The mucilage phenomenon in the northern Adriatic Sea.  
A critical review of the present scientific hypotheses

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Summary. - In the summers of 1988, 1989, and 1991 large quantities of sticky mucilaginous masses occurred in the Adriatic Sea, particularly in its northern part. The mucilage phenomenon has been studied by scientists during past events, but the previous scientific reports back to the thirties of this century. Great efforts have been made since 1988 to understand the nature of the phenomenon. Although remarkable scientific results have been achieved, many questions related to such a complex phenomenon have remained open. In this paper results and hypotheses related to the chemical and biological composition, causes, triggering mechanisms, and responsible organisms for the mucilage phenomenon are briefly reviewed. Finally, some suggestions for future researches are proposed.

Key words: mucilages, Adriatic Sea, triggering mechanisms, responsible organisms.


Parole chiave: mucillagini, Mare Adriatico, meccanismi di innesco, organismi responsabili.

Introduction

In the summers of 1988, 1989 and 1991 (and again in 1997) large quantities of sticky mucilaginous masses ("cvjetanje mora", "mare sporco"), occurred in the Adriatic Sea particularly in its northern part [1-5]. Part of the material floating on the sea surface was deposited on beaches by wind and currents, reducing their suitability for bathing and threatening tourism. Suspended and sinking mucilaginous aggregates (up to 4 m in size) created serious problems for fisheries.

These and past mucilage events (documented in scientific publications since the last century) [6-9] started in late spring/early summer periods, when usually the decay of a series of spring phytoplankton blooms occurs in conditions of marked stratification of the water column and significantly decreased water exchange rate between the northern and central Adriatic Sea. In late summer physical factors (e.g. water mixing by storms) are probably important to breakdown or transfer of aggregates in deeper layers, where the prevailing decomposition processes combined with export by currents contribute to end the events.

In 1992 a workshop on the marine mucilage was held at Cesenatico in Italy with the aims to:

1) define and delineate the phenomenon and its consequences on the marine ecosystem;
2) speculate about possible trigger mechanism(s);
3) propose future research, monitoring and remedial activities [10].

The scientific results presented at the workshop have been undoubtedly of great interest, even if some basic questions could not be definitely answered. In successive years more research was done, adding new data and hypotheses.

The present knowledge on some important aspects of the mucilage phenomenon in the northern Adriatic is briefly summarized in this review, based on the results from Cesenatico workshop proceedings and numerous other scientific papers. Some lines for future researches are also proposed.
Furthermore, a periodical nature of the phenomenon in the northern Adriatic has been documented in scientific publications since the past century [6]. This suggests that fluctuations of environmental conditions, primarily meteorological (climatic), hydrological, and oceanographic, might have some role in triggering the mucilage events.

**Meteorological and hydrological fluctuations**

Statistical analyses have excluded significant relationships between the frequency of the mucilage phenomenon and the sun spot activity [9]. In contrast, a covariation with unusually marked gradients of the atmospheric pressure for the period January-April, causing a water return to the northern Adriatic from southern regions, has been observed [36, 37]. Higher atmospheric pressure differences corresponded to mucilage events in the past 100 years (1872-1989). Interestingly, near bottom anoxia occurred in large areas of the northern Adriatic basin [38] during periods of extremely low (1977) and high (1989) barometric pressures, respectively [39].

High pressure, as well as reduction of rainfall and wave motion were also claimed as necessary, if not causative conditions for the mucilage events [40], Veggiati [41] also hypothesized a link between the phenomenon with natural causes, mainly climatological.

Tomasino [42] elaborated a predictive model for the mucilage events essentially based on the nutrient status in the northern Adriatic in late winter and the spring Po river discharge rates. However, the 1977 event has not been predicted by this model.

Two essentially different types of multiannual patterns of the Po flow rate, the major external nutrient source in the northern Adriatic, have been observed in spring since 1917 (when hydrological monitoring started in this river). During the thirties and from the fifties up to the seventies the maxima and minima of the mean flow rate for the period May-June alternated quite regularly every 1-2 years. In contrast, the twenties, forties and eighties were characterized by lower freshwater inputs in several successive springs followed by years of higher discharges in that season, with marked daily pulses (5000-9000 m³ s⁻¹). Approximately at the end of such a multiannual sequence of the spring flow rate (1928, 1951, 1988, 1989, 1991, 1997) the mucilage phenomenon occurred [4] (R. Precali, 1998, personal communication).

**Changes of nutrient concentrations in the Po river and influence on the marine ecosystem**

During the late seventies and early eighties the annual mean orthophosphate and inorganic nitrogen concentrations in the Po waters have at least doubled compared to the early seventies [43, 44]. After 1985, the orthophosphate concentration has gradually decreased, probably as a consequence of polyphosphate reduction in Italian detergents. In contrast, the inorganic nitrogen concentration has remained high. Thus, the mean N/P ratio in the Po river, already much higher than the Redfield stoichiometric ratio of 16, further increased in the late 1980s (up to 60).

Changes of nutrient concentration and ratios in the Emilia-Romagna coastal area during the eighties and early nineties were similar as in the Po river [45]. As a consequence, phytoplankton biomass (chlorophyll a concentration) have concurrently decreased in summer and autumn, more markedly since 1988, due primarily to a decreased frequency of dinoflagellate blooms.

Changes of nutrient and chlorophyll a concentrations, and potential primary production rate, presumably related to the modifications of the Po nutrient contents, have been also observed in the open northern Adriatic waters [46, 47]. During the early seventies and the late eighties the chlorophyll a concentrations and primary production rates were lower than in the early eighties when the orthophosphate concentration in the Po River was at the maximum. This is particularly evident from data collected in the February-April periods.

In the May-August periods the chlorophyll a concentrations and primary production rates were higher throughout the eighties and early nineties compared to the early seventies, despite the decreased orthophosphate input [47]. The unexpected high phytoplankton activity and biomass during the late 1980s can be related to unusual meteorological conditions, high barometric pressure, and long periods of calm and sunny weather [39, 48]. In those years the sea surface temperature has been higher than expected from long-term averages, particularly in spring and summer [47]. These condition might have greatly stimulated phytoplankton photosynthesis. Remarkably, the water transparency was not significantly different in the periods of the 1980s compared to the 1970s, i.e., the optical (photosynthetically active radiation) field probably did not change significantly [47]. Moreover, extremely low bottom oxygen saturations were observed during the late 1980s, including an anoxia event in a large area (about 4000 km²) of the northeastern Adriatic (November 1989) [49, 50]. In conclusion, the observed changes can be readily linked to fluctuations of meteorological and oceanographic conditions, rather than to the freshwater nutrient impact, particularly considering that the phosphorus load and marine primary production have decreased in the last decade. Finally, in the more recent period (1992-95), when the meteorological conditions have changed relatively to the late 1980s, the oxygen content did not decrease significantly below the lower limits typical for the early seventies and early eighties [11] (Center for Marine Research, Rovinj, unpublished data).
Composition of the phytoplankton community

An analysis of the data on phytoplankton composition, collected since 1970, indicated that some changes have occurred in the northern Adriatic ecosystem [4, 51]. As an example, in the seventies *Skeletonema costatum*, *Nitzschia seriata*, and *Proorocentrum micans* were prominent bloom constituents in the open waters under the direct influence of the Po river discharges [52]. In contrast, during the eighties other species (*Nitzschia delicatissima* and *Chaetoceros* spp.) were playing this role [4].

Moreover, a significant increase (up to 20 times) of the spring diatom abundance (and decrease of orthosilicate concentration in the upper water column) was observed in the surface layer during the eighties compared with the seventies, which was particularly evident in the eastern, more oligotrophic region. However, a shift towards smaller diatom species [55] contributed to maintain the average total phytoplankton standing crop approximately at the same level. Concurrently, the episodes of dinoflagellate blooms have been reduced, partly compensating the diatom increase.

Short-term unusual changes in the phytoplankton community due to a mucilage event can also occur, like, for example, in 1989 in the Gulf of Trieste [54].

Which is (are) the “triggering” mechanism(s) of the phenomenon?

The causes and the “triggering” mechanism(s) of the mucilage phenomenon have not yet been explained. Several hypotheses have been proposed, which can be grouped as following.

Environmental changes factor

The assumption that a particular freshwater discharge pattern of the Po river over a decade may be essential for the occurrence of the phenomenon was based on the most recent observations [4]. It is thought that species showing increased exudation rates have been selected and adapted to an increased nutrient availability in the years of high Po outflows during spring, which preceded the mucilage events. These species might have been highly stimulated in conditions of extremely reduced vertical and horizontal water mixing and increased irradiance (due to an increased frequency of calm and sunny weather). The initial growth in relatively restricted areas off the Po river, caused by nutrient injections, might have, in a later phase, been drastically limited by dilution with oligotrophic waters, particularly poor in orthophosphate. This might have caused stress conditions and favoured an unusual high polysaccharide excretion, and, at the same time, very stable physical conditions in the water column and reduced water mass exchange favoured aggregation up to very high degrees.

Other authors have outlined the possible role of changes of environmental conditions at the interface Po plumes/oligotrophic waters, as a stress factor causing high exudation rates. This is consistent with the hypothesis reported above, and also supported by diver observations of the aggregates’ appearance in the eastern, more oligotrophic region, preceding that in the western more eutrophic ones [4], as well as in laboratory experiments with *Cylindrotheca closterium* simulating these conditions [55].

Changes in nutrient ratios and, generally, drastic nutrient limitation, were also considered as a triggering factor of hyperexudation and mucilage [24, 56-59]. As an example, it is known that when phosphorus is no longer available for nucleic acid synthesis, but conditions stimulating carbon fixation persist, a large excess of produced carbohydrates can be released [28]. The aggregate formation might be a strategy to benefit the algal component with a higher nutrient supply, regenerated by microheterotrophs. However, even if expected to have an important role, nutrients cannot be the only determinant, because the phenomenon did not occur after 1991 even though nutrient ratios and P limitation remained unchanged.

In addition to nutrient limitation, exudation may be further enhanced by high temperatures and irradiances [24]. The levels of these parameters were unusually high during the late 1980s, due to the particular meteorological and oceanographic conditions.

Changes in the grazer pressure

Grazing could play an important role in the development of the phenomenon [8, 22, 59], because observations have indicated that the initial spring copepod stock might be too low to control a fast growth of diatoms caused by freshwater nutrient injections in very favourable environmental conditions (calm sea, reduced freshwater dilution). In addition, the grazing pressure can be further reduced due to a deterrent effect of exudates produced in the transitional and stationary phase of the phytoplankton growth, enabling the population to persist and continue exuding geliform substances [60]. At the same time the mucus can negatively influence the naupliar copepod population, which, for example, decreased greatly during the summer mucilage events of 1989 and 1991 [61], while the principal adult copepod species from the northern Adriatic were apparently not able to feed on the marine snow associated phytoplankton [62]. In fact, analysis of zooplankton fatty acids indicated that during the mucilage event the animals were under drastic starvation, consuming their fat reserves including polyunsaturated fractions [63].
A possible role of bacteria

Lack of nutrients (e.g., nutrient exhaustion during phytoplankton bloom) can also impede bacterial growth and therefore the degradation of exudates just when they are produced at high rates [8]. Moreover, preferential degradation of organic P in respect with C led to a “storage” of low degradable matter, including polysaccharides [64].

Virus infections

Virus infection and phytoplankton cell lysis were also considered as the causes of polysaccharide accumulation [65]. Several compounds, indicating lysis and a possible virus presence, were identified in mucilages. Marine snow formation was stimulated in natural phytoplankton community when material of the size range of 2-200 nm containing large number of viruses was added [66]. Virus-like particles were detected in “dissolved” organic matter in the water column during mucilage events. Remarkably, infections, if they occurred, might also be related to changes in environmental (meteorological and oceanographic), which lead to conditions favourable for an increased viral activity.

Aggregation mechanisms

A recent hypothesis links gradual aggregation processes of marine snow in the pycnocline layer with surface gelatinous mass formation, which include intermediate stages of stringers, clouds, and creamy surface [7, 67]. In this layer the residence time of aggregates is increased, which enhances the probability of their random collision and sticking. However, in 1991 turbid layers of gel-like dispersed material, approximately −0.5 m, were observed in the open northern Adriatic, in correspondence of various haloclines formed in the upper part of the water column, as well as in surface near-coastal waters [4]. These observations support the assumption that larger aggregates (clouds) and creamy layers may be formed directly by coagulation of this substance accumulated in unusual quantities, and entrapping plankton organisms, suspended detritus and marine snow. Remarkably, the fatty acid composition of marine snow and mucilaginous large aggregates did not differ substantially [63]; this implies a similar origin of the matrix, but not necessarily the same mechanism of aggregation.

A possible role of Zeolite A (allumino-silicates) and carboxylic acids-polyacrylates (acrylic acid and derivatives, acrylamide and maleic anhydride), as nuclei for mucilage aggregation, has also been considered [68]. These compounds have gradually substitute polyphosphate in detergents in Italy just during the mid-eighties immediately before the first mucilage appearance in 1988. However, experiments with Cylindrotheca closterium have not confirmed that the addition of Zeolite A and PCA causes or even influence significantly the mucilage production [69].

Organism(s) responsible for the phenomenon

In papers describing the events in the past, pelagic and benthic diatoms (or sometimes dinoflagellates) were assumed to be the main exudate producers [6]. Generally, this assumption was based on microscope observations of already formed mucilage material, by which the mucilage producers cannot be distinguished from organisms embedded during the aggregation.

After the 1988 event some researches have tried to verify if some benthic diatom species or Cylindrotheca closterium might be the principal producers of mucus [18, 19, 55]. Although those species produced mucus and string-like mucilage in the laboratory, a conclusive evidence about causative organisms has not been obtained, especially for deeper open sea regions.

Planktonic diatoms were highly dominant in most of the samples in similar species ratios as in the water [4]. However, less abundant species (e.g. C. closterium, Navicula spp.) have been found in relatively higher ratios in the aggregates compared to the surrounding water [22], particularly in aged mucilaginous material from eastern areas of the northern Adriatic [4]. Laboratory experiments have suggested that C. closterium may have a better capability to reproduce in mucilages than other species, and that it has an important role in the formation of mucilaginous filaments [10, p. 145].

Microscopic observations suggesting an important role of diatoms were also apparently confirmed by measurements of various biomarkers in mucilages (OC, fatty acids, hydrocarbons, pigments), and spectrofluorimetric spectra [17, 21, 31, 70]. Recent experiments in situ in the gulf of Trieste have shown that polysaccharide production can represent a major fraction of dissolved organic carbon (DOC) and be associated mainly to diatoms, in some case to dinoflagellates, while the role of nanoflagellates and cyanobacteria appears to be relatively less important [71-73].

However, mucilage derived from heterotrophic bacteria subsisting in large numbers on diatom extracellular products might have some of the same chemical properties [28]. Consequently, they might in particular conditions contribute significantly to the phenomenon development. Researches on the capability of the heterotrophic populations from the Gulf of Trieste to produce extracellular polysaccharides are in progress [74].
Moreover, cyanobacteria might have an important role in the 1991 event, when in July they contributed up to 70% in terms of carbon content in mucilages from the Gulf of Trieste [24, 29]. Unusually high cyanobacteria DOC excretion was hypothesized from data on irradiance levels higher than 150 μE m−2 s−1, measured down to 10 m depth at the investigated station. Very high cyanobacterial abundance (at least an order of magnitude higher than usual in summer) has also been measured in the northern Adriatic waters during late June and in July 1991, just after the mucilage event started [75]. This suggests that, even if cyanobacteria were not the main organisms responsible for the initial mucilage production, they might have an important role in successive phases of the development of the phenomenon, further fuelling the mucoid matter.

Statistical analyses of data on the phytoplankton community from the Gulf of Trieste during 1990-93 have shown unusual high dinoflagellate/diatom ratios in June and July 1991 in the presence of mucilaginous aggregates [76]. These results led the authors to elaborate two different hypotheses: 1) the aggregates were imported from the open sea or 2) they were produced by a few diatom species (e.g., C. closterium) that were scarce in seawater, but have high exudation rates. At that time, the unusual intense cyanobacterial bloom occurred, the microphytoplankton (mainly diatoms and dinoflagellates) abundances in the open northern Adriatic waters were much lower than expected [75], (Center for Marine Research, Rovinj, unpublished results).

Concluding remarks

The trigger mechanism(s) of gel-like material production may be tightly related to environmental changes that, at the same time, created oceanographic conditions favourable for build-up and accumulation of aggregated material within the northern Adriatic area; the result is a massive mucilage event. For this reason, future activities should be designed to verify if and how changes of environmental conditions could influence the nutrient ratios and nutrient limitation mechanisms, as well as grazing pressure. Further, environmental variability could induce changes in the composition, activity, and behaviour of phytoplankton (primarily diatoms, at the community and single species levels), and auto- and heterotrophic microbial communities. Moreover, it could promote viral activity causing phytoplankton and/or bacteria infection. The role of bacteria and related research hypotheses are elaborated in more detail by Azam et al. [64]. Various possible aggregation mechanisms should be also studied in relation to the physical structure and dynamics of the water column.

Furthermore, experiments should be performed with particular species, which are dominant in the critical period (May-June) in different area, taking also into account that structural changes of the biological communities can also occur in some years (e.g. the cyanobacterial bloom in 1991).

A different timing and phenomenological characteristics of the mucilage events have been observed in the eastern compared to western open waters, as well as in the Kvarner regions, gulfs of Trieste and Venice, or Emilia-Romagna and Marche coastal regions that can be related to both physical and biological conditions. For this reason the monitoring and study of these mechanisms should be enlarged to other northern Adriatic areas.

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