus* and *C. silvestrii*. The fish taxa group included the species *D. rerio*, *O. latipes*, *P. promelas*, and *O. niloticus*. Overall, the sensitivity response of both taxa to the toxicity of CE and EO was similar to that of *Daphnia* sp. The fish *O. niloticus* and the crustacean *A. salina* showed significant lower sensitivity than *Daphnia* sp. to the CE from *Tephrosia vogelii* (Fabaceae) and the EO from *Piper aduncum* (Piperaceae), respectively (Li et al., 2015; Miura et al., 2021). Conversely, the fish *D. rerio* was significantly more sensitive than *D. magna* to the toxicity of the CE from *Solidago canadensis* (Asteraceae) (Huang et al., 2014). In the case of CE from *T. vogelii* and EO from *P. aduncum*, the previously mentioned mode of action of their main compounds (rotenone and dillapiole) does not indicate a common trend driving the sensitive response of aquatic taxa. Regarding *S. canadensis* it is known that it has saponins among its components (Zhu et al., 2022), which are highly toxic to fish, as discussed above. Algae, bacteria, echinoderms, insects, and plants were among the contrast aquatic taxa groups that were not included in the subgroup analyses. Some of these taxa showed significant lower sensitivity to the toxicity of CE compared to *Daphnia* sp., namely in decreasing order of sensitivity: bacteria *V. fisheri* ($R = 20.88$) $<$ plant *L. minor* ($R = 8.12$) $<$ algae *Selenastrum capricornutum* ($R = 3.46$). It was expected that shared traits across each functional group could influence how organisms from different taxa respond to the toxicity of CE and EO. However, divergences in the sensitivity of aquatic organisms within the same taxa group to various pesticides and their corresponding modes of action have previously been reported (Rico and Van den Brink, 2015). Hence, further research is essential to elucidate the connection between the physiological traits and intrinsic sensitivity of aquatic species from different taxa and family groups to the modes of action of CE and EO compounds.

These findings reinforce the importance of conducting ecotoxicity assays with several species to fully predict environmental adverse effects, as also suggested by Ferraz et al. (2022). They also underlined the need for tests to be performed according to standard guidelines to enable a broader comparison between studies. In this study, most of the excluded empirical studies were so because they did not comply with the selection criteria, often by failing to accomplish with the recommended standard guidelines for toxicity testing, particularly in terms of inconsistent exposure times and the use of different units to report results. Furthermore, several studies neglected to provide information regarding the composition of the plant preparations under investigation, which limits using the generated ecotoxicity data for risk management purposes. Last, but not least, based on the probable low environmental concentrations of CE or EO, at least in some aquatic systems, using chronic toxicity indicators may be more relevant for ecological risk assessments, and could have influenced the outcomes of the present study. However, data on the nonlethal and cumulative effects of CE/EO on aquatic organisms is even more limited. Besides, it should be emphasized that our study selection was based on an exhaustive search, with 7188 studies screened, including 557 studies addressing the issue of toxicity to non-target aquatic organisms, that were identified in the screening, though not considered to be within the scope of the study. Therefore, the scarcity of studies included in the meta-analysis reflects the current state of the field, where there is a lack of research providing sufficient and adequate ecotoxicological data on the subject.

5. Conclusions

The meta-analysis conducted in the present study, the first on this topic despite the already existing ecotoxicity database, suggests that aquatic taxa sensitivity to CE and EO relative to *Daphnia* sp. is heterogeneous and contrasting, resulting in a non-significant overall effect size. The magnitude of effects was strongly influenced by plant family, but not dependent on preparation type, extraction type, or contrast aquatic taxa groups. Whereas the variability in aquatic taxa sensitivity to CE relative to *Daphnia* sp. points to species-specific sensitivities, regarding EO *Daphnia* sp. showed slightly higher sensitivity compared to other aquatic taxa. Nevertheless, the toxicity of both CE and EO was significantly influenced by the plant family, particularly Lamiaceae, with *Daphnia* sp. more sensitive than other aquatic taxa. Moreover, the variability found seemed to be linked to the solvents employed and not to the extraction technique. It is, however, important to note that interpretations need to be considered with caution due to the limited number of studies included in the analysis. Further research is needed to clarify these issues, particularly the role that recent emerging green methods, such as SFE, will have on the toxicity of CE and EO to aquatic organisms.

Therefore, this meta-analysis provides valuable insights into the complexity of the relationships between the toxicity of CE and EO to aquatic taxa and signals the probable need for a holistic and species-specific approach. While *Daphnia* sp. proved to be a valuable model organism for evaluating CE and EO toxicity in aquatic environments, other taxa should be considered as well, particularly the fish *D. rerio*. The crustacean *T. platyurus* appeared as a viable tool, being essential to include organisms from other taxonomic groups such as algae to provide a broad understanding of the potential ecological impact of these products. Also, because the sensitivity of *Artemia* sp. to CE was similar to that of *Daphnia* sp., and given the great practical advantages of using *Artemia* sp. test, it makes it a promising candidate for initial toxicity screenings. However, as highlighted above, additional data on the sensitivity of a diverse range of aquatic taxa to CE and EO of known composition, particularly of the major components, is required. Our study aims to encourage further research into the issue of CE and EO toxicity to aquatic ecosystems in order to support more robust meta-analyses in the future, as well as to answer and/or review the questions raised by the present meta-analysis.

CRediT authorship contribution statement

All authors contributed to the study conception and design. SA wrote the first draft of protocols and performed the literature search, study selection, data extraction, with the contribution of VF and MM-S. VF performed the meta-analysis. The first draft of the manuscript was written by SA and VF, and the multiple versions were reviewed and edited by VF and MM-S. Supervision and funding acquisition were undertaken by VF and MM-S. All authors read and approved the final manuscript.

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.

Data availability

The matrix used for the analyses is provided in the Supplementary Material.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.168467.

References

Abubakar, A.R., Haque, M., 2020. Preparation of medicinal plants: basic extraction and fractionation procedures for experimental purposes. J. Pharm. Bioallied Sci. 12 (1), 1–10. https://doi.org/10.4103/jpbs.JPBS_175_19.

Amoatey, P., Baawain, M.S., 2019. Effects of pollution on freshwater aquatic organisms. Water Environ. Res. 91 (10), 1272–1287. https://doi.org/10.1002/wer.1221.

Arena, M., Sgolastra, F., 2014. A meta-analysis comparing the sensitivity of bees to pesticides. Ecotoxicology 23 (3), 324–334. https://doi.org/10.1007/s10646-014-1190-1.

Batiha, G.E.-S., Beshbishy, A.M., Ikram, M., Mulla, Z.S., El-Hack, M.E.A., Taha, A.E., Algammal, A.M., Elewa, Y.H.A., 2020. The pharmacological activity, biochemical properties, and pharmacokinetics of the major natural polyphenolic flavonoid: quercetin. Foods 9 (3), 374. https://doi.org/10.3390/foods9030374.

Bentov, S., Abehsera, S., Sagi, A., 2016. The mineralized exoskeletons of crustaceans. In: Cohen, E., Moussian, B. (Eds.), Extracellular Composite Matrices in Arthropods. Springer International Publishing, Cham, pp. 137–163.

Blinova, I., 2004. Use of freshwater algae and duckweeds for phytotoxicity testing. Environ. Toxicol. 19 (4), 425–428. https://doi.org/10.1002/tox.20042.

Borenstein, M., Hedges, L.V., Higgins, J.P., Rothstein, H.R., 2009. Introduction to Meta-analysis, first ed. John Wiley and Sons, New York, p. 421.

Boudreau, T.M., Sibley, P.K., Mabury, S.A., Muir, D.G.C., Solomon, K.R., 2003. Laboratory evaluation of the toxicity of perfluorooctane sulfonate (PFOS) on *Selenastrum capricornutum*, *Chlorella vulgaris*, *Lemna gibba*, *Daphnia magna*, and *Daphnia pulicaria*. Arch. Environ. Contam. Toxicol. 44 (3), 0307–0313. https://doi.org/10.1007/s00244-002-2102-6.

Boularbah, A., Schwartz, C., Bitton, G., Aboudrar, W., Ouhammou, A., Morel, J.L., 2006. Heavy metal contamination from mining sites in South Morocco: 2. Assessment of metal accumulation and toxicity in plants. Chemosphere 63 (5), 811–817. https://doi.org/10.1016/j.chemosphere.2005.07.076.

Brusotti, G., Cesari, I., Dentamaro, A., Caccialanza, G., Massolini, G., 2014. Isolation and characterization of bioactive compounds from plant resources: the role of analysis in the ethnopharmacological approach. J. Pharmaceut. Biomed. 87, 218–228. https://doi.org/10.1016/j.jpba.2013.03.007.

Bubalo, M.C., Vidović, S., Redovniković, I.R., Jokić, S., 2018. New perspective in extraction of plant biologically active compounds by green solvents. Food Bioprod. Process. 109, 52–73. https://doi.org/10.1016/j.fbp.2018.03.001.

Bullangpoti, V., Mujchariyakul, W., Laksanavilat, N., Junhirun, P., 2018. Acute toxicity of essential oil compounds (thymol and 1,8-cineole) to insectivorous guppy, *Poecilia reticulata* Peters, 1859. Agric. Nat. Resour. 52 (2), 190–194. https://doi.org/10.1016/j.anres.2018.06.011.

Caliman, F.A., Gavrilescu, M., 2009. Pharmaceuticals, personal care products and endocrine disrupting agents in the environment – a review. Clean Soil Air Water 37 (4–5), 277–303. https://doi.org/10.1002/clen.200900038.

Chemat, F., Abert Vian, M., Ravi, H.K., Khadhraoui, B., Hilali, S., Perino, S., Fabiano Tixier, A.-S., 2019. Review of alternative solvents for green extraction of food and natural products: panorama, principles, applications and prospects. Molecules 24 (16), 3007. https://doi.org/10.3390/molecules24163007.

Choudhary, N., Sekhon, B.S., 2011. An overview of advances in the standardization of herbal drugs. J. Pharm. Edu. Res. 2 (2), 55–70.

Costa, R.O., Vieira, B.H., Espindola, E.L.G., Ribeiro, A.I., Ferro, J.L.R., Fernandes, J.B., da Silva Matos, D.M., 2021. Toxicity of rhizomes of the invasive *Hedychium coronarium* (Zingiberaceae) on aquatic species. Biol. Invasions 23 (7), 2221–2231. https://doi.org/10.1007/s10530-021-02501-y.

Daam, M.A., Rico, A., 2018. Freshwater shrimps as sensitive test species for the risk assessment of pesticides in the tropics. Environ. Sci. Pollut. Res. 25, 13235–13243. https://doi.org/10.1007/s11356-016-7451-1.

Ebani, V.V., Mancianti, F., 2020. Use of essential oils in veterinary medicine to combat bacterial and fungal infections. Vet. Sci. 7 (4), 193. https://doi.org/10.3390/vetsci7040193.

EMEA (European Medicines Agency), 2018. Draft guideline on the environmental risk assessment of medicinal products for human use – Revision 1 (EMEA/CHMP/SWP/4447/00 Rev. 1). In: Committee for Medicinal Products for Human Use (CHMP). 15 November 2018.

EU (European Union), 2006. Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the registration, evaluation, authorisation and restriction of chemicals (REACH). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02006R1907-20140410.

EU (European Union), 2009. Regulation (EC) N° 1107/2009 of the European Parliament and of the Council of 21 October 2009 concerning the placing of plant protection products on the market and repealing Council Directives 79/117/EEC and 91/414/EEC. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32009R1107.

Falkowski, M., Jahn-Oyac, A., Odonne, G., Flora, C., Estevez, Y., Touré, S., Boulogne, I., Robinson, J.-C., Béreau, D., Petit, P., Azam, D., Coke, M., Issaly, J., Gaborit, P., Stien, D., Eparvier, V., Dusfour, I., Houël, E., 2020. Towards the optimization of botanical insecticides research: *Aedes aegypti* larvicidal natural products in French Guiana. Acta Trop. 201, 105179 https://doi.org/10.1016/j.actatropica.2019.105179.

Ferraz, C.A., Pastorinho, M.R., Palmeira-de-Oliveira, A., Sousa, A.C.A., 2022. Ecotoxicity of plant extracts and essential oils: a review. Environ. Pollut. 292, 118319 https://doi.org/10.1016/j.envpol.2021.118319.

Foo, Y.Z., O'Dea, R.E., Koricheva, J., Nakagawa, S., Lagisz, M., 2021. A practical guide to question formation, systematic searching and study screening for literature reviews in ecology and evolution. Methods Ecol. Evol. 12 (9), 1705–1720. https://doi.org/10.1111/2041-210X.13654.

Gottardi, M., Kretschmann, A., Cedergreen, N., 2016. Measuring cytochrome P450 activity in aquatic invertebrates: a critical evaluation of in vitro and in vivo methods. Ecotoxicology 25 (2), 419–430. https://doi.org/10.1007/s10646-015-1600-z.

Griffiths, M., Strobel, B., Hama, J., Cedergreen, N., 2020. Toxicity and risk of plant-produced alkaloids to *Daphnia magna*. Environ. Sci. Eur. 33, 10. https://doi.org/10.21203/rs.3.rs-105938/v1.

Gueretz, J.S., Somensi, C.A., Martins, M.L., Souza, A.P.d., 2017. Evaluation of eugenol toxicity in bioassays with test-organisms. Ciência Rural 47.

Gupta, A., Naraniwal, M., Kothari, V., 2012. Modern extraction methods for preparation of bioactive plant extracts. Int. J. Appl. Nat. Sci. 1 (1), 8–26.

Gurevitch, J., Koricheva, J., Nakagawa, S., Stewart, G., 2018. Meta-analysis and the science of research synthesis. Nature 555 (7695), 175–182. https://doi.org/10.1038/nature25753.

Hajra, A., Mazumder, A., Verma, A., Ganguly, D.P., Mohanty, B.P., Sharma, A.P., 2013. Antinutritional factors in plant origin fish feed ingredients: the problems and probable remedies. Adv. Fish. Res. 5, 193–202.

Hedges, L.V., Gurevitch, J., Curtis, P.S., 1999. The meta-analysis of response ratios in experimental ecology. Ecology 80 (4), 1150–1156.

Huai, H., Dong, Q., Liu, A., 2010. Ethnomedicinal analysis of toxic plants from five ethnic groups in China. Ethnobot. Res. Appl. 8, 169–179. https://doi.org/10.17348/era.8.0.169-179.

Huang, Y., Bai, Y., Wang, Y., Kong, H., 2014. *Solidago canadensis* L. extracts to control algal (Microcystis) blooms in ponds. Ecol. Eng. 70, 263–267. https://doi.org/10.1016/j.ecoleng.2014.05.025.

Hutchinson, T.H., Shillabeer, N., Winter, M.J., Pickford, D.B., 2006. Acute and chronic effects of carrier solvents in aquatic organisms: a critical review. Aquat. Toxicol. 76 (1), 69–92. https://doi.org/10.1016/j.aquatox.2005.09.008.

Ifeoma, O., Oluwakanyinsol, S., 2013. Screening of herbal medicines for potential toxicities. In: Gowder, S.J.T. (Ed.), New Insights into Toxicity and Drug Testing. IntechOpen Limited, London, pp. 63–88. Chapter 4. https://doi.org/10.5772/54493.

Iordache, A.M., Nechita, C., Voica, C., Roba, C., Botoran, O.R., Ionete, R.E., 2022. Assessing the health risk and the metal content of thirty-four plant essential oils using the ICP-MS technique. Nutrients 14 (12), 2363. https://doi.org/10.3390/nu14122363.

Ivanescu, B., Burlec, A.F., Crivoi, F., Rosu, C., Corciova, A., 2021. Secondary metabolites from *Artemisia* genus as biopesticides and innovative nano-based application strategies. Molecules 26 (10), 3061. https://doi.org/10.3390/molecules26103061.

Jayasinghe, C.D., Jayawardena, U.A., 2019. Toxicity assessment of herbal medicine using zebrafish embryos: a systematic review. Evid. Based Complement. Alternat. Med. 7272808 https://doi.org/10.1155/2019/7272808.

Jiang, X., Cao, Y., Jørgensen, L.v.G., Strobel, B.W., Hansen, H.C.B., Cedergreen, N., 2018. Where does the toxicity come from in saponin extract? Chemosphere 204, 243–250. https://doi.org/10.1016/j.chemosphere.2018.04.044.

Jugreet, B.S., Suroowan, S., Rengasamy, R.R.K., Mahomoodally, M.F., 2020. Chemistry, bioactivities, mode of action and industrial applications of essential oils. Trends Food Sci. Technol. 101, 89–105. https://doi.org/10.1016/j.tifs.2020.04.025.

Kovalakova, P., Cizmas, L., McDonald, T.J., Marsalek, B., Feng, M., Sharma, V.K., 2020. Occurrence and toxicity of antibiotics in the aquatic environment: a review. Chemosphere 251, 126351. https://doi.org/10.1016/j.chemosphere.2020.126351.

Lajeunesse, M.J., Koricheva, J., Gurevitch, J., Mengersen, K., 2013. Recovering missing or partial data from studies: a survey of conversions and imputations for meta-analysis. In: Koricheva, J., Gurevitch, J., Mengersen, K. (Eds.), Handbook of Meta-analysis in Ecology and Evolution. Princeton University Press, pp. 195–206.

Lambert, J.H.D., Temmink, J.H.M., Marquis, J., Parkhurst, R.M., Lugt, Ch.B., Lemmich, E., Wolde-Yohannes, L., de Savigny, D., 1991. Endod: safety evaluation of a plant molluscicide. Regul. Toxicol. Pharmacol. 14 (2), 189–201. https://doi.org/10.1016/0273-2300(91)90006-H.

Lezoul, N.E.H., Belkadi, M., Habibi, F., Guillén, F., 2020. Extraction processes with several solvents on total bioactive compounds in different organs of three medicinal plants. Molecules 25 (20), 4672. https://doi.org/10.3390/molecules25204672.

Li, W., Huang, C., Wang, K., Fu, J., Cheng, D., Zhang, Z., 2015. Laboratory evaluation of aqueous leaf extract of *Tephrosia vogelii* against larvae of *Aedes albopictus* (Diptera: Culicidae) and non-target aquatic organisms. Acta Trop. 146, 36–41. https://doi.org/10.1016/j.actatropica.2015.02.004.

Luz, T.R.S.A., de Mesquita, L.S.S., Amaral, F.M.M.d., Coutinho, D.F., 2020. Essential oils and their chemical constituents against *Aedes aegypti* L. (Diptera: Culicidae) larvae. Acta Trop. 212, 105705. https://doi.org/10.1016/j.actatropica.2020.105705.

Margot, J., Rossi, L., Barry, D.A., Holliger, C., 2015. A review of the fate of micropollutants in wastewater treatment plants. WIREs Water 2 (5), 457–487. https://doi.org/10.1002/wat2.1090.

Martins, J., Teles, L.O., Vasconcelos, V., 2007. Assays with *Daphnia magna* and *Danio rerio* as alert systems in aquatic toxicology. Environ. Int. 33 (3), 414–425. https://doi.org/10.1016/j.envint.2006.12.006.

Masetti, A., 2016. The potential use of essential oils against mosquito larvae: a short review. Bull. Insectol. 69, 307–310.

Miura, P.T., Jonsson, C.M., Queiroz, S.C.d.N.d., Chagas, E.C., Chaves, F.C.M., Reyes, F.G.R., 2021. Ecological risk assessment of *Piper aduncum* essential oil in non-target organisms. Acta Amaz 51, 71–78. https://doi.org/10.1590/1809-4392202002691.

Musee, N., Ngwenya, P., Motaung, L.K., Moshuhla, K., Nomngongo, P., 2023. Occurrence, effects, and ecological risks of chemicals in sanitizers and disinfectants: a review. J. Environ. Chem. Ecotoxicol. 5, 62–78. https://doi.org/10.1016/j.enceco.2023.01.003.

Nogueira, J.V., 2021. Estudo da ecotoxicidade de óleos essenciais de Perpétua da Areias (*Helichrysum italicum*) e Tomilho Bela-Luz (*Thymus mastichina*). Coimbra, Escola Superior Agrária de Coimbra, p. 47.

Ntungwe, N.E., Dominguez-Martin, E.M., Roberto, A., Tavares, J., Isca, V.M.S., Pereira, P., Cebola, M.J., Rijo, P., 2020. *Artemia* species: an important tool to screen general toxicity samples. Curr. Pharm. Des. 26 (24), 2892–2908. https://doi.org/10.2174/1381612826666200406083035.

O'Dea, R.E., Lagisz, M., Jennions, M.D., Koricheva, J., Noble, D.W., Parker, T.H., Nakagawa, S., 2021. Preferred reporting items for systematic reviews and meta-analyses in ecology and evolutionary biology: a PRISMA extension. Biol. Rev. 96 (5), 1695–1722.

OECD (Organisation for Economic Cooperation and Development), 2004. Test No. 202: *Daphnia* sp. acute immobilisation test. In: OECD Guidelines for the Testing of Chemicals, Section 2, OECD Publishing, Paris. https://doi.org/10.1787/9789264069947-en.

Ofosu, F.K., Daliri, E.B.-M., Elahi, F., Chelliah, R., Lee, B.-H., Oh, D.-H., 2020. New insights on the use of polyphenols as natural preservatives and their emerging safety concerns. Front. Sustain. Food Syst. 4, 525810 https://doi.org/10.3389/fsufs.2020.525810.

Olaru, O.T., Venables, L., M, V.D.V., Nitulescu, G.M., Margina, D., Spandidos, D.A., Tsatsakis, A.M., 2015. Anticancer potential of selected *Fallopia Adans* species. Oncol. Lett. 10 (3), 1323–1332. https://doi.org/10.3892/ol.2015.3453.

Pastorino, P., Prearo, M., Anselmi, S., Broccoli, A., Provenza, F., Barcelò, D., Renzi, M., 2022. Ecotoxicity of basil (*Ocimum Basilicum*) extract in aquaculture feeds: is it really eco-safe for the aquatic environment? Ecol. Indic. 142, 109173 https://doi.org/10.1016/j.ecolind.2022.109173.

Pavela, R., Benelli, G., 2016. Essential oils as ecofriendly biopesticides? Challenges and constraints. Trends Plant Sci. 21 (12), 1000–1007. https://doi.org/10.1016/j.tplants.2016.10.005.

Pelosi, C., Joimel, S., Makowski, D., 2013. Searching for a more sensitive earthworm species to be used in pesticide homologation tests – a meta-analysis. Chemosphere 90 (3), 895–900. https://doi.org/10.1016/j.chemosphere.2012.09.034.

Rico, A., Van den Brink, P.J., 2015. Evaluating aquatic invertebrate vulnerability to insecticides based on intrinsic sensitivity, biological traits, and toxic mode of action. Environ. Toxicol. Chem. 34 (8), 1907–1917. https://doi.org/10.1002/etc.3008.

Rowley, A.F., 2016. The immune system of crustaceans. In: Ratcliffe, M.J.H. (Ed.), Encyclopedia of Immunobiology. Academic Press, Oxford, pp. 437–453.

Rubach, M.N., Baird, D.J., Boerwinkel, M.-C., Maund, S.J., Roessink, I., Van den Brink, P.J., 2012. Species traits as predictors for intrinsic sensitivity of aquatic invertebrates to the insecticide chlorpyrifos. Ecotoxicology 21 (7), 2088–2101. https://doi.org/10.1007/s10646-012-0962-8.

Sasidharan, S., Chen, Y., Saravanan, D., Sundram, K.M., Latha, L.Y., 2011. Extraction, isolation and characterization of bioactive compounds from plants' extracts. Afr. J. Tradit. Complement. Altern. Med. 8 (1), 1–10. https://doi.org/10.4314/ajtcam.v8i1.60483.

Schmid, S., Rundberget, J.T., Song, Y., Tollefsen, K.E., 2023. Age and synchronization of *Daphnia magna* affect sensitivity to teflubenzuron in acute standardized toxicity tests. Environ. Toxicol. Chem. 42 (8), 1806–1815. https://doi.org/10.1002/etc.5688.

Seremet, O.C., Olaru, O.T., Gutu, C.M., Nitulescu, G.M., Ilie, M., Negres, S., Zbarcea, C.E., Purdel, C.N., Spandidos, D.A., Tsatsakis, A.M., 2018. Toxicity of plant extracts containing pyrrolizidine alkaloids using alternative invertebrate models. Mol. Med. Rep. 17 (6), 7757–7763. https://doi.org/10.3892/mmr.2018.8795.

da Silva Sá, G.C., Bezerra, P.V.V., da Silva, M.F.A., da Silva, L.B., Barra, P.B., Ximenes, M.F.F.M., Uchôa, A.F., 2022. Arbovirus vectors insects: are botanical insecticides an alternative for its management? J. Pest. Sci. 96, 1–20. https://doi.org/10.1007/s10340-022-01507-2.

Tak, J.H., Isman, M.B., 2017. Enhanced cuticular penetration as the mechanism of synergy for the major constituents of thyme essential oil in the cabbage looper, *Trichoplusia ni*. Ind. Crop. Prod. 101, 29–35. https://doi.org/10.1016/j.indcrop.2017.03.003.

Teodorovic, I., Planojevic, I., Knezevic, P., Radak, S., Nemet, I., 2009. Sensitivity of bacterial *vs.* acute *Daphnia magna* toxicity tests to metals. Cent. Eur. J. Biol. 4, 482–492. https://doi.org/10.2478/s11535-009-0048-7.

Thangaleela, S., Sivamaruthi, B.S., Kesika, P., Bharathi, M., Kunaviktikul, W., Klunklin, A., Chanthapoon, C., Chaiyasut, C., 2022. Essential oils, phytoncides, aromachology, and aromatherapy – a review. Appl. Sci. 12 (4495), 20. https://doi.org/10.3390/app12094495.

Wallace, B.C., Lajeunesse, M.J., Dietz, G., Dahabreh, I.J., Trikalinos, T.A., Schmid, C.H., Gurevitch, J., 2017. Open MEE: intuitive, open-source software for meta-analysis in ecology and evolutionary biology. Methods Ecol. Evol. 8 (8), 941–947. https://doi.org/10.1111/2041-210X.12708.

Wojtunik-Kulesza, K.A., 2022. Toxicity of selected monoterpenes and essential oils rich in these compounds. Molecules 27 (5), 1716. https://doi.org/10.3390/molecules27051716.

Wu, N.C., Seebacher, F., 2020. Effect of the plastic pollutant bisphenol A on the biology of aquatic organisms: a meta-analysis. Glob. Chang. Biol. 26 (7), 3821–3833. https://doi.org/10.1111/gcb.15127.

Yap, P.S.X., Yusoff, K., Lim, S.-H.E., Chong, C.-M., Lai, K.-S., 2021. Membrane disruption properties of essential oils – a double-edged sword? Processes 9 (4), 595. https://doi.org/10.3390/pr9040595.

You, A.-S., Choi, Y.-W., Jeong, M.-H., Hong, S.-S., Park, Y.-K., Jang, H.-S., Park, J.-Y., Park, K.-H., 2011. Acute ecotoxicity evaluation of thyme white, clove bud, cassia, lavender, lemon eucalyptus essential oil of plant extracts. Korean J. Pestic. Sc. 15 (4), 350–356.

Zhu, X., Li, W., Shao, H., Tang, S., 2022. Selected aspects of invasive Solidago canadensis with an emphasis on its allelopathic abilities: a review. Chem. Biodivers. 19 (10), e202200728 https://doi.org/10.1002/cbdv.202200728.

Zubairi, S.I., Othman, Z.S., Sarmidi, M.R., Aziz, R.A., 2016. Environmental friendly bio-pesticide Rotenone extracted from Derris sp.: areview on the extraction method, toxicity and field effectiveness. J. Teknol. 78, 47–69. https://doi.org/10.11113/jt.v78.5942.