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# MITIGATION MEASURES TO REDUCE THE RISK OF INTRODUCTION AND SPREAD OF AQUATIC INVASIVE SPECIES THROUGH SHELLFISH AND MACROALGAL MOVEMENTS

*Aquatic Invasive Species growing on mussel socks (Photo credit: Fisheries and Oceans Canada, Gulf Region).*

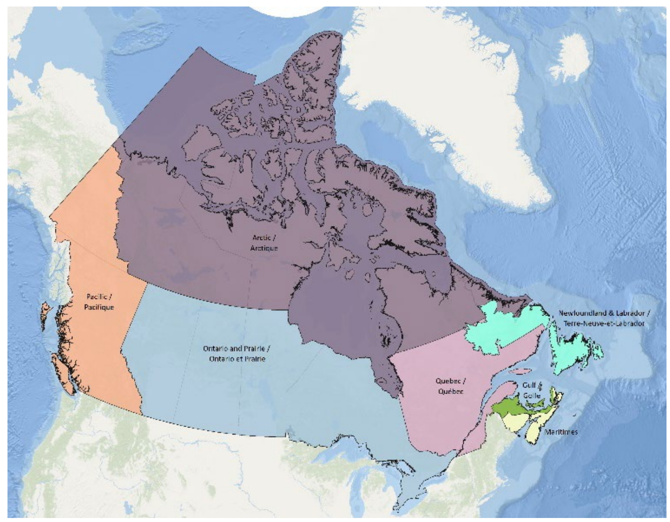


*Figure 1. Map of Fisheries and Oceans Canada (DFO) Regions.*

## CONTEXT

Shellfish and macroalgal movements (e.g., transfers for aquaculture purposes) are an important vector for the introduction and spread of Aquatic Invasive Species (AIS) in marine ecosystems. To date, a comprehensive review has not been conducted on the effectiveness of treatments that could be used in Canada to kill or remove marine AIS from shellfish and macroalgae being moved and their impacts on those species. Thus, a wide variety of treatments are currently in use without national guidance and consistency. DFO's Aquaculture Directorate (formerly National Aquaculture Management Program) and Aquatic Invasive Species National Core Program intend to use this advice to develop standards (or guidelines) for reducing the risk of spreading AIS. These standards would provide guidance related to shellfish and macroalgal movements to a number of governing bodies including DFO Introduction and Transfer Committees. Recommendations in the document could be used to inform decision-making, including management and policy, with regards to Canadian AIS mitigation for shellfish and macroalgal species that may be vectors of marine AIS.

This Science Advisory Report is from the national peer review of December 12-14, 2022, on Science Advice on Mitigation Measures to Reduce the Risk of Spreading Aquatic Invasive Species (AIS) through Aquaculture Mediated Transfers. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

## SUMMARY


- Shellfish and macroalgal movements are a known vector for the introduction and spread of Aquatic Invasive Species (AIS). Physical or chemical treatments are one means to reduce this risk, although a comprehensive review of the effectiveness of available options has not been conducted in Canada.
- To understand the effectiveness and limitations of these various treatments, a literature review of existing options was conducted. That review covered both mortality/removal of AIS and survival of shellfish and macroalgal species being moved.
- No single treatment was found applicable to all AIS while also maintaining shellfish survival in the context of species movements.
- Numerous physical and chemical treatment options were identified as being effective (100% mortality/removal) at killing/removing specific AIS.
- Numerous physical and chemical treatment options were identified as having no/low impacts (≥90% survival) on moved shellfish species, while impacts on moved macroalgae remain a significant gap.
- Only a few physical and chemical treatment options applicable to multiple AIS, while keeping moved shellfish species alive, were identified (see Tables 3 and 4).
- There are a number of considerations that may limit the usefulness of those treatments in real-world settings or for other AIS or shellfish and macroalgal species.
- Key uncertainties include comparing results between taxa, field and laboratory studies, and different experimental designs, scales, and methods of measuring AIS mortality and the use of quantitative and qualitative data.
- This literature review identified a significant number of gaps (e.g., longer-term impacts on moved species, lack of data on macroalgae, lack of information at commercial scales) with respect to the effectiveness of physical and chemical treatments on specific AIS and their impacts on moved species (shellfish and macroalgae), especially combined treatment options (e.g., heat and chemical applications).

Additional considerations such as taxa, season, and site-specific characteristics (e.g., temperature, salinity, pH, humidity) will need to be considered when applying this advice.

# INTRODUCTION

Aquatic Invasive Species (AIS) that are introduced and spread in ecosystems outside of their natural range can threaten Canada's biodiversity, economy, and society. Shellfish and macroalgal movements are considered an important vector of AIS. Thus, preventing introductions and further spread of AIS is crucial. The International Council for the Exploration of the Sea (ICES) Code of Practice on the Introduction and Transfer of Marine Organisms provides a framework to evaluate new intentional introductions, and recommends procedures for species that are part of current commercial practices to reduce the risk of unwanted introductions and translocations (ICES 2005). Canada's provincial, territorial, and federal governments jointly implemented the National Code on Introduction and Transfer of Aquatic Organisms (DFO 2017) to protect Canadian ecosystems. Thus, mitigation measures for AIS may be recommended or required as a condition of license to reduce the risk of introduction and transfer of aquatic organisms, particularly AIS.

Despite the fact that mitigation measures are used as a condition of license for DFO-approved Introduction and Transfer permits, there are no national DFO standards for proposed mitigation measures used to treat moved shellfish or macroalgae to reduce the risk of introduction and spread of AIS. To date, a comprehensive review has not been conducted on the effectiveness of treatments that could be used in Canada to kill or remove marine AIS from shellfish and macroalgae and their impacts on those species. Further, a wide variety of methods are currently in use without national guidance or consistency. Thus, a literature review on those methods was undertaken—limited to marine invertebrate and macroalgal species, with an emphasis on epibiont AIS, which have the potential to be transported externally on shellfish/macroalgal species during movements (e.g., aquaculture transfers). Internally transported species (e.g., those living in mantle water), as well as viruses, bacteria, phytoplankton, and protozoans, were outside the scope of this work. There are numerous considerations that may limit the usefulness of treatments in real-world settings in the context of moving species which include, but were not limited to: the ease of application and feasibility/practicality under field conditions, associated health and safety hazards, cost, and disposal. These considerations were outside the scope of the present review and will have to be further evaluated.

The specific objectives of this advisory process were to:

1. Review and characterize existing methods to mitigate the risk of spreading marine epibiont invertebrate and macroalgal AIS during shellfish/macroalgal movements.
2. Assess the effectiveness of existing methods to kill/remove marine epibiont invertebrate and macroalgal AIS and their impacts on shellfish and macroalgal species including, but not exclusively limited to, survival.
3. Provide treatment options that could kill/remove AIS while ensuring survival of moved shellfish and macroalgal species.
4. Identify data gaps and sources of uncertainty.

DFO's Aquaculture Directorate and Aquatic Invasive Species National Core Program intend to use this advice to develop standards or guidelines for reducing the risk of spreading AIS. Those standards would provide guidance related to shellfish and macroalgal movements, and be relevant to both programs as well as to regional DFO Introduction and Transfer Committees. Recommendations could be used to inform management decision-making and policy development.

# METHODS

A literature review of physical and chemical treatments used as mitigation measures to control marine AIS and epibionts was completed to document the effectiveness of treatments on AIS (i.e., mortality/removal) and their impacts on moved shellfish and macroalgal species (i.e., survival). Literature was collected from several sources including: Web of Science (Web of Knowledge), DFO's Federal Science Library (WAVES), Google Scholar (Google™), and ResearchGate, considering all publications until November 2022. Publications included peer-reviewed journal articles, governmental and consultant reports (i.e., secondary/grey literature), relevant websites, and personal communications/expert opinions where applicable.

Representative AIS or epibiont species from various functional and taxonomic groups (tunicates, bivalves, gastropods, crustaceans, sea stars, macroalgae, polychaetes, bryozoans, sponges, and hydrozoans) were selected according to their presence (or their expected arrival) in Canadian marine environments (Table 1). Species of shellfish (classified into small and large size categories) and macroalgae known to have been or currently cultivated in Canada with the potential to be moved among water bodies were included in this review (Table 2). In some cases, when data were limited for a specific AIS or moved species, data were included for AIS or moved shellfish/macroalgal species that could serve as suitable proxies for a particular species or taxonomic group. Proxy species were chosen to represent target species based on their morphological similarity or taxonomic relatedness to the species, their belonging to the same functional group, or their similarity in habitat preferences or distribution.

Publications were retained if they met the following criteria:

1. Included a detailed description of one or several physical or chemical treatments used to kill or remove surface-dwelling AIS and/or epibionts;
2. Quantitatively or qualitatively evaluated treatment effectiveness (mortality, removal) on the AIS and/or impacts (survival, viability, and/or growth) on the species being moved; and
3. Could be applicable for the treatment of Canadian marine shellfish or macroalgae prior to their movement (e.g., aquaculture transfers, scientific experimental permits).

The most commonly identified treatments were assessed for their effectiveness on a subset of marine AIS/epibionts as well as for their impacts on a selection of moved shellfish and macroalgal species and included physical (pressure washing, air drying, freshwater, heat) and chemical (chlorine-based compounds, acetic acid, citric acid, brine, hydrated lime, Virkon®) sprays/immersions or combinations of treatments. Treatments identified as proactive and preventive management methods (e.g., biological and mechanical control) were deemed to be longer-term ones that would not be applicable in the short-term context of species' movements (e.g., aquaculture transfers) and were thus briefly mentioned in the Research Document but excluded from assessment of treatment methods. Similarly excluded was the use of some biofouling mitigation techniques—specifically chemical antifoulants, bioactive netting (e.g., copper, zinc, antifouling paints) and very high heat, all meant for treating inorganic materials and structures—detrimental to the survival and growth of the cultured organisms and posing a risk to the environment or human health. Treatments such as freezing and extreme heat, which were effective at causing AIS mortality, but also caused significant mortality of moved species, were not included as they would not be useful for aquaculture or scientific transfers where the commercial/scientific product must be kept alive. Retained studies/trials were classified as "laboratory" in cases where the experiment was conducted in a laboratory setting where all conditions were closely controlled, monitored, and measured or in cases where experiments were conducted outside in tanks or buckets where some parameters were controlled. Studies were classified as "field" when they were conducted on aquaculture farms, where conditions were likely more loosely controlled, monitored, and/or measured.

Data were classified by treatment and target AIS/moved species. Treatment parameters (concentrations, exposure times, temperature, etc.) and associated removal/mortality (%) or survival (%) were reported. Quantitative results on the effectiveness of physical and chemical treatments on AIS were categorized as effective when they resulted in 100% mortality/removal of AIS. Quantitative results on the impact of treatments on moved species were indicated in survival percentages (%), and a treatment with ≥90% survival was considered to have no or minimal impacts on the moved species. Qualitative results were referred to as "Effective" or "Not effective" and "Impacted" or "Not impacted" for the effectiveness on AIS and impacts on moved species, respectively.

The most effective treatment options that were lethal (100% or qualitatively effective) to the greatest number of AIS with no or minimal impacts on the moved species (≥90% survival or qualitatively not impacted) were identified, along with measures of associated uncertainty. Levels of uncertainty (very high, high, moderate, and low) were assigned to each treatment option for each AIS species (or taxonomic group) and moved shellfish species. Uncertainty levels were assigned based on the number of studies available, their quality, and agreement among studies with the identified treatment options. When a taxonomic group included multiple species (e.g., polychaetes), the level of uncertainty increased (as results were not species-specific). Uncertainty scores were not calculated for ineffective treatments (see Massé-Beaulne et al. 2025 for details).

*Table 1. Marine Aquatic Invasive Species (AIS) and epibionts that were assessed in the present work.*

| Representative group | AIS and epibionts species |
|---|---|
| Colonial tunicates | Golden star tunicate (*Botryllus schlosseri*), violet tunicate (*Botrylloides violaceus*), carpet sea squirt (*Didemnum vexillum*), and compound sea squirt (*Diplosoma listerianum*) |
| Solitary tunicates | Clubbed tunicate (*Styela clava*), vase tunicate (*Ciona intestinalis*), European sea squirt (*Ascidiella aspersa*), and sea grape (*Molgula manhattensis*) |
| Bivalves | Blue mussel (*Mytilus edulis*), Mediterranean mussel (*Mytilus galloprovincialis*), Eastern oyster (*Crassostrea virginica*), and Pacific oyster (*Crassostrea gigas*) |
| Gastropods | Slipper snails (*Crepidula fornicata*, *Crepidula adunca*) and oyster drills (*Urosalpinx cinerea*, *Eupleura caudata*) |
| Crustaceans | European green crab (*Carcinus maenas*), Asian shore crab (*Hemigrapsus sanguineus*), Japanese skeleton shrimp (*Caprella mutica*), and common rock barnacle (*Semibalanus balanoides*) |
| Sea stars | Common sea star (*Asterias rubens*) and mottled star (*Evasterias troschelii*) |
| Macroalgae | Oyster thief (*Codium fragile), Undaria* sp., *Cladophora* sp., *Ulva* sp., Rhodophyta, *Fucus* spp., *Gracilaria* sp., and *Caulerpa* sp. |

| Representative group | AIS and epibionts species |
|---|---|
| Polychaetes | Tube worms [*Hydroides elegans, Spirobranchus paumotanus* (=*Pomatoceros taeniata*), *Sabella spallanzanii*], mud worms (*Polydora ciliata*, *Polydora hoplura*, *Polydora websteri*, *Boccardia polybranchia*), and Terebellidae worms |
| Bryozoans | Kelp-encrusting bryozoan (*Membranipora* sp.), brown bryozoan (common bugula) (*Bugula neritina*), red crust bryozoan (*Cryptosula pallasiana*), and *Schizoporella* spp. |
| Sponges | Boring sponge (*Cliona celata*) and calcareous sponge (*Leucosolenia* sp.) |
| Hydrozoans | Pink-mouth hydroid (*Ectopleura crocea*) |

*Table 2. Shellfish and macroalgal species cultivated in Canada (Atlantic and Pacific coasts) that were assessed in the present work. Mussels (small < 50 mm; large ≥ 50 mm), oysters and scallops (small < 70 mm; large ≥ 70 mm).*

| Region | Group | Moved and cultured species |
|---|---|---|
| Atlantic, Pacific | Mussels | Blue mussel (*Mytilus edulis*) |
| | Macroalgae | Sugar kelp (*Saccharina latissima*) |
| Atlantic | Oysters | Eastern oyster (*Crassostrea virginica*) and European flat oyster (*Ostrea edulis*) |
| | Scallops | Bay scallop (*Argopecten irradians*), giant scallop (*Placopecten magellanicus*), and Iceland scallop (*Chlamys islandica*) |
| | Macroalgae | Atlantic kelp (*Saccharina longicruris*) |
| Pacific | Mussels | Mediterranean mussel (*Mytilus galloprovincialis*) |
| | Oysters | Pacific oyster (*Crassostrea gigas*) |
| | Scallops | Japanese weathervane scallop (*Mizuhopecten yessoensis*) |
| | Clams | Manila clam (*Ruditapes philippinarum* formerly *Venerupis philippinarum*), varnish clam (*Nuttallia obscurata*), and Pacific geoduck (*Panopea generosa*) |
| | Macroalgae | Bull kelp (*Nereocystis luetkeana*), giant kelp (*Macrocystis pyrifera*), Pacific dulse (*Develarea mollis*), sieve kelp (*Neoagarum fimbriatum*), and winged kelp (*Alaria marginata*) |

# ASSESSMENT

## Effectiveness and impacts of treatments

The introduction and spread of AIS via shellfish/macroalgal movements can be reduced by using control treatments. More than 200 references were considered during this literature review, of which 115 scientific publications and grey literature reports were further reviewed to assess the effectiveness of various physical and chemical treatments for the removal and/or mortality of marine AIS/epibionts, and for their impacts on a selection of moved shellfish and macroalgal species. The four types of physical treatments (pressure washing, air drying, freshwater, heat) described in the literature pertaining to mitigation measures for the management of marine AIS resulted in a total of 64 literature sources (47 primary publications, 17 technical reports). A total of 32 literature sources (25 primary publications, 7 technical reports) were included pertaining to the survival of moved shellfish species exposed to those treatments. The review also identified a variety of chemical treatments (chlorinated-based compounds, acetic acid, citric acid, brine, lime, Virkon®) from 51 literature sources (32 primary publications, 19 technical reports) for the control of marine AIS. A total of 31 literature sources (22 primary publications, 9 technical reports) were included pertaining to the survival of moved shellfish species exposed to chemical treatments. Finally, a few unpublished results were considered for both physical and chemical treatments.

Species-specific treatments from the literature review are presented in Massé-Beaulne et al. (2025; see Tables 5−10 for detailed information). Treatment options that met the criteria of being “Effective” at killing a range of AIS (100% mortality) while not impacting the moved species (90–100% survival) were identified to help inform future management decisions (Tables 3 and 4 for physical and chemical treatments, respectively). Associated levels of uncertainty are presented for each AIS or functional group both for mortality of AIS and survival of moved species.

Although multiple treatments (e.g., pressurized water, air drying, freshwater, heated seawater, acetic acid, brine) were identified as effective at killing AIS or epibiont species, while not having impacts on moved species, no single treatment was found applicable to all AIS while maintaining shellfish survival (≥90% survival) in the context of species movements (Tables 3 and 4). The treatments were fundamentally species- and environment-specific, with considerable variability in mortality of AIS and survival of moved species. Context dependency of these treatments was a function of treatment type, duration/intensity/method of application, location, time of year, and species. Furthermore, very little information was found on impacts of treatments on survival of moved macroalgae and no effective treatment for killing AIS associated with cultured macroalgae in Canada was identified.

*Table 3. Summary of physical treatments for marine aquatic invasive species and moved species. Effective treatments on selected AIS or epibionts (100% Mortality/removal or Effective) and survival of moved shellfish (≥90% Survival or Not impacted) are based on a review of the scientific literature of treatments for Argopecten irradians (AI), Ascidiella aspersa (AA), barnacles (BA), Botrylloides violaceus (BV), Botryllus schlosseri (BS), bryozoans (BZ), Caprella mutica (CMU), Carcinus maenas (CM), Ciona intestinalis (CI), Codium fragile (CF), Crassostrea gigas (CG), Crassostrea virginica (CV), Didemnum vexillum (DV), Diplosoma listerianum (DL), gastropods (GA), Hemigrapsus sanguineus (HM), hydrozoans (HZ), macroalgae (MA), Molgula spp. (MO), Mytilus edulis (ME), Mytilus galloprovincialis (MG), Ostrea edulis (OE), Placopecten magellanicus (PM), polychaetes (PL), sea stars (SS), sponges (SP), and Styela clava (SC). Associated levels of uncertainty are provided and are based on the data available, their quality, and agreement among studies with the identified treatment options. Note that uncertainty scores were not calculated for ineffective treatments. (s/l): small/large. (juv.): treatment was on juveniles or young stages. See Massé-Beaulne et al. (2025) for detailed results.*

| Physical treatments | | AIS Mortality | | | | | | Moved species Survival | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | AIS (100% Mortality or Effective) | | | | Not effective | No data | Moved species (≥90% Survival or Not impacted) | | | | Impacted | No data |
| | | Uncertainty | | | | | | Uncertainty | | | | | |
| | | Low | Moderate | High | Very high | | | Low | Moderate | High | Very high | | |
| **Pressurized water** | 700 psi; 10 s | - | - | - | - | BS, BV, CM[5], GA[5], ME(l)[5], ME(s), SS[5] | AA, BA, BZ, CF, CG(s/l), CI[1,5], CMU, CV(s/l), DL, DV[1], HM, HZ, MA[1], MG(s/l), MO, PL, SC, SP | - | ME(s) | ME(l)[5] | - | - | AI(s/l), CG(l)[3], CG(s), CV(s/l), MG(s/l), OE(s/l), PM(s/l) |
| **Air drying** | 24 h | CI | BS, BV[5], SC | AA[5], CF[5], DL[5], DV[5], MA, MG(s), PL | MO[5] | BA, BZ[5], CV(s), GA[5], ME(s) MG(l), SP[5] | CG(l)[1], CG(s), CM[1], CMU, CV(l), HM, HZ, ME(l)[1], SS | - | CV(s), ME(s) | MG(l) | - | MG(s) | AI(s/l), CG(l)[3], CG(s), CV(l), ME(l)[3], OE(s/l), PM(s/l) |
| **Freshwater immersion** | 24 h | CF, CMU, SC | BS, BV, PL | DV, MA | SP[5] | CV(l)[5], CV(s), HM, ME(s) | AA, BA, BZ, CG(s/l)[2], CI[2], CM[2,5], DL, GA, HZ[2], ME(l), MG(l)[2], MG(s), MO, SS | - | ME(s) | CV(l) | CV(s) | - | AI(s/l), CG(s/l)[4], ME(l), MG(l)[4], MG(s), OE(l), OE(s)[4] PM(l), PM(s)[4] |

| Physical treatments | | AIS Mortality | | | | | | Moved species Survival | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | AIS (100% Mortality or Effective) | | | | Not effective | No data | Moved species (≥90% Survival or Not impacted) | | | | Impacted | No data |
| | | Uncertainty | | | | | | Uncertainty | | | | | |
| | | Low | Moderate | High | Very high | | | Low | Moderate | High | Very high | | |
| **Freshwater immersion + Air drying** | 8 h + 1 h | - | - | BS, BV, DL, DV | - | CV(l)[5], ME(s) | AA, BA, BZ, CF, CG(s/l), CI, CM, CMU, CV(s), GA, HM, HZ, MA, ME(l), MG(l)[2], MG(s), MO, PL[1], SC, SP, SS | - | - | CV(l), ME(s) | - | - | AI(s/l), CG(s/l), CV(s), ME(l), MG(s/l)[4], OE(s/l), PM(s/l) |
| **Freshwater spray + Air drying** | 10 min + 1 h | - | - | BS, BV, DL, DV | - | ME(s) | AA, BA, BZ, CF, CG(s/l), CI, CM, CMU, CV(s/l), GA, HM, HZ, MA, ME(l), MG(s/l), MO, PL, SC, SP, SS | - | - | ME(s) | - | - | AI(s/l), CG(s/l), CV(s/l), ME(l), MG(s/l), OE(s/l), PM(s/l) |
| **Heated seawater immersion** | 50°C; 60 s | CI | MA, ME(s/l), MG (s/l), SC | CM(juv.), HZ | CF, SS[5] | CG(s), CV(s/l), PL | AA, BA[1], BS, BV[1], BZ[1], CM(adult)[1,5], CMU[1], CG(l)[2], DL, DV[1], GA, HM, MO, SP | CG(s) | ME(l)[5] | - | - | ME(s), MG(s/l), OE(s) | AI(s/l), CG(l)[4], CV(l)[4,5], CV(s)[4], OE(l), PM(s/l) |
| | 60°C; 10 s | - | CI, MA, ME(s/l), MG(s) | CM(juv.), HZ | CF, SS[5] | CG(s), CV(s/l), MG(l), PL, SC | AA, BA[1], BS, BV[1], BZ[1], CG (l)[2], CM(adult)[1,5], CMU[1], DL, DV[1], GA, HM, MO, SP | CG(s) | CV(s; 55–65 mm) | - | CV(l)[5] | CV(s; 35–45 mm), ME(s/l), MG(s/l) OE(s) | AI(s/l), CG(l)[4], OE(l), PM(s/l) |

| Physical treatments | | AIS Mortality | | | | | | Moved species Survival | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | AIS (100% Mortality or Effective) | | | | Not effective | No data | Moved species (≥90% Survival or Not impacted) | | | | Impacted | No data |
| | | Uncertainty | | | | | | Uncertainty | | | | | |
| | | Low | Moderate | High | Very high | | | Low | Moderate | High | Very high | | |
| | 60°C; 30 s | SC | CI, MA, ME(s/l), MG(s) | CM(juv.), HZ | BA, CF, SS[5] | CG(s), CV(s/l), MG(l), PL | AA, BS, BV[1], BZ[1], CG(l)[2], CM(adult)[1,5], CMU[1], DL, DV[1], GA, HM, MO, SP | CG(s) | - | - | CV(l)[5] | CV(s), ME(s/l), MG(s/l), OE(s) | AI(s/l), CG(l)[4], OE(l), PM(s/l) |
| **Steam** | 100°C; 50 psi | - | - | - | MA, SC | - | AA, BS, BV, CI, DL, DV, HM, MO | - | - | - | - | - | - |

[1]No data with these parameters; 100% mortality with other parameters (see detailed Table 5 in Massé-Beaulne et al. 2025)
[2]No data with this parameter; not effective with other parameters (see detailed Table 5 in Massé-Beaulne et al. 2025)
[3]No data with these parameters; impacted with other parameters (see detailed Table 8 in Massé-Beaulne et al. 2025)
[4]No data with these parameters; ≥90% survival with other parameters (see detailed Table 8 in Massé-Beaulne et al. 2025)
[5]Based on qualitative results only

*Table 4. Summary of chemical treatments for marine aquatic invasive species and moved species. Effective treatments on selected AIS or epibionts (100% Mortality/removal or Effective) and survival of moved shellfish (≥90% Survival or Not impacted) are based on a review of the scientific literature of treatments for Argopecten irradians (AI), Ascidiella aspersa (AA), barnacles (BA), Botrylloides violaceus (BV), Botryllus schlosseri (BS), bryozoans (BZ), Caprella mutica (CMU), Carcinus maenas (CM), Ciona intestinalis (CI), Codium fragile (CF), Crassostrea gigas (CG), Crassostrea virginica (CV), Didemnum vexillum (DV), Diplosoma listerianum (DL), gastropods (GA), Hemigrapsus sanguineus (HM), hydrozoans (HZ), macroalgae (MA), Molgula spp. (MO), Mytilus edulis (ME), Mytilus galloprovincialis (MG), Ostrea edulis (OE), Placopecten magellanicus (PM), polychaetes (PL), sea stars (SS), sponges (SP), and Styela clava (SC). Associated levels of uncertainty are provided and are based on the data available, their quality, and agreement among studies with the identified treatment options. Note that uncertainty scores were not calculated for ineffective treatments. [ ]: concentration of the chemical. (s/l): small/large. (juv.): treatment was on juveniles or young stages. See Massé-Beaulne et al. (2025) for detailed results.*

| Chemical treatments | | AIS Mortality | | | | | | Moved Species Survival | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | AIS (100% Mortality or Effective) | | | | Not effective | No data | Moved Species (≥90% Survival or Not impacted) | | | | Impacted | No data |
| | | Uncertainty | | | | | | Uncertainty | | | | | |
| | | Low | Moderate | High | Very high | | | Low | Moderate | High | Very high | | |
| **Sodium hypochlorite immersion** | [0.5%]; 20 s | - | - | DV | BV | CM[5], MG(s), PL[5] | AA, BA, BS, BZ, CF, CG(l)[2], CG(s), CI[2], CMU, CV(s/l), DL, GA, HM, HZ, MA[1], ME(l), ME(s)[1], MG(l)[2], MO, SC[1], SS, SP | - | - | MG(s) | - | - | AI(s/l), CG(l)[4], CG(s), CV(s/l), ME(l), ME(s)[3], MG(l)[4], OE(s/l), PM(s/l) |
| | [0.01%]; 12 h | - | - | - | SC | CG(l) | AA, BA, BS, BV[1], BZ, CF, CG(s), CI[2], CM[2,5], CMU, CV(s/l), DL, DV[1], GA, HM, HZ, MA[1], ME(l), ME(s)[1], MG(l)[2], MG(s)[1], MO, PL[2,5], SP, SS | - | - | MG(s) | CG(l)[5] | - | AI(s/l), CG(s), CV(s/l), ME(l), ME(s)[3], MG(l)[4], OE(s/l), PM(s/l) |
| **Acetic acid [4−5%] immersion** | 30 s | - | BZ, CI, DV[5], HZ, ME(s) | BV, SS | - | BA[5], CG(s/l), CV(l), CV(s)[5], GA[5], MG(s/l), PL[5] | AA, BS[1,5], CF, DL, CM, CMU, HM, MA[1], ME(l)[2], MO, SC[1], SP[1,5] | CG(s), MG(s/l) | OE(s) | - | - | CG(l), CV(l), ME(s/l) | AI(s/l), CV(s), OE(l), PM(s/l) |
| | 1 min | BV, BZ, CI | DV[5], HZ, ME(s), SC | BS[5], MA, PL[5], SS | - | BA[5], CG(s/l), CV(s)[5], GA[5], MG(s/l) | AA, CF, CM, CMU, CV(l)[2], DL, HM, ME(l)[2], MO, SP[1,5] | MG(s/l) | CG(s), OE(s) | - | - | CG(l), CV(l), ME(s/l) | AI(s/l), CV(s), OE(l), PM(s/l) |

| Chemical treatments | | AIS Mortality | | | | | | Moved Species Survival | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | AIS (100% Mortality or Effective) | | | | Not effective | No data | Moved Species (≥90% Survival or Not impacted) | | | | Impacted | No data |
| | | Uncertainty | | | | | | Uncertainty | | | | | |
| | | Low | Moderate | High | Very high | | | Low | Moderate | High | Very high | | |
| | 5 min | BV, BZ, CI, ME(s) | DV[5], HZ, MA, SC | BS[5], CG(l), PL[5], SS | - | CV(s[5]), GA[5], MG(s/l) | AA, BA[2], CF, CG(s)[2], CM, CMU, CV(l)[2], DL, HM, ME(l)[2], MO, SP[1,5] | - | - | - | - | CG(l), CV(l), ME(s/l) | AI(s/l), CG(s)[4], CV(s), MG(s/l)[4], OE(l), OE(s)[4], PM(s/l) |
| **Acetic acid [4−5%] immersion + Air drying** | 5 min + 1 h | - | - | AA, BS, BV, CI, DL, DV, ME(s) | - | - | BA, BZ[1,5], CF, CG(s/l), CM, CMU, CV(s/l), GA, HM, HZ, MA[1], ME(l), MG(s/l)[2], MO, PL[1,5], SC, SP, SS | - | - | - | - | ME(s) | AI(s/l), CG(s/l), CV(s/l), ME(l), MG(s/l)[3], OE(s/l), PM(s/l) |
| | 4 min + 24 h | - | - | BS[5], BV[5], CI[5], MA, PL[5] | BZ[5] | MG(s/l) | AA[1], BA, CF, CG(s/l), CM, CMU, CV(s/l), DL[1], DV[1], GA, HM, HZ, MO, ME(l), ME(s)[1], SC, SP, SS | - | - | - | - | ME(s)[5], MG(s/l) | AI(s/l), CG(s/l), CV(s/l), ME(l), OE(s/l), PM(s/l) |
| **Citric acid [5%] immersion** | 10 s | - | - | HZ | - | CI, MA, MG(s/l), SC | AA, BA, BS, BV, BZ, CF, CG(s/l), CM, CMU, CV(s/l), DL, DV, GA, HM, ME(s/l), MO, PL, SP, SS | - | - | MG(s/l), OE(s) | - | - | AI(s/l), CG(s/l), CV(s/l), ME(s/l), OE(l), PM(s/l) |
| **Saturated brine [300ppt] immersion** | 15 min | - | CF, MA[5], MO[5], SP[5], SS[5] | - | - | BA[5], CG(s), CV(s/l), ME(s), MG(l), PL | AA, BS, BV[2,5], BZ, CG(l)[2], CI[2], CM, CMU, DL, DV[1], GA[2,5], HM, HZ, ME(l), MG(s), SC[2] | ME(s) | CV(s) | CG(s), CV(l), OE(s) | MG(l) | PM(s) | AI(s/l), CG(l)[4], ME(l), MG(s), OE(l), PM(l) |

| Chemical treatments | | AIS Mortality | | | | | | Moved Species Survival | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | AIS (100% Mortality or Effective) | | | | Not effective | No data | Moved Species (≥90% Survival or Not impacted) | | | | Impacted | No data |
| | | Uncertainty | | | | | | Uncertainty | | | | | |
| | | Low | Moderate | High | Very high | | | Low | Moderate | High | Very high | | |
| **Saturated brine [300 ppt] immersion + Air drying** | 15 min + 2 h | AA, BS, CI[5], DL, DV, MO, SC | BV, CF, SP | PL[5] | GA | CG(l), CM[5], ME(s) | BA, BZ, CG(s), CMU, CV(s/l)[2], HM, HZ, MA, MG(s/l), SS[1], ME(l)[2,5] | - | - | - | - | - | AI(s/l), CG(l)[3], CG(s), CV(s/l)[4], ME(s)[4], ME(l), MG(s/l), OE(s/l), PM(s/l) |
| | 30 s + 1 h | BS | BV, CI[5], DL, DV | - | - | CG(l), CM[5], CV(s/l), ME(l)[5], ME(s) | BA, BZ, CF[1], CG(s), CMU, GA[1], HM, HZ, MA, MG(s/l), MO[1], PL[1,5], SC[1], SP[1], SS[1] | - | ME(s) | CV(l) | CV(s) | - | AI(s/l), CG(l)[3], CG(s), ME(l), MG(s/l), OE(s/l), PM(s/l) |
| **Hydrated lime [4%] immersion** | 5 min | MO[5] | CF | BV[5], SC[5] | BS[5], BZ[5], HZ[5], SS[5] | BA[5], CG(l), CI, CM, CV(s/l), DV, GA[5], ME(s/l), SP | AA, CG(s), CMU, DL, HM, MA, MG(s/l), PL | CV(s/l) | ME(l) | AI(l), CG(l) | - | PM(s) | AI(s), CG(s), ME(s)[4], MG(s/l), OE(s/l), PM(l) |
| **Saturated brine [300 ppt] X hydrated lime [4%] + Air drying** | 1 min + 1 h | - | - | BS[5], BV[5] | CI[5] | - | AA, BA, BZ, CF, CG(s/l), CM, CMU, CV(s/l)[2,5], DL, DV, GA, HM, HZ, MA, ME(s/l), MG(s/l), MO, PL, SC, SP, SS | - | - | - | - | - | AI(s/l), CG(s/l), CV(s/l)[4,5], ME(s/l), MG(s/l), OE(s/l), PM (s/l) |

| Chemical treatments | | AIS Mortality | | | | | | Moved Species Survival | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | AIS (100% Mortality or Effective) | | | | Not effective | No data | Moved Species (≥90% Survival or Not impacted) | | | | Impacted | No data |
| | | Uncertainty | | | | | | Uncertainty | | | | | |
| | | Low | Moderate | High | Very high | | | Low | Moderate | High | Very high | | |
| **Virkon® [3%]** | 30 s | - | - | CI(juv.) | - | ME(l) | AA, BA, BS, BV, BZ, CF, CG(s/l), CI(adult)[2], CM, CMU, CV(s/l), DL, DV, GA, HM, HZ, MA, MO, ME(s), MG(s/l), PL, SC, SP, SS | - | - | ME(l) | - | - | AI(s/l), CG(s/l), CV(s/l), ME(s), MG(s/l), OE(s/l), PM(s/l) |

[1]No data with these parameters; 100% mortality with other parameters (see detailed Tables 6 and 7 in Massé-Beaulne et al. 2025)
[2]No data with this parameter; Not effective with other parameters (see detailed Tables 6 and 7 in Massé-Beaulne et al. 2025)
[3]No data with these parameters; impacted with other parameters (see detailed Tables 9 and 10 in Massé-Beaulne et al. 2025)
[4]No data with these parameters; ≥90% survival with other parameters (see detailed Tables 9 and 10 in Massé-Beaulne et al. 2025)
[5]Based on qualitative results only

### Sources of Uncertainty

It was difficult to make generalized conclusions as there was often high variability in the results across studies, often leading to conflicting or counter-intuitive conclusions, which was likely due to differences in experimental design, methods/logistics, time of the year, and physical variables (e.g., air humidity) among the studies.

This review highlighted the many gaps in information with respect to specific AIS, moved species, and treatments. Very little data were available for most juvenile stages of AIS and macroalgae in general. Similarly, there were gaps in both the short-term and long-term impacts of treatments on moved species, especially for early life-history stages and macroalgae. There was a lack of studies conducted at commercial scales. Very few studies have examined the effect of seasonality on treatment effectiveness or impacts. Further, additional taxonomic groups (either AIS or moved species) may be considered in the future which may require different treatment techniques.

The results on mortality and survival extracted from the literature were either quantitative or qualitative. Thus, differences in resolution contributed to uncertainty when drawing conclusions. For example, qualitative results on mortality (effective/not effective) or survival (impacted/not impacted) may or may not be comparable to quantitative studies with controls that characterized treatment effectiveness for killing AIS (100% mortality) or keeping moved species alive (≥90% survival). Thus, caution should be exercised when considering qualitative results alone.

The majority of published studies reviewed had different experimental designs, scales, conditions, and methods of measuring mortality of AIS and survival of moved species, which contributed to the level of uncertainty and limited comparisons of effectiveness among studies. Further, there are a multitude of environmental factors that can influence the effectiveness of specific treatments including, but not limited to, temperature, salinity, pH, and relative humidity, which may not have been examined in the studies. Furthermore, many studies were conducted under laboratory conditions with the results not necessarily translating into equally effective options in real-world applications.

Most publications included in this literature review assessed post-treatment mortality of AIS or survival of organisms over relatively short time scales (e.g., immediate or minutes, hours or days, weeks or months). Thus, the long-term impacts (chronic effects) on moved shellfish and macroalgal species are largely unknown.

Although several treatment options were identified through this review, there was surprisingly little information on how combinations of treatments may be more effective at killing AIS while ensuring survival of moved species. More research is needed on how various physical and chemical treatments could be used in combination to be more effective and on the specific relative contributions of each treatment.

## CONCLUSIONS AND ADVICE

The literature review documented the effectiveness of existing physical and chemical treatments to kill/remove specific AIS (invertebrate and macroalgal species; Table 1) and the impacts of those treatments on moved shellfish and macroalgal species (Table 2). Although multiple treatments (e.g., pressurized water, air drying, freshwater, heated seawater, acetic acid, brine) were identified as effective at killing certain AIS, while not having impacts on moved species, those treatments were fundamentally species- and environment-specific, with considerable variability in mortality of AIS and survival of moved species. Context dependency of these treatments was a function of treatment type, duration/intensity/method of application, location, time of year, environmental parameters, and species. Hence, there is limited ability to draw broad conclusions related to the treatment of AIS in Canada's three oceans and their impacts on species of interest that are being moved. However, it was possible to identify some treatments that had high AIS mortality (100%) with limited impacts on moved species (≥90% survival) that can inform future management decisions (see Tables 3 and 4). Further, in order to help managers identify treatment options for their specific question, a schematic has been developed that shows them how to obtain the best options, depending on two scenarios: mitigating a range of AIS or targeting a specific AIS (Table 5). This decision tool is not prescriptive, but rather highlights treatment options for AIS that also include potential impacts on moved species. As stated in Table 5, given the strong species- and treatment-specific variability, reference to Massé-Beaulne et al. (2025) for species-specific treatments is recommended, as requirements (exposure times, temperatures, etc.) may be different than those presented in Tables 3 and 4 for a given species.

In summary, this literature review identified several treatment options applicable to certain AIS (while keeping moved species alive), key uncertainties and remaining knowledge gaps, as well as future research needs. These include the following:

- No single treatment was found applicable to all AIS while maintaining shellfish survival in the context of species movements.
- A few physical and chemical treatment options applicable to multiple AIS, while keeping moved shellfish species alive, were identified (see Tables 3 and 4).
- The most appropriate treatment type (from the most applicable treatment options summarized in Tables 3 and 4) is conditional on which AIS, or range of AIS, need to be treated and what species are to be moved (see Table 5 for a conceptualization of the process to derive treatment advice, depending on AIS and species being moved).
- Key uncertainties arise from high variability in results due to differences among taxa; differences between field and laboratory studies; differences among experimental designs, scales, and methods of measuring AIS mortality; and the use of quantitative versus qualitative data to assess effectiveness/impacts.
- This literature review identified a significant number of gaps with respect to the effectiveness of physical and chemical treatments for specific AIS and their impacts on moved species (shellfish and macroalgae). These include a lack of: studies on longer-term or sub-lethal impacts on moved species, data on moved macroalgae, studies at commercial scales, and research on temporal variation in effectiveness/impacts of treatments. There is a particular dearth of information on combined treatment options.

*Table 5. Conceptualization of a process to be used by managers for selection of most appropriate treatment type(s) to maximize both mortality of the Aquatic Invasive Species (AIS) and survival of the moved shellfish species in the context of movements of marine organisms (e.g., aquaculture transfers, scientific transfers).*

| Step 1<br>Are you aiming to mitigate an AIS assemblage (or unknown AIS threat) or targeting just one AIS? | |
|---|---|
| Scenario A<br>AIS assemblage/unknown AIS | Scenario B<br>Species-specific<br>(targeting just one AIS) |
| Step 2A<br>Identify possible effective physical and chemical treatment options in Tables 3 and 4 that would include all AIS groups of concern (e.g., colonial tunicates, bryozoans, *Codium fragile*), which also ensure a high survival of the moved species (e.g., small *Mytilus edulis*—see “ME(s)” in Tables 3 and 4).<br><br>Step 3A<br>From treatment options identified in Step 2A, evaluate feasibility/applicability of treatments, since they are context dependent, and determine optimal treatment(s) in your given situation.<br><br>Step 4A<br>Recommend/implement optimal treatment(s) for your given situation. | Step 2B<br>Identify possible effective physical and chemical treatment options in Tables 3 and 4 for your AIS of interest (e.g., *Ciona intestinalis*, which is included in solitary tunicates—see “CI” in Tables 3 and 4), which also ensure a high survival of the moved species (e.g., small *Mytilus edulis*—see “ME(s)” in Tables 3 and 4).<br><br>Step 3B<br>From treatment options identified in Step 2B, find optimal treatment(s) specific for the targeted AIS species (e.g., *C. intestinalis*) (see Tables 5–7; Massé-Beaulne et al. 2025), which ensure treatment effectiveness for that specific AIS and high survival of the moved species (e.g., small *Mytilus edulis*) (see Tables 8–10; Massé-Beaulne et al. 2025).<br><br>Step 4B<br>From treatment options identified in Step 3B, evaluate feasibility/applicability of treatments, since they are context dependent, and determine optimal treatment(s) in your given situation.<br><br>Step 5B<br>Recommend/implement optimal treatment(s) for your given situation. |

# FEASIBILITY AND OTHER CONSIDERATIONS

Although a large number of effective treatment options was identified from the literature for the control of marine AIS, while assuring survival of moved species, there are a number of considerations that may limit their usefulness in real-world settings including, but not limited to: the ease of application and practicality under field conditions, associated health and safety hazards, cost, and disposal. For example, sufficient freshwater may not be easily accessible in some locations, and/or it may not be possible to heat or chill immersion treatments at some sites, and/or it could be too costly or time-consuming for some small operations. Although beyond the scope of this CSAS process, specific treatments will have additional logistical considerations.

Furthermore, some of the treatments that were identified as ineffective (or may be effective, but have high levels of uncertainty) may be effective under different concentrations, pressures, temperatures, and/or exposure times. Future research could refine these treatment methods and discern the point at which they become effective.

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