

Needs and perspectives of odour research in the aquatic sciences

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Abstract Over more than four decades odour research in the aquatic sciences has increasingly focused on cyanobacteria and the common odour-causing compounds, geosmin and 2-methylisoborneol. Success in future research requires a long-term perspective. Key areas for investigation are secondary metabolites and cyanobacteria, regulatory mechanisms for geosmin and other compounds' synthesis; understanding their spatial and temporal distribution (particularly relating to the food web in a habitat); and molecular mechanisms for liberation of geosmin by microorganisms.

Keywords Cyanobacteria; geosmin; geosmin distribution; 2-methylisoborneol; odour research goals

Odour research in aquatic sciences based on chemical compounds was initiated in the 1960s when the structure, and shortly after, the configuration of the two most frequently observed odour compounds, geosmin and 2-methylisoborneol were determined. Although cyanobacteria were already included in these early studies, the traditional view that *Streptomyces* are the primary sources of muddy odours in waters was not abandoned until [Tabachek and Yurkowski \(1976\)](#) provided evidence that cyanobacteria, rather than streptomycetes, are the primary sources of these compounds in lake ecosystems. In the following decades our knowledge of the sources of these odours has widened. New odour compounds have been described, and their spatial and temporal distribution in aquatic ecosystems studied. Ultra-trace analytical methods for the detection of odour compounds have been developed and questions concerning the biosynthesis and degradation of these compounds investigated. Sensory analyses, descriptions of odours in the water and elimination of odours during water treatment are important technical challenges that have been addressed. An outstanding information content of the work of more than two decades is summarised in the proceedings of the now seven symposia on Off-Flavours in the Aquatic Environment held in different countries over the world and published in special issues of *Water Science and Technology* ([Persson et al., 1983, 1988, 1992](#); [Hrudey et al., 1995](#); [Bruchet et al., 1999](#); [Matia et al., 2004](#); and this issue). Although up to now approximately 435 articles (ISI web of knowledge) have appeared in these volumes and other journals and books solely on geosmin, many questions in aquatic odour research remain unresolved. This is both important and ambitious.

A general weakness of the research projects undertaken to date is that long-term goals have only rarely been investigated. Severe odour problems usually appear episodically, and corresponding research support induced by such outbreaks has followed the same pattern. Research projects requiring long-term planning are in a minority. The strategies are often subjected to the requirements of water authorities that question expensive research on ephemeral or apparently "solved" or "vanished" problems (although they tend to resurface in the long-term).

Another important area that is deficient is a comprehensive knowledge of the secondary metabolism of cyanobacteria. Cyanobacteria are by far the most important odour

producers. They are Gram-negative bacteria that have many properties in common with heterotrophic bacteria but show fundamental differences in their regulation of secondary metabolites. Thus, approaches based on applied bacterial work (e.g. antibiotics research) which are based on the premise that the synthesis of secondary metabolites and their excretion are induced with the onset of the stationary growth phase may not be applicable, since neither of these facts hold for cyanobacteria. Cyanobacteria, which are photoautotrophic microorganisms, do not show a logarithmic and stationary growth phase in the strict sense, with up- and down-regulation of enzymes, and a direct dependence of odour production rates on the availability of nutrients is not observed. In addition, as other cyanobacterial secondary metabolites (microcystins and other oligopeptides), geosmin is stored in the cells rather than excreted. Thus, many research projects on this topic have reached the rather unwelcome conclusion that changes in exogenous factors may induce modulations, but not significant differences, in the synthesis rates of geosmin and other secondary metabolites.

There are some key goals in future odour research that should have high priority. Geosmin is the primary focus here, but any other major odour compound is equally as relevant. One of the most important knowledge gaps that should be addressed is the regulation mechanisms of geosmin synthesis. As in microcystin-producing genera, low, medium and high geosmin-producing cyanobacteria strains have been isolated and described. The genetic basis for these differences is not even remotely understood. A prerequisite to study the control mechanisms is the knowledge of the biosynthetic steps, the enzymes and the corresponding genes involved. In the case of geosmin, remarkable progress has recently been made, but for 2-methylisoborneol, for example, no work has been carried out in this area since 1981.

Another primary research goal should be directed towards the spatial and temporal distribution of geosmin in lakes and running waters. An absolute requirement for this work, however, is the differentiation between dissolved and cell-bound geosmin, because both fractions show different dynamics. The dynamics of the cell-bound geosmin can only be understood in the context of the food web in a particular aquatic habitat, and limnological aspects of the source-water should be essential components in any study. Cell-bound geosmin is a constituent of some of the primary producers in a food web, which produce and store this compound in their cells. Primary consumers (crustaceae, protozoa, rotifers, etc.) digest these geosmin-containing particles, and it is the physiology of the primary consumers that determines in which binding form geosmin is released into the water, or whether it is stored or degraded by intracellular enzymes (possibly cytochrome oxidases). Bacteria may be more important for the dynamics of bound geosmin only in those habitats where primary consumers are of low abundance (anoxic zones).

Tightly coupled with the understanding of the geosmin flow through the food web is the knowledge whether, and where, bioaccumulation occurs. Since most fish do not ingest cyanobacteria and/or streptomycetes, or if so, this is only incidentally, the importance of primary consumers versus dissolved geosmin for the tainting of fish has to be investigated more carefully. Any management, including biocontrol, requires such information.

Another important goal should be to find a means to differentiate between geosmin produced by cyanobacteria and streptomycetes (or other heterotrophic taxa such as myxobacteria or soil fungi). Particularly when low geosmin concentrations are observed in the water, such analyses would be extremely helpful to trace the sources and to develop management approaches to improve water quality. Because geosmin is also introduced by the run-off from the ground, the terrestrial zone has to be included in these analyses. Another often-related issue that has so far not been addressed is the determination of the producers of geosmin in water distribution systems.

A last suggestion for further research would be the study of the molecular mechanisms for the liberation of geosmin by geosmin-producing microorganisms. A simple way of liberation is clearly caused by cell death. However, induction of exporters that would translocate geosmin into the extracellular environment under certain conditions cannot fully be excluded. The tools in molecular biology that could be applied to solve this question are already available. This topic is of particular importance in understanding the physiology of cyanobacterial biofilms that frequently are important odour producers in running waters and lakes.

Many more research perspectives will emerge in the future and the few primary goals presented here represent some of the key areas of focus that would improve our present knowledge in some of the important and outstanding issues in odour research.

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