Research Prospects on the Ecological Characteristics of Fouling Ascidians (Postprint)

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Abstract

Sea squirts exhibit rapid growth and reproduction, producing large quantities of larvae that attach within short timeframes. They constitute important members of marine fouling communities and pose serious threats to offshore artificial structures. Fouling sea squirts are primarily composed of 103 species from 29 genera across 9 families, including Ascidia sydneiensis, Botryllus schlosseri, Diplosoma listerianum, Styela clava, and Herdmania momus. Among these, 64 species are found in the Pacific Ocean, 23 in the Indian Ocean, 44 in the Atlantic Ocean, and only 3 in the Arctic Ocean. Furthermore, their attachment and fouling patterns exhibit distinct regional and seasonal characteristics, and are depth-dependent. Future research should enhance ecological surveys and taxonomic studies of fouling sea squirts, elucidate attachment and fouling characteristics in deep-sea and polar regions, reveal the molecular regulatory mechanisms of larval attachment and metamorphosis, and improve larval collection and cultivation techniques, with the aim of better understanding the biological and ecological characteristics of sea squirts, enriching and advancing marine ecology, establishing foundations for the prevention and control of marine fouling organisms, and promoting the development of marine economic industries.

Full Text

Preamble

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An Overview of Fouling Ascidians

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Abstract: Ascidians, characterized by rapid growth and early sexual maturation, are important benthic organisms in marine ecosystems and represent one of the major groups of fouling organisms. Following colonization on aquaculture facilities, ascidians cause a series of problems including competition for food and settlement substrate with cultivated species, blockage of netting meshes, increased cage weight, and reduced water flow, leading to deterioration of the aquaculture environment. Consequently, the growth and quality of cultivated species are negatively affected. To date, a total of 103 ascidian species within 29 genera and 9 families (Ascidiidae, Cionidae, Clavelinidae, Didemnidae, Molgulidae, Perophoridae, Polyclinidae, Pyuridae, and Styelidae) have been identified from fouling communities worldwide. Dominant species include the solitary ascidians *Ascidia sydneiensis*, *Symplegma brakenhielmi*, *Diplosoma listerianum*, *Botryllus schlosseri*, *Phallusia nigra*, *Styela clava*, *Herdmania momus*, *Microcosmus exasperatus*, *Molgula manhattensis*, and the compound species *Ciona intestinalis*. The distribution of fouling ascidians shows distinct geographic patterns: 64 species occur in the Pacific Ocean, 23 in the Indian Ocean, 44 in the Atlantic Ocean, and 3 in the Arctic Ocean. In the Pacific, common species include *Molgula manhattensis* and *Ascidia longistriata*; *Styela plicata*, *S. canopus*, *Diplosoma listerianum*, *Symplegma brakenhielmi*, *Microcosmus exasperatus*, *A. sydneiensis*, *Phallusia nigra*, *Botryllus schlosseri*, and *Styela rustica* are found in the Indian and Atlantic Oceans, whereas *Styela rustica* is the dominant fouling species in the Arctic Ocean. Season is a major factor affecting ascidian fouling. Summer represents the peak settlement period in the Pacific Ocean, while in the Indian Ocean the highest ascidian fouling biomass occurs in spring and autumn. Additionally, larval settlement of different ascidians shows distinct substrate preferences. *Phallusia nigra* and *Ascidia canalata* are generally abundant on floating units, whereas *Herdmania momus* prefers to settle on horizontal surfaces of submerged objects. Current fouling control methods have various limitations in practical applications. Understanding gene regulation during ascidian larval metamorphosis may provide an effective approach for developing novel antifouling technologies. Moreover, studying fouling communities colonizing various artificial facilities can elucidate the impacts of alien ascidians on local biodiversity. Compared with traditional morphological identification, DNA-based methodology may resolve taxonomic problems related to ascidians. Biofouling can alter substrate surface microenvironments and affect material corrosion processes. Thus, the effects of fouling ascidians, particularly compound species, on material corrosion deserve further study. At present, most investigations on fouling ascidians are limited to tropical and temperate zones, particularly in shallow waters. To thoroughly elucidate species composition, biodiversity, distribution, population dynamics, and the role of ascidians in fouling communities, future studies should be extended to polar regions and deep waters.

Keywords: fouling ascidians; species composition; distribution; settlement

Introduction

Ascidians represent the dominant group in the subphylum Urochordata, phylum Chordata. Their planktonic larval stage does not feed, while adults are sessile filter-feeders [1]. As important components of marine fouling communities, these organisms grow rapidly and produce large numbers of larvae that attach within short time periods [2], enabling them to quickly colonize artificial substrates [3]. They possess strong environmental adaptability and spatial competitiveness, even altering the diversity and structural characteristics of native benthic communities [4,5]. In marine environments, ascidians are not only crucial members of benthic ecosystems [6,7] but also key targets of concern in marine fouling communities. For aquaculture industries, besides competing for food [8] and habitat space with economically important shellfish such as mussels, pearl oysters, and oysters, they prey on larvae and displace juvenile shellfish, interfere with shell opening and byssus secretion, and can become vectors for harmful algal dispersal [13]. Ascidian attachment inevitably blocks mesh openings in culture cages, reducing water exchange between internal and external environments, decreasing dissolved oxygen levels, polluting local water environments [14], and even damaging culture equipment. As environmental conditions vary widely across marine regions worldwide, the species composition and abundance of fouling ascidians change accordingly. Research on fouling ascidians is therefore both theoretically significant and practically important for enriching marine biological knowledge and providing a foundation for effective prevention and control of marine fouling organisms.

This paper synthesizes previous literature to comprehensively analyze the ecological characteristics of fouling ascidians in major oceans worldwide from perspectives of species composition, distribution patterns, and attachment features. The aim is to better understand ascidian biological and ecological traits, enrich and advance marine ecological research, provide data for marine fouling organism prevention and control, and promote the development of marine economic industries.

1. Species Composition and Distribution

Analysis of existing literature reveals that fouling ascidians are diverse, with numerous species appearing on artificial facilities across global marine regions. The Pacific Ocean hosts 64 species, the Indian Ocean 23 species, the Atlantic Ocean 44 species, and the Arctic Ocean only 3 species. Dominant species include *Ascidia sydneiensis* (Sydney sea squirt), *Styela clava*, *Botryllus schlosseri* (Star ascidian), *Diplosoma listerianum* (Mole ascidian), and *Herdmania momus*, primarily distributed in tropical and temperate waters. Table 1 lists the main fouling ascidian species found in major oceans.

1.1 Pacific Ocean

Along the North American coast, in southwestern British Columbia waters, the dominant fouling ascidian is *Styela clava*, followed by *Botryllus schlosseri* and *Botrylloides violaceus*. In southern California waters, the dominant species is *Ciona intestinalis*, with *Styela plicata* and *Ciona savignyi* as common species [16]. At the Panama Canal entrance in Central America, the dominant fouling ascidians are *Symplegma brakenhielmi* and *Styela rubra*, with *Polyclinum constellatum* and *Botrylloides nigrum* also present [17]. In southeastern South American waters, *Pyura chilensis* is dominant [18,19], followed by *Ascidia sydneiensis*. In the southwestern Pacific, New Zealand waters have *Ciona intestinalis* as the dominant fouling ascidian, followed by *Styela clava* and *Didemnum vexillum*, with *Diplosoma listerianum*, *Botrylloides leachii*, *Symplegma brakenhielmi*, and *Cnemidocarpa bicornuta* also occurring [50-52].

In the western Pacific, Japanese waters are dominated by *Botrylloides violaceus* and *Diplosoma listerianum*, followed by *Ciona intestinalis* and *Styela clava*. *Perophora japonica* and *Corella japonica* are rare fouling species found only in Shimizu-cho waters off eastern Japan [20,21]. In Hiroshima waters, *Ciona intestinalis* is the dominant fouling species [20]. In the Yellow Sea and Bohai Sea, fouling ascidians are mainly *Ciona intestinalis*, *Molgula manhattensis*, and *Styela clava*, followed by *Diplosoma listerianum*, *Botryllus schlosseri*, and *Botryllus tsingtaoensis*. *Botrylloides violaceus*, *Styela canopus*, and *Ascidia longistriata* are common species in fouling communities [22-26]. In the East China Sea, dominant fouling ascidians include *Styela clava* and *Molgula manhattensis*, followed by *Ascidia sydneiensis*, *Botrylloides violaceus*, with common species being *Diplosoma listerianum*, *Microcosmus australis*, *Trididemnum areolatum*, *Polyclinum constellatum*, and *Microcosmus exasperatus*. Additionally, *Pyura lignosa* appears [27-33]. In the South China Sea, *Styela clava* and *Symplegma oceania* are absolutely dominant, followed by *Ciona intestinalis* and *Herdmania pallida*, with common species including *Ciona intestinalis*, *Molgula manhattensis*, *Botryllus schlosseri*, *Phallusia arabica*, and rare species such as *Microcosmus exasperatus*, *Ascidia sydneiensis*, and *Styela rectangularis* [34-49].

1.2 Indian Ocean

In the Arabian Sea' s eastern coast, at Mumbai Port in the northeast, the dominant fouling ascidian is *Symplegma reptans*, with *Botrylloides chevalense* as a common species. In the southeastern Kollam pearl oyster farming area, ascidians account for 26.6% of total fouling organisms, with *Symplegma reptans* (green-gilled compound ascidian) being dominant [53]. In the Red Sea' s northern Gulf of Aqaba at Eilat, fouling ascidians are dominated by *Didemnum granulatum*, with common species including *Halocynthia spinosa*, *Phallusia nigra*, *Ascidia canalata*, *Didemnum candidum*, and *Botryllus eilatensis* [55,56].

1.3 Atlantic Ocean

In the North Sea off northwestern Europe, fouling ascidians on nearshore artificial facilities are dominated by *Ascidiella aspersa*, *Botryllus schlosseri*, and *Botrylloides violaceus* [57-59]. Along the northeastern North American coast, shellfish aquaculture facilities are primarily fouled by *Corella parallelogramma*, while offshore facilities are fouled by *Molgula citrina*, *Ciona intestinalis*, *Botryllus schlosseri*, and *Styela clava* [61,62]. In the Caribbean Sea at the Panama Canal entrance, dominant fouling ascidians are *Microcosmus exasperatus* and *Pyura vittata*, followed by *Styela clava* and *Herdmania momus* [17]. In the southeastern Paria Gulf, *Styela clava* is dominant, with *Clavelina oblonga* as a common species. Along South American coasts, fouling ascidians are mainly *Didemnum speciosum* and *D. perlucidum.* From north to south, dominant species sequentially include *Didemnum speciosum*, *Botryllus niger*, *D. perlucidum*, *Molgula citrina*, and *Botryllus schlosseri.* On yacht hulls, dominant fouling ascidians are *Styela clava* and *Pyura vittata* [64-69].

1.4 Arctic Ocean

The White Sea, located at the Arctic Ocean' s southernmost extent, has water temperatures ranging from -0.98 to 14.78°C and highest salinity in certain months. Fouling ascidians on aquaculture facilities in this region are dominated by *Styela rustica* and *Boltenia echinata*, with *Molgula citrina* occasionally appearing [70-72].

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2. Attachment Characteristics

2.1 Geographic and Temporal Patterns

Fouling ascidian distribution shows obvious geographic specificity, with most species preferring warmer waters—tropical regions exhibit significantly higher diversity than temperate and cold waters. In the Pacific' s Yellow Sea and Bohai Sea, *Styela clava* is the dominant fouling ascidian [25,26], while in the East China Sea and South China Sea, *Styela clava* dominates [29,45]. Although *Ascidia sydneiensis* is a dominant species in the South China Sea, its numbers decrease significantly in the East China Sea. *Clavelina oblonga* and *Distaplia bermudensis* are endemic to Atlantic waters [63] and are not found in the higher-latitude Yellow and Bohai Seas [29,45], while *Boltenia echinata* appears only in the Arctic Ocean.

Seasonal variation is another key factor affecting ascidian fouling, with differences among sea regions. In the Pacific, ascidian attachment peaks in summer, with *Styela clava* and *Molgula manhattensis* showing peak attachment in specific months [26]. In the Indian Ocean, spring and autumn represent the attachment peak—for example, in the northern Red Sea' s Eilat area, the dominant ascidian *Phallusia nigra* shows maximum attachment in spring, while *Didemnum* species peak in autumn [56]. In the northeastern Atlantic coastal region, fouling communities at ports, docks, and aquaculture facilities consistently contain ascidians, with peak settlement occurring in certain months [58].

2.2 Substrate and Depth Preferences

Attachment substrate differences can influence fouling ascidian composition. *Corella parallelogramma* and *Molgula* species prefer cement pilings [73], while *Pyura chilensis* mainly attaches to ropes [11]. *Ciona intestinalis* appears to favor metal surfaces with greater attachment area than wooden panels [74], and *Phallusia nigra* and *Ascidia canalata* are generally abundant on floating artificial facility components [56]. *Herdmania momus* prefers horizontal surfaces of fouled objects.

Depth is another critical factor affecting ascidian fouling, with different species showing distinct fouling zones. In Chilean coastal waters, the dominant fouling ascidian *Pyura chilensis* typically fouls depths between 13-30 m [55], while *Molgula* species and *Ciona intestinalis* can become dominant in fouling communities at platform depths of 60 m [60].

2.3 Successional Dynamics

The duration of artificial structure submersion affects ascidian species composition and dominance in fouling communities. Ascidian species and fouling intensity decrease with increasing offshore distance and water openness. However, some species appear to be community pioneers—for instance, dominant *Diplosoma listerianum*, *Molgula* species, and *Ciona intestinalis* can account for 70% of fouling communities in the first year, while *Botryllus schlosseri* and *Botrylloides violaceus* mainly appear on newly deployed artificial objects [59]. *Diplosoma listerianum* is gradually replaced by hydroids over time [68].

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3. Research Prospects

3.1 Invasion Vectors and Ecological Impacts

Ocean shipping and aquaculture often serve as vectors introducing fouling ascidians to new habitats. These organisms can tolerate temperature fluctuations and pollution, grow rapidly, mature quickly, and produce numerous non-feeding planktonic larvae that can swiftly attach to floating docks, buoys, and ship hulls in calm, nutrient-rich bays [75]. With rapid marine economic development, monitoring changes in fouling communities on artificial facilities and studying impacts of invasive ascidians on local biodiversity and production activities should be prioritized.

3.2 Material Corrosion and Antifouling Development

Biofouling alters substrate surface microenvironments, affecting material corrosion behavior and processes. While barnacles can cause localized corrosion of certain metals [76] and oyster attachment mucus can corrode substrates [77], no studies have reported on ascidians, particularly compound ascidians, despite their being major fouling organisms. Future research should investigate how heavy ascidian fouling affects artificial facility material corrosion.

Controlling ascidian larval attachment is key to preventing fouling damage. Using larvae in antifouling research helps quickly evaluate technology effectiveness and provides references for applied research. However, current larval sources rely on field collection of mature individuals and indoor desiccation stimulation, which cannot guarantee sufficient larvae for statistical analysis. Research on ascidian larval collection, culture, and storage should be strengthened to ensure adequate experimental subjects.

Conventional antifouling methods—including manual removal, antifouling paint application, and biocide addition—have limitations. Since gene regulation plays important roles in ascidian larval metamorphosis [78], examining how various treatments affect expression of genes related to larval attachment and metamorphosis could elucidate antifouling mechanisms at the transcriptome and proteome levels, advancing broad-spectrum antifouling technology development.

3.3 Taxonomic and Biogeographic Research

Traditional taxonomy relies on morphological features and structural characteristics. However, morphological similarities among some ascidians (e.g., *Ciona intestinalis* and *Ciona savignyi* have long been considered the same species [79]), combined with environmental differences, often lead to misclassification. Molecular biology methods can provide powerful evidence at the molecular level to resolve these issues.

Current fouling organism research focuses primarily on tropical and temperate coastal waters, with extreme environment studies in deep sea and polar regions limited to individual areas [80-82]. Future work should continue in-depth systematic studies of hotspot regions while expanding to unknown waters and extreme environments to thoroughly elucidate population dynamics and development trends of fouling ascidians and their relationships with other fouling community organisms. This will provide scientific foundations for marine fouling prevention and control and accumulate data for marine ecological science, ultimately enabling construction of ecological mathematical models.

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