**Toxoplasma gondii** Infection in Marine Animal Species, as a Potential Source of Food Contamination: A Systematic Review and Meta‑Analysis

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**Abstract**

**Purpose** Many marine animals are infected and susceptible to toxoplasmosis, which is considered as a potential transmission source of *Toxoplasma gondii* to other hosts, especially humans. The current systematic review and meta-analysis aimed to determine the prevalence of *T. gondii* infection among sea animal species worldwide and highlight the existing gaps.

**Methods** Data collection was systematically done through searching databases, including PubMed, Science Direct, Google Scholar, Scopus, and Web of Science from 1997 to July 2020.

**Results** Our search strategy resulted in the retrieval of 55 eligible studies reporting the prevalence of marine *T. gondii* infection. The highest prevalence belonged to mustelids (sea otter) with 54.8% (95% CI 34.21–74.57) and cetaceans (whale, dolphin, and porpoise) with 30.92% (95% CI 17.85–45.76). The microscopic agglutination test (MAT) with 41 records and indirect immunofluorescence assay (IFA) with 30 records were the most applied diagnostic techniques for *T. gondii* detection in marine species.

**Conclusions** Our results indicated the geographic distribution and spectrum of infected marine species with *T. gondii* in different parts of the world. The spread of *T. gondii* among marine animals can affect the health of humans and other animals; in addition, it is possible that marine mammals act as sentinels of environmental contamination, especially the parasites by consuming water or prey species.

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Introduction

Marine species constitute a very diverse group of animals with global distribution, mostly along coastal regions or habitat [1]. The human population density in coastal areas greatly increased during the recent decades and zoonotic pathogens can be transmitted to humans directly or indirectly from marine animals [2]. Thus, the health of marine mammals can substantially influence human’s well-being. Toxoplasmosis, caused by the intracellular protozoan Toxoplasma gondii, is a zoonotic infection with felids as definitive hosts, and a wide range of homoeothermic vertebrates as intermediate hosts [3, 4]. Pregnant women and immunocompromised patients are at a higher risk for developing the clinical disease with harsh outcomes, including congenital toxoplasmosis (hydrocephalus, chorioretinitis, and cerebral calcifications) and life-threatening encephalitis [5–7]. Understanding T. gondii transmission routes in wild, free-ranging marine mammals is problematic. There are three possible routes by which marine animals could become infected with T. gondii, including: ingestion of oocysts, ingestion of bradyzoites in tissue cysts of other intermediate hosts or vertically. Oocysts are shed via cat feces into the environment, which can readily infect several animal species [8, 9]. Small T. gondii oocysts show remarkable resistance to common disinfectants and remain alive in moist surroundings, even when exposed to a vast range of salinity and temperature.
conditions. This environmental tolerance leads to in fast and extensive dispersal of infection, particularly following heavy rain falls. The runoff originated from rainfalls alongside wastewater outfalls being likely contaminated with stray/feral cat fecal material make a huge depot of infective oocysts, which are usually discharged into a water body, i.e., sea and ocean, posing potential risk of *T. gondii* infection in those species dwelling in marine habitats [10]. In another way, marine animals acquired infection through ingestion of *T. gondii* protozoal cyst containing numerous bradyzoites. In areas where definitive hosts are rare and the viability of oocysts are likely limited due to freezing conditions, such as the Canadian Arctic, this could explain how animals are exposed to *T. gondii*. A number of investigators have pointed out that oocysts and bradyzoites of *T. gondii* are concentrated by oysters, clams and mussels during filter-feeding activity. It is noteworthy that the role of vertical transmission of toxoplasmosis in marine animals is unknown [9]. These are highly promising findings, but the precise mode of transmission is still open to question. Experimentally, oocyst sporulation occurs in seawater, remaining infective for animals for 6–24 months, depending on the temperature [11, 12].

During the last decades, a number of studies have reported *T. gondii* infection in marine animals, such as cetaceans, pinnipeds, sirenians, and sea otters (*Enhydra lutris*) [13–16]. Disseminated clinical disease has also been documented in adult or sometimes neonate marine mammals from Europe, USA, and Australia [17–19], with some degree of morbidity observed, for example, in the sea otters [13, 20, 21] and in the Pacific harbor seal (*Phoca vitulina richardsi*) [22, 23]. Furthermore, it seems that some species have been threatened and endangered in part due to toxoplasmosis [3, 24].

The increasing amount of anthropogenic toxicants discharged into the marine environment, as well as morbillivirus infection, can suppress the immunity of marine mammals and give rise to clinical toxoplasmosis susceptibility, yet in others cases, no links to concurrent disease have been identified [25, 26]. Since *T. gondii* is a pronounced hallmark of aquatic pollution and marine species are superb sentinel animals in marine life [27–29], it would be beneficial to assess the status of *T. gondii* infection in these animals. Thus, the current systematic review and meta-analysis aimed to investigate the prevalence of *T. gondii* infection among marine animal species worldwide and highlight the existing gaps.

**Materials and Methods**

**Search Strategy**

This study was prepared and performed in accordance with the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) statement [30]. Data were systematically searched and collected from English language databases including PubMed, Science Direct, Google Scholar, Scopus, ISI Web of Science, published from inception to 1 January, 2020 by two investigators (FR and ASP).

The search process was performed using the following keywords and medical subject headings (MeSH) terms: “Toxoplasma gondii”, “Toxoplasmosis”, “T. gondii” in combination with “fishes”, “marine mammals”; “oyster”, “Shellfish”, “mussels”, “dolphin”, “shark”, “crab”, “seal”, “sea lion”, “whale”, “sea otter”, “porpoise”, “shrimp”, “Manatees”, “Walruses”, “Eel”, “crayfish”, and “turtle”. To avoid missing of any paper, the reference list of relevant papers was screened manually.

**Study Selection**

For the first screening, the two independent authors (ASP and FR) surveyed the title and the abstract of all papers returned from the search process. To ensure the eligibility for inclusion to the systematic review, full texts of papers were also reviewed by investigators (ASP and FR), and any disagreement on articles selected was resolved.

**Quality Evaluation**

Selected articles were assessed according to a checklist used in previous studies [31]. This checklist was based on contents of the strengthening the reporting of observational studies in epidemiology (STROBE) checklist containing questions about various methodological aspects such as type of study, sample size, study population, data collection approaches and tools, sampling methods, variables estimation status, methodology, research objectives and demonstration of results according to the objectives [32]. For each question, a score was attributed and articles with a score of at least seven were selected articles. In addition, any disagreements with selected papers were reviewed by another author.

**Selection Criteria and Data Extraction**

Papers were included in the meta-analysis with the following criteria: (1) original articles; (2) studies in English language; (2) articles available in full-text; (3) studies that evaluated the prevalence of *T. gondii* infection in marine animals. On the other hand, the exclusion criteria entailed: case reports, review articles, letter to the editor, unclear or not technically acceptable diagnostic criteria, insufficient information, congress articles, as well as those with unavailable full-text. After reviewing all articles, papers without sufficient information and that did not obtain the minimum quality score were excluded.
Meta-Analysis

In this study, a forest plot was used to visualize the summarized results and heterogeneity among the included studies. The size of every square indicated the weight of every study as well as crossed lines presented confidence intervals, CI. To assess heterogeneity index, Cochran’s $Q$ test and $I^2$ statistics were applied. Additionally, a funnel plot was designed to determine the small study effects and their publication bias, based on Egger’s regression test. The meta-analysis was conducted using Stats Direct statistical software (http://www.statsdirect.com). A $P$ value less than 0.05 was considered statistically significant. Additional meta-analysis was performed based on the type of host, location and diagnostic method.

Results

A total of 5175 papers were analyzed by exploration of PubMed, Science Direct, Scopus, Google Scholar, and ISI Web of Science databases, and finally 55 records were found to be eligible for the current systematic review and meta-analysis. The searching and study selection procedures are illustrated in Fig. 1. Based on Continent, the highest number of investigations was from Europe (30 studies) with a total prevalence of 12.99%, and marine mustelids were the most infected group with 53.12%. It is also worth noting that 24 studies from North America were included in this systematic review, indicating a total prevalence of 21.15%, and an exceptionally high infection rate among cetaceans was observed in this continent (80.85%). In Asian countries, a low prevalence rate of 1.78% was reported and the pinnipeds were the most infected group with 29.2%. In South America,
a pooled prevalence of 8.03% was reported with the highest infection in cetaceans (30.35%). In Oceania, the pooled prevalence was 17.73% and cetaceans were the most infected species (26.12%). In addition, the pooled prevalence rate in Antarctica was 39.21% in pinnipeds. On the other hand, no reports were found for the North Pole and the African continent (Fig. 2).

According to Table 1, T. gondii infection was detected in dolphins (45 entries), whales (29 entries), seals (31 entries), sea lions (5 entries), sea otters (10 entries), porpoise (3 entries), oysters/mussels/shellfish (11 entries), fishes (4 entries), shrimp (2 entries), manatees (2 entries), walruses, eel and crayfish (single record for each) using serological and/or molecular techniques. Most reports were from the USA and Brazil with 24 records for each country, followed by Scotland (15 records), Italy (13 records), China (10 records), Spain (9 records), Canada and United Kingdom (8 records for each), Mexico (5 records), Norway and Russia (4 records for each), New Zealand (3 records), Japan (2 records) as well as single records from Iran, Turkey, Portugal, Netherlands, Peru, Australia and Solomon Islands. Altogether, eight serological methods were employed to determine T. gondii infection among marine animals. These include the modified agglutination test (MAT) as the most used technique (41 records), followed by immunofluorescence antibody test (IFA) (30 records) and immunohistochemistry (IHC) (21 records). Moreover, 17 entries used conventional polymerase chain reaction (PCR), being this the most used molecular technique, followed by nested-PCR (7 records) and quantitative PCR (qPCR) (4 records). Subgroup analysis (Table 2) showed that most studies were focused on cetaceans (whale, dolphin and porpoise) (36 studies), whereas the highest prevalence rate of T. gondii infection belonged to marine mustelids (sea otter, 10 studies) with 54.8% (95% CI 34.21–74.57%). Pooled proportion of T. gondii infection in dolphin species was of 51.07%. According to Egger’s test, the prevalence rates in cetaceans (P value = 0.0489) and pinnipeds (P value = 0.0004) were statistically significant.

Discussion

The present systematic review and meta-analysis aimed to determine the prevalence rate of T. gondii infection worldwide. The obtained data were categorized based on the species of marine animals, continents, and diagnostic techniques. Among marine animals, the prevalence of T. gondii infection was higher in the population of sea otters (54.8%). In a study, Miller et al. [33] suggested that coastal freshwater runoff is a risk factor for toxoplasmosis in southern sea otters.

![Fig. 2](image-url) Pooled prevalence of T. gondii in marine animal species in different continents

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| Species               | Location          | Continent   | Test               | Sample size | Positive (%) | References                      |
|----------------------|-------------------|-------------|-------------------|-------------|--------------|---------------------------------|
| **Dolphin**          |                   |             |                   |             |              |                                 |
| *Tursiops truncatus* | USA               | North America | MAT               | 141         | 138 (97.9)  | Dubey et al. [17]               |
| *Sousa chinensis*    | Australia         | Australia   | IHC               | 4           | 4 (100)     | Bowater et al. [47]             |
| *Stenella coeruleoalba* | Spain           | Europe     | MAT               | 36          | 4 (11.1)    | Cabezón et al. [48]            |
| *Delphinus delphis*  | Spain             | Europe     | MAT               | 4           | 2 (50)      | Cabezón et al. [48]            |
| *Tursiops truncatus* | Spain             | Europe     | MAT               | 7           | 4 (57.1)    | Cabezón et al. [48]            |
| *Phocoena phocoena*  | Spain             | Europe     | MAT               | 1           | 1 (100)     | Cabezón et al. [48]            |
| *Grampus griseus*    | Spain             | Europe     | MAT               | 9           | 0           | Cabezón et al. [48]            |
| *Tursiops aduncus*   | Solomon Islands   | Oceania    | Immunoblotting    | 58          | 8 (13.8)    | Omata et al. [49]              |
| *Tursiops truncatus* | Russia            | Europe     | ELISA             | 59          | 27 (45.7)   | Alekseev et al. [50]           |
| *Tursiops truncatus* | USA               | North America | MAT               | 52          | 27 (51.9)   | Dubey et al. [44]              |
| *Tursiops truncatus* | Russia            | Europe     | ELISA             | 74          | 39 (52.7)   | Alekseev et al. [51]           |
| *Tursiops truncatus* | USA               | North America | MAT               | 7           | 7 (100)     | Dubey et al. [18]              |
| *Delphinus delphis*  | United Kingdom    | Europe     | Sabin Feldman    | 21          | 6 (28.5)    | Forman et al. [52]             |
| *Grampus griseus*    | United Kingdom    | Europe     | Sabin Feldman    | 1           | 0           | Forman et al. [52]             |
| *Lagenorhynchus acutus* | United Kingdom | Europe     | Sabin Feldman    | 1           | 0           | Forman et al. [52]             |
| *Tursiops truncatus* | United Kingdom    | Europe     | Sabin Feldman    | 1           | 0           | Forman et al. [52]             |
| *Stenella coeruleoalba* | United Kingdom | Europe | Sabin Feldman    | 5           | 0           | Forman et al. [52]             |
| *Stenella coeruleoalba* | Italy            | Europe     | IFA               | 8           | 4 (50)      | Di Guardo et al. [53]          |
| *Tursiops truncates* | Italy             | Europe     | Nested-PCR and MAT | 8       | 7 (87.5)    | Pretti et al. [54]             |
| *Stenella coeruleoalba* | Italy            | Europe     | Nested-PCR and MAT | 6       | 6 (100)     | Pretti et al. [54]             |
| *Inia geoffrensis*   | Brazil            | South America| MAT              | 95          | 82 (86.3)   | Santos et al. [55]             |
| *Tursiops truncatus* | Mexico            | North America | MAT               | 63          | 55 (87.3)   | Alvarado-Esquível et al. [56]   |
| *Tursiops truncatus* | Mexico            | North America | MAT               | 3           | 3 (100)     | Alvarado-Esquível et al. [56]   |
| *Cephalorhynchys hectori* | New Zealand      | Oceania | PCR               | 49          | 17 (34.7)   | Roe et al. [57]                |
| *Tursiops truncatus* | Spain             | Europe     | IFA               | 24          | 2 (8.3)     | Bernal-Guadarrama et al. [58]   |
| *Stenella coeruleoalba* | Italy            | Europe     | IFA               | 18          | 8 (44.4)    | Profeta et al. [59]            |
| *Tursiops truncatus* | Italy             | Europe     | IFA               | 3           | 2 (66.6)    | Profeta et al. [59]            |
| *Grampus griseus*    | Scotland          | Europe     | IFA               | 7           | 2 (28.5)    | et al. [26]                    |
| *Delphinus delphis*  | Scotland          | Europe     | IFA               | 13          | 2 (15.4)    | van de Velde et al. [26]       |
| *Stenella coeruleoalba* | Scotland         | Europe     | IFA               | 9           | 0           | van de Velde et al. [26]       |
| *Lagenorhynchus albirostris* | Scotland  | Europe | IFA               | 6           | 1 (16.6)    | van de Velde et al. [26]       |
| *Stenella coeruleoalba* | Italy            | Europe     | PCR               | 10          | 6 (60)      | Pintore et al. [60]            |
| *Tursiops truncatus* | Italy             | Europe     | PCR               | 1           | 1 (100)     | Pintore et al. [60]            |
| *Steno bredanensis*  | Brazil            | South America | IHC              | 3           | 0           | Costa-Silva et al. [61]        |
| *Lagenodelphis hosei* | Brazil           | South America | IHC              | 2           | 0           | Costa-Silva et al. [61]        |
| *Sotalia guianensis* | Brazil            | South America | IHC              | 27          | 1 (3.7)     | Costa-Silva et al. [61]        |
| *Tursiops truncatus* | Brazil            | South America | IHC              | 4           | 1 (25)      | Costa-Silva et al. [61]        |
| *Pontoporia blainvillii* | Brazil           | South America | IHC              | 102         | 0           | Costa-Silva et al. [61]        |
| *Stenella frontalis* | Brazil            | South America | IHC              | 6           | 0           | Costa-Silva et al. [61]        |
| *Stenella longirostris* | Brazil           | South America | IHC              | 5           | 0           | Costa-Silva et al. [61]        |
| *Stenella clymene*   | Brazil            | South America | IHC              | 6           | 0           | Costa-Silva et al. [61]        |
| *Stenella coeruleoalba* | Brazil           | South America | IHC              | 2           | 0           | Costa-Silva et al. [61]        |
| *Delphinus delphis*  | Brazil            | South America | IHC              | 1           | 0           | Costa-Silva et al. [61]        |
Table 1 (continued)

| Species                  | Location       | Continent  | Test   | Sample size | Positive (%) | References                  |
|--------------------------|----------------|------------|--------|-------------|---------------|-----------------------------|
| *Delphinus delphis*      | Brazil         | South America | IHC    | 1           | 0             | Costa-Silva et al. [61]     |
| *Inia geofrensis*        | Brazil         | South America | IHC    | 1           | 0             | Costa-Silva et al. [61]     |
| **Whale**                |                |            |        |             |               |                             |
| *Balaenoptera acuto-      | Norway         | Europe     | MAT    | 202         | 0             | Oksanen et al. [62]         |
| rostrata                 |                |            |        |             |               |                             |
| *Delphinapterus leucas*  | USA            | North America | MAT    | 3           | 0             | Dubey et al. [17]           |
| *Globicephala melas*     | Spain          | Europe     | MAT    | 1           | 0             | Cabezón et al. [48]        |
| *Orcinus orca*           | Japan          | Asia       | PCR    | 8           | 1 (12.5)      | Omata et al. [49]          |
| *Delphinapterus leucas*  | Russia         | Europe     | ELISA  | 147         | 7 (4.7)       | Alekseev et al. [51]       |
| *Megaptera novaeangliae* | United Kingdom | Europe     | Sabin Feldman | 1   | 1 (100)     | Forman et al. [52]         |
| *Ziphius cavirostris*    | United Kingdom | Europe     | Sabin Feldman | 1   | 0           | Forman et al. [52]         |
| *Physeter macrocephalus* | Portugal       | Europe     | qPCR   | 5           | 0             | Hermosilla et al. [63]     |
| *Balaenoptera physalus*  | Italy          | Europe     | IFA    | 1           | 0             | van de Velde et al. [26]   |
| *Globicephala melas*     | Italy          | Europe     | IFA    | 1           | 0             | van de Velde et al. [26]   |
| *Balaenoptera physalus*  | Scotland       | Europe     | IFA    | 1           | 0             | van de Velde et al. [26]   |
| *Orcinus orca*           | Scotland       | Europe     | IFA    | 3           | 0             | van de Velde et al. [26]   |
| *Globicephala melas*     | Scotland       | Europe     | IFA    | 10          | 4 (40)        | van de Velde et al. [26]   |
| *Balaenoptera acuto-      | Scotland       | Europe     | IFA    | 5           | 0             | van de Velde et al. [26]   |
| rostrata                 |                |            |        |             |               |                             |
| *Mesoplodon bidens*      | Scotland       | Europe     | IFA    | 4           | 0             | van de Velde et al. [26]   |
| *Physeter macrocephalus* | Scotland       | Europe     | IFA    | 2           | 0             | Alekseev et al. 2017 [64]  |
| *Balaenoptera borealis*  | Scotland       | Europe     | IFA    | 1           | 0             | Iqbal et al. [65]          |
| *Delphinapterus leucas*  | Russia         | Europe     | ELISA  | 87          | 10 (11.5)     | Profeta et al. [59]        |
| *Delphinapterus leucas*  | Canada         | North America | PCR   | 34          | 15 (44.1)     | Profeta et al. [59]        |
| *Globicephala melas*     | Italy          | Europe     | PCR    | 1           | 0             | Pintore et al. [60]        |
| *Kogia sima*             | Brazil         | South America | IHC   | 7           | 0             | Costa-Silva et al. [61]    |
| *Peponocephala electra* | Brazil         | South America | IHC   | 5           | 0             | Costa-Silva et al. [61]    |
| *Globicephala macro-      | Brazil         | South America | IHC   | 3           | 0             | Costa-Silva et al. [61]    |
| rhynchus                 |                |            |        |             |               |                             |
| *Physeter macrocephalus* | Brazil         | South America | IHC   | 3           | 0             | Costa-Silva et al. [61]    |
| *Kogia breviceps*        | Brazil         | South America | IHC   | 2           | 0             | Costa-Silva et al. [61]    |
| *Megaptera novaeangliae* | Brazil         | South America | IHC   | 2           | 0             | Costa-Silva et al. [61]    |
| *Orcinus orca*           | Brazil         | South America | IHC   | 2           | 1 (50)        | Costa-Silva et al. [61]    |
| *Mesoplodon europaeus*   | Brazil         | South America | IHC   | 1           | 0             | Costa-Silva et al. [61]    |
| *Balaenoptera physalus*  | Italy          | Europe     | PCR    | 7           | 1 (14.2)      | Marcer et al. [66]         |
| **Seals**                |                |            |        |             |               |                             |
| *Phoca groenlandica*     | Norway         | Europe     | MAT    | 316         | 0             | Oksanen et al. [62]        |
| *Phoca hispida*          | Norway         | Europe     | MAT    | 48          | 0             | Oksanen et al. [62]        |
| *Cystophora cristata*    | Norway         | Europe     | MAT    | 78          | 0             | Oksanen et al. [62]        |
| *Phoca vitulina*         | USA            | North America | MAT  | 380         | 29 (7.6)      | Lambourn et al. [67]       |
| *Phoca vitulina*         | USA            | North America | MAT  | 311         | 51 (16.4)     | Dubey et al. [17]          |
| *Phoca hispida*          | USA            | North America | MAT  | 32          | 5 (15.6)      | Dubey et al. [17]          |
| *Erignathus barbatus*    | USA            | North America | MAT  | 8           | 4 (50)        | Dubey et al. [17]          |
| *Phoca largha*           | USA            | North America | MAT  | 9           | 1 (11.1)      | Dubey et al. [17]          |
| *Phoca fasciata*         | USA            | North America | MAT  | 14          | 0             | Dubey et al. [17]          |
| *Phoca groenlandica*     | Canada         | North America | MAT  | 112         | 0             | Measures et al. [68]       |
| Species                        | Location               | Continent       | Test     | Sample size | Positive (%) | References           |
|-------------------------------|------------------------|-----------------|----------|-------------|---------------|----------------------|
| Cystophora cristata           | Canada                 | North America   | MAT      | 60          | 1 (1.6)       | Measures et al. [68]  |
| Halichoerus grypus            | Canada                 | North America   | MAT      | 122         | 11 (9)        | Measures et al. [68]  |
| Phoca vitulina                | Canada                 | North America   | MAT      | 34          | 3 (8.8)       | Measures et al. [68]  |
| Phoca vitulina stejnegeri     | Japan                  | Asia            | ELISA    | 77          | 3 (3.9)       | Fujii et al. [9]      |
| Phoca vitulina vitulina       | Spain                  | Europe          | MAT      | 56          | 3 (5.3)       | Cabezón et al. [48]   |
| Halichoerus grypus            | Spain                  | Europe          | MAT      | 47          | 11 (23.4)     | Cabezón et al. [48]   |
| Pusa hispida                  | Canada                 | North America   | DAT      | 788         | 80 (10.1)     | Simon et al. [69]     |
| Erignathus barbatus           | Canada                 | North America   | DAT      | 20          | 2 (10)        | Simon et al. [69]     |
| Phoca vitulina                | Canada                 | North America   | MAT      | 9           | 2 (22.2)      | Simon et al. [69]     |
| Leptonychotes weddellii       | Antarctic Peninsula    | South America   | DAT      | 31          | 13 (41.9)     | Rengifo-Herrera et al. [70] |
| Mirounga leonina              | Antarctic Peninsula    | South America   | DAT      | 13          | 10 (76.9)     | Rengifo-Herrera et al. [70] |
| Lobodon carcinophaga          | Antarctic Peninsula    | South America   | DAT      | 2           | 1 (50)        | Rengifo-Herrera et al. [70] |
| Arctocephalus gazella         | Antarctic Peninsula    | South America   | DAT      | 165         | 4 (2.4)       | Rengifo-Herrera et al. [70] |
| Arctocephalus gazella         | Antarctica             | Antarctica      | DAT      | 21          | 12 (57.1)     | Jensen et al. [71]    |
| Leptonychotes weddellii       | Antarctica             | Antarctica      | DAT      | 33          | 17 (51.5)     | Jensen et al. [71]    |
| Mirounga leonina              | Antarctica             | Antarctica      | DAT      | 48          | 11 (22.9)     | Jensen et al. [71]    |
| Arctocephalus australis       | Peru                   | South America   | IFA      | 27          | 0             | Jankowski et al. [72] |
| Halichoerus grypus            | Scotland               | Europe          | IFA      | 13          | 0             | van de Velde et al. [26] |
| Phoca vitulina                | Scotland               | Europe          | IFA      | 17          | 2 (11.7)      | van de Velde et al. [26] |
| Phoca vitulina richardi       | Alaska                 | North America   | IFA      | 34          | 0             | Bauer et al. [73]     |
| Pusa caspica                  | Iran                   | Asia            | MAT      | 36          | 30 (83.3)     | Namroodi et al. [74]  |
| Sea lions                     |                        |                 |          |             |               |                      |
| Zalophus californianus        | USA                    | North America   | MAT      | 45          | 19 (42.2)     | Dubey et al. [17]     |
| Otaria flavescens             | Mexico                 | North America   | MAT      | 2           | 0             | Alvarado-Esquivel et al. [56] |
| Zalophus californianus        | Mexico                 | North America   | MAT      | 4           | 2 (50)        | Alvarado-Esquivel et al. [56] |
| Zalophus californianus        | USA                    | North America   | IFA      | 1630        | 46 (2.8)      | Carlson-Bremer et al. [75] |
| Phocarctos hookeri            | New Zealand            | Oceania         | ELISA    | 50          | 5 (10)        | Michael et al. [76]   |
| Sea otters                    |                        |                 |          |             |               |                      |
| Lontra canadensis             | USA                    | North America   | LAT      | 103         | 46 (44.6)     | Tocidlowski et al. [77] |
| Enhydra lutris nereis         | USA                    | North America   | IFA      | 223         | 115 (51.5)    | Miller et al. [78]    |
| Enhydra lutris nereis         | USA                    | North America   | IFA      | 80          | 29 (36.2)     | Miller et al. [78]    |
| Enhydra lutris kenyoni        | USA                    | North America   | IFA      | 21          | 8 (38.1)      | Miller et al. [78]    |
| Enhydra lutris kenyoni        | USA                    | North America   | IFA      | 65          | 0             | Miller et al. [78]    |
| Enhydra lutris nereis         | USA                    | North America   | Microscopic test | 35 | 15 (42.8) | Miller et al. [79] |
| Enhydra lutris               | USA                    | North America   | MAT      | 145         | 107 (73.7)    | Dubey et al. [17]     |
| Lontra canadensis             | USA                    | North America   | IFA      | 40          | 7 (17.5)      | Gaydos et al. [80]    |
| Lutra lutra                   | Scotland               | Europe          | IFA      | 32          | 17 (53.1)     | van de Velde et al. [26] |
| Enhydra lutris kenyoni        | USA                    | North America   | MAT      | 70          | 65 (92.8)     | Verma et al. [81]     |
| Porpoise                      |                        |                 |          |             |               |                      |
| Phocoena phocoena             | United Kingdom         | Europe          | Sabin Feldman | 70 | 1 (1.4)    | Forman et al. [52]    |
| Phocoena phocoena             | Netherlands            | Europe          | MAT      | 31          | 4 (12.9)      | van de Velde et al. [26] |
| Phocoena phocoena             | Scotland               | Europe          | IFA      | 98          | 2 (2)         | van de Velde et al. [26] |
| Oysters/mussels/shellfish     |                        |                 |          |             |               |                      |
| Mytella guyanensis            | Brazil                 | South America   | Nested PCR | 300 | 0       | Esmerini et al. [82]  |
(Enhydra lutris nereis) in southern California. Furthermore, it has been shown that exposure to T. gondii among sea otters was highly influenced by individual animal prey choice and habitat use [34]. Toxoplasmosis had considerable morbidity and mortality rates in the sea otter [35]. T. gondii encephalitis in sea otters causes high mortality rate and is responsible for slow population recovery, particularly for the endangered Southern sea otter [27]. In addition, cetaceans were the most infected animals in North America, South America, and Oceania. Modified agglutination test (MAT) was the most applied diagnostic assay for T. gondii detection in marine animals. This technique is widely employed in research of toxoplasmosis in humans and in all species of animals because it is considered as a rapid and simple approach without the requirement for special facilities [36]. Molecular methods, particularly polymerase chain reaction (PCR) and nested PCR, were used in marine animals usually as a food source for humans like fishes, shrimp, oysters, and crayfish, amongst others. Some studies indicate that consumption of contaminated raw shellfish and mussels can be considered a

| Species                  | Location          | Continent   | Test       | Sample size | Positive (%) | References               |
|--------------------------|-------------------|-------------|------------|-------------|--------------|--------------------------|
| *Crassostrea rhizopho-    | Brazil            | South America | Nested PCR | 300         | 10 (3.3)     | Esmerini et al. [82]     |
| *Mytilus galloprovincialis* | Turkey           | Europe      | HRM        | 53          | 21 (39.6)    | Aksoy et al. [37]        |
| *Ostreae concha*         | China             | Asia        | PCR        | 398         | 0            | Zhang et al. [83]        |
| *Mytilus galloprovincialis* | Italy            | Europe      | qPCR       | 53          | 7 (13.2)     | Marangi et al. [84]      |
| *Crassostrea virginica*  | USA               | North America | PCR        | 230         | 4 (1.7)      | Marquis et al. [85]      |
| *Crassostrea rhizopho-    | Brazil            | South America | PCR        | 624         | 17 (2.7)     | Ribeiro et al. [86]      |
| *Oysters*                | China             | Asia        | Nested PCR | 998         | 26 (2.6)     | Cong et al. [87]         |
| *Perna canaliculus*      | New Zealand       | Oceania     | Nested PCR | 104         | 13 (12.5)    | Coupe et al. [88]        |
| *Mytilus edulis*         | China             | Asia        | Nested PCR | 2215        | 55 (2.4)     | Cong et al. [89]         |
| *Crassostrea virginica*  | USA               | North America | qPCR       | 1440        | 446 (30.9)   | Marquis et al. [90]      |
| *Fishes*                 | China             | Asia        | PCR        | 309         | 0            | Zhang et al. [83]        |
| *Cyprinus carpio*        | China             | Asia        | PCR        | 309         | 0            | Zhang et al. [83]        |
| *Hypophthalmichthys molitrix* | China        | Asia        | PCR        | 456         | 1 (0.2)      | Zhang et al. [83]        |
| *Fishes*                 | Italy             | Europe      | qPCR       | 147         | 32 (21.7)    | Marino et al. [91]       |
| *Shrimp*                 | China             | Asia        | PCR        | 426         | 0            | Zhang et al. [83]        |
| *Macrobrachium nipponense* | China            | Asia        | PCR        | 813         | 1 (0.1)      | Zhang et al. [83]        |
| *Manatees*               | Mexico            | North America | MAT        | 3           | 0            | Alvarado-Esquivel et al. [56] |
| *Trichechus inunguis*    | USA               | North America | MAT        | 74          | 29 (39.1)    | Mathews et al. [15]      |
| *Walruses*               | USA               | North America | MAT        | 53          | 3 (5.6)      | Dubey et al. [17]        |
| *Eel*                    | China             | Asia        | PCR        | 98          | 0            | Zhang et al. [83]        |
| *Crayfish*               | China             | Asia        | PCR        | 618         | 4 (0.64)     | Zhang et al. [83]        |

IHC immunohistochemistry, IFA immunofluorescence antibody test, DAT direct agglutination test, LAT latex agglutination test, HRM real time PCR/high-resolution melting analysis, IHAT indirect hemagglutination test.
significant health danger due to their ability to infect a wide variety of hosts such as other marine animals and humans. However, they are particularly at risk for *T. gondii* infection, and therefore, they can be considered a bioindicator for monitoring waterborne pathogens [37, 38]. The high prevalence rate of *T. gondii* in the examined marine species may indicate that the nearby terrestrial environment in the studied area was heavily contaminated by *T. gondii*, and consequently, contamination was transferred to the aquatic environment. Furthermore, marine hosts may associate with *T. gondii* infection as paratenic hosts in some area [39]. Hence, contamination of marine animal species is an important bioindicator for contamination of aquatic environments.

Each cat, as final host for *T. gondii*, shed over 3–810 million oocysts. The sporulation of the oocysts takes 1–5 days, and they can remain infective in the soil for up to 18 months [40]. Furthermore, experiments showed that oocysts of *T. gondii* can sporulate in sea water and survive at 4 °C for 24 months and then infect mice [12]. One important factor in infected hosts is the strain of the parasite, which plays a major role in the toxoplasmosis prognosis. So far, the genotypes *T. gondii* were classified as classical types I, II, III, mix/recombinant atypical, and African lineages [41]. Comparison between *T. gondii* genotypes from the marine and terrestrial environments would help clarify routs and mechanisms of land-sea transmission. Type I strains, which are highly virulent and pathogenic, can lead to acquired ocular toxoplasmosis in individuals with disseminated congenital form of *T. gondii* [42, 43]. Aksoy et al. [37] reported *T. gondii* type 1 infection in *Mytilus galloprovincialis* (Mediterranean mussel), one of the most consumed shellfish in Turkey. The authors suggested that these types of contaminated seafood may be involved in the transmission of the parasite to humans and other hosts. Type II *T. gondii* strains are the vast majority of human infections and have a worldwide distribution. Type II strains are causative agents for numerous asymptomatic toxoplasmosis cases in Europe, it can be pathogenic for two important categories of subjects, namely immature fetuses and immunocompromised individuals [43]. On the basis of a previous study, Dubey et al. [44] showed Type II *T. gondii* from a striped dolphin (*Stenella coeruleoalba*) in Costa Rica. It is noteworthy that Type III *T. gondii* in mice are classified as avirulent strain. Study carried out by Hancock et al. [45] showed the first report of type III *T. gondii* in a Hawaiian monk seal. This genotype was determined to be restriction fragment length polymorphisms (RFLP) of the SAG2 gene. On the other hand, it has previously been shown that Type X strains of *T. gondii* are virulent for southern sea otters from coastal California [27]. Additionally, one interesting study has demonstrated Type X strains of *T. gondii* in canids, coastal-dwelling felids, nearshore-dwelling sea otters, and marine bivalve. It is assumed that contaminated runoff to feline faecal rapidly reaches sea from lands, and

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**Table 2** Prevalence of *Toxoplasma* infection in marine animals and subgroup analyses

| Types of animals (species) | No. of studies | Prevalence (95% CI) | Heterogeneity | Egger's test |
|---------------------------|----------------|---------------------|---------------|--------------|
| Cetaceans (whale, dolphin, porpoise) | 36 | 30.92 (17.85–45.76) | 97.5 | 1377.98 | <0.0001 | 4.87 | 0.0489 |
| Pinipeds (seals, sea lions, walruses) | 18 | 12.16 (7.26–18.98) | 96.3 | 460.63 | <0.0001 | 4.10 | 0.0001 |
| Sirenians (manatees) | 2 | 36.51 (24.66–53.96) | 96.6 | 147.12 | <0.0001 | 4.34 | 0.0165 |
| Marine fissipeds (sea otter) | 6 | 26.5 (18.41–43.66) | 96.6 | 147.12 | <0.0001 | 4.34 | 0.0165 |
| Fishes (fish, eel) | 5 | 1.64 (0.02–7.22) | 96.3 | 147.12 | <0.0001 | 4.34 | 0.0165 |
| Decapoda (crayfish, shrimp) | 2 | 1.64 (0.02–7.22) | 96.3 | 147.12 | <0.0001 | 4.34 | 0.0165 |
| Mollusca (oysters, mussels, shellfish) | 10 | 7.45 (2.06–15.81) | 99.1 | 962.83 | <0.0001 | 7.56 | 0.0078 |
otters could be infected with *T. gondii* via the consumption of filter-feeding marine invertebrates [46].

The prevalence rate of marine *T. gondii* infection in various regions of the world was very different, and ranged from 0 to 100%. These differences may originate from different types of marine animals, sample sizes, and diagnostic approaches in the reviewed studies. Regarding continents, North America showed the highest *T. gondii* infection in marine animals that may suggest the level of fecal contamination of the soil and water reservoirs. Our analysis also showed that there is either no available data (Africa) or very limited literature (Antarctica, Oceania, and South America) on the prevalence of *T. gondii* infection in significant parts of the globe. Therefore, it is essential to conduct more studies to determine the putative role of *T. gondii* on marine species. The main limitation expressed in the included studies regarding prevalence of *T. gondii* infection in marine animal species was related to the use of different diagnostic methods with varying sensitivity and specificity due to their great impact on the results. The use of an accurate and reliable technique can help to correctly interpret the results of *T. gondii* prevalence in marine species in different parts of the world.

**Conclusion**

The results of current study indicated that the global prevalence rate of *T. gondii* infection was high in marine animals. It is well demonstrated that *T. gondii* parasite has a very successful adaptation in aquatic environments. Despite the worldwide range and broad marine animals host record of *T. gondii* infection, there was no evidence regarding toxoplasmosis in these animals in most parts of the world. Therefore, it is necessary to develop surveillance for detection of *T. gondii* in aquatic animals in different regions with appropriate molecular and serological techniques. It is also important to know the ecology of this parasite in aquatic environment to design appropriate strategies for monitoring, controlling, and prevention of the transmission of toxoplasmosis to humans or other hosts.

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**Declarations**

**Conflict of Interest** The authors declare that there is no conflict of interest regarding the publication of this article.

**Availability of Data and Material** Data supporting the conclusions of this article are included within the article.

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