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ENVIRONMENTAL FATE OF THE ANTIFOULING COMPOUND ZINC PYRITHIONE IN SEAWATER

KATJA S. GRUNNET†‡ and INGELA DAHLLÖF*†
†Danish National Environmental Research Institute, Box 358, Frederiksbergvej 399, 4000 Roskilde, Denmark
‡University of Copenhagen, Department of Chemistry, Universitetsparken 5, 2100 København Ø, Denmark

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Abstract—To perform a thorough risk assessment of the new antifouling compound zinc pyrithione (ZnPT₂), additional information regarding the fate of the compound is needed. The present study examined the recovery and transchelation of ZnPT₂ in controlled laboratory experiments, photodegradation experiments, and a fate study in a large-scale field experiment. Chemical analyses were performed using a newly developed method for simultaneous analyses of ZnPT₂ and copper pyrithione (CuPT₂). Furthermore, two antifouling paints containing ZnPT₂ were examined for the fate of leaching biocide. Naturally occurring ligands and metals in seawater influence the stability of ZnPT₂. The presence of free Cu²⁺, which is present naturally in the seawater or is released from copper-containing paints, results in a partial transchelation of ZnPT₂ into CuPT₂. A complete transchelation of ZnPT₂ into CuPT₂ was observed when Cu²⁺ was present at an equimolar concentration in the absence of interfering ligands. When ZnPT₂ was leached from antifouling paints containing both ZnPT₂ and Cu₂O, CuPT₂ was found, with no trace of ZnPT₂. Photodegradation was low in natural waters and absent from 1 m or more below the surface. The results show that ZnPT₂ has a low persistence in seawater when leached from antifouling paints. However, the more stable and toxic transchelation product CuPT₂ is formed, which has the potential to accumulate in the sediments and, therefore, should be included in both chemical analysis and risk assessment of ZPT₂.

Keywords—Zinc pyrithione Copper pyrithione Transchelation Photodegradation Antifouling paint

INTRODUCTION

Zinc pyrithione (ZnPT₂) has been used during the last decade as a booster biocide in antifouling paints for small leisure boats. The release of ZnPT₂ from the paint can result from self-polishing of the paint or simple weathering of the paint from the hull. Persistence of ZnPT₂ in natural waters is believed to be low because of rapid photodegradation [1,2], and to our knowledge, ZnPT₂ has not yet been detected in natural waters [3]. A concentration of total pyrithione has, however, been detected in the Mercy River, UK, at 105 ± 5 nM (± standard error of the mean) [4].

Zinc pyrithione belongs to the group of metal–chelate complexes that exist according to the equilibria between metal ions, ligands, and their respective stability constants. The presence of competing metal ions or ligands in solution influences the stability of metal–chelate complexes through transchelation reactions. Until now, only a few estimations of the transchelation potential of ZnPT₂ have been performed [2], because an analytical method for the simultaneous analysis of ZnPT₂ and one of its more stable transchelation product, copper pyrithione (CuPT₂), has been lacking. Knowledge about the transchelation potential is important in the risk assessment of ZnPT₂, because the toxicity may change with an altered chemical composition. For example, CuPT₂ is more toxic than ZnPT₂ to phytoplankton communities, with median effect concentrations of less than 14.5 nM for CuPT₂ and less than 19.8 M for ZnPT₂ [5].

Here, we present results from controlled transchelation experiments, photodegradation, and fate studies of ZnPT₂ in a large-scale experiment. An analytical method for simultaneous determination of ZnPT₂ and CuPT₂ also is introduced. Furthermore, the fate of ZnPT₂ leached from antifouling paints is investigated and discussed. These results will help to explain the risk from using ZnPT₂ as an antifouling agent against marine life.

MATERIALS AND METHODS

Sample analysis

Before extraction, 1 ml of 2 μM xylene cyanol (Sigma Chemical, St. Louis, MO, USA) was added as internal standard to 1-L water samples. The water samples were extracted using solid-phase extraction (SPE) cartridges (6 ml, 200 mg of polymeric sorbent packing; Strata X; Strata Phenomenex, Torrance, CA, USA). The SPE cartridge was preconditioned with 6 ml of elution solvent (mixture of acetonitrile, methanol, and deionized water [70:20:10]), followed by rinsing with 6 ml of deionized water. The sample was passed through the cartridge at a rate of 10 to 15 ml/min under vacuum (off-line SPE-manifold vacuum system; Supelco Visiprep SPE Vacuum Manifolds, Bellefonte, PA, USA). To clean the retained compounds from salts, the cartridge was washed with 6 ml of deionized water and allowed to dry under vacuum for 1 to 2 min. Finally, the compounds were eluted five times with 1 ml of elution solvent each time, evaporated in a warm water bath under a gentle N₂ stream to approximately 1 ml, and transferred into a vial for high-performance liquid chromatographic (HPLC) analysis.

The HPLC system was a Hewlett-Packard (Palo Alto, CA, USA) Series 1100 with an on-line degasser, a quaternary gradient pump, an automatic sample loop adjusted to 40 μl, a thermostable column compartment maintained at 26°C, a wide-pore C-18 guard column (inner diameter, 3.0 mm; length, 4 mm; Phenomenex), a Jupiter C-18 analytical column (inner diameter, 4.6 mm; length, 250 mm; particle size, 5 μm; Phen-
Reagents and chemicals

Both ZnPT$_2$ and CuPT$_2$ (purity, $\geq$95%; Arch Chemicals, Dublin, Ireland) were used for standards, and xylene cyanol (Sigma) was used as internal standard. Standard solutions were made in methanol (Merck, Darmstadt, Germany) and contained 1, 7, 13, 19, and 25 $\mu$M ZnPT$_2$ or CuPT$_2$ and 2 $\mu$M internal standard.

A Cu(NO$_3$)$_2$ standard solution for atomic absorption spectroscopy (Spectrosol; BDH Chemicals, Poole, UK) and a CuCl$_2$ standard solution (Titrisol$^\circledR$; Merck) were used in the transchelation experiments.

Two antifouling paints were tested. The first was Alu-Safe 7120 (Hempel’s Marine Paints, Lyngby, Denmark), a copper-free paint containing ZnPT$_2$. The second was Mille Ocean 7110 (Hempel’s Marine Paints, Roskilde, Denmark). Neither ZnPT$_2$, CuPT$_2$, nor the internal standard was observed when analyzing unpolished paint containing ZnPT$_2$. The second was Mille Ocean 7110 (Hempel’s Marine Paints), a copper-containing internal standard was added to the bottles at a nominal ZnPT$_2$ concentration of 25 nM. Immediately after preparation, the samples to give a nominal Cu$^{2+}$ concentration of 15 $\mu$mol/L. For trials with equimolar copper and ZnPT$_2$ concentrations, a salt solution was prepared to contain 25 nmol/L of Cu$^{2+}$. In all transchelation experiments, 1 ml of 25 $\mu$M ZnPT$_2$ working standard solution with internal standard was added to the copper-containing water samples to give a final concentration of 25 nM, and extraction began immediately thereafter. Three replicates were included in each treatment.

Antifouling paint-leaching experiment

Three wooden panels were treated with two layers of Hempel’s Yacht Primer 26030 according to the manufacturer’s recommendations before covering an area of 7 cm$^2$ with two layers of either Alu-Safe or Mille Ocean antifouling paint. Antifouling paint was carefully applied with a small brush to the decided area to a thickness of approximately 0.5 mm. Application was performed twice, with a 16-h interval. After final drying (24 h), each panel was immersed in separate 1,000-ml Scott Duran bottles containing seawater and placed on magnetic stirrers (slow stirring) to ensure constant water motion around the panels for optimal and reproducible leaching. Each sample (1 L) was in contact with the panel for 1 h before addition of internal standard, followed by extraction and analysis. The panel was subsequently transferred into a fresh, unexposed sample of seawater of 1 L. Samples (1-h exposure) were taken four times on the first day of the experiment (day 0; hours 1, 2, 3, and 4) and once a day on days 1, 2, 4, 5, 6, 8, and 12 of the Mille Ocean experiment. The Alu Safe experiment was stopped after sampling on day 4. Between the 1-h samples, the panels were immersed in seawater under the same stirring conditions.

Photodegradation

The exposure sites were as follows: in the laboratory (light intensity, 4.3 W/m$^2$; $\lambda$, >400 nm), outside the laboratory in direct sunlight (light intensity, 415 W/m$^2$; $\lambda$, >400 nm), and in the water column of Isefjorden. Clear Scott Duran (1,000-ml) glass bottles were prepared to contain nominal concentrations of 25 nM CuPT$_2$ in seawater. Triplicate preparations were placed at each exposure site and exposed to light for 1 h as described previously [1]. Before and after exposure, the bottles were immediately wrapped in black plastic bags or aluminum foil to prevent further photodegradation during transport and extraction. The bottles in Isefjorden were placed at 0.5, 1, 2, and 3 m below the surface and exposed on May 30, 2004, between 1:16 and 2:18 PM. Isefjorden has a depth of 4 m at the selected site, and penetrating sunlight is expected to be reduced the most in the top of the water column. The weather was fine, with thin, high clouds. The bottles were tied to a string, and each string had four bottles attached. The strings were secured on a floating bridge anchored up in the bay, and all bottles faced the sun. Chlorophyll $a$ was measured by filtering 100 ml from a depth-integrated water sample of the top 2.5 m. The filter was padded dry and extracted in 10 ml of 96% ethanol and thereafter measured with a spectrophotometer (10-AU; Turner Designs, Sunnyvale, CA, USA). Light absorption by colored dissolved organic matter (CDOM) was measured on the glass-fiber filtrate using a Shimadzu UV-2401PC UV-VIS spectrophotometer (Shimadzu, Kyoto, Japan). Absorption spectra were measured from 300 to 700 nm and modeled according to the method described by Stedmon et al. [6].
Large-scale experiment

A large-scale experiment was set up in the shallow waters of Isefjorden. To an enclosure containing approximately 3,000 L of the fjord water, ZnPT₂ was added to create a nominal concentration of 50 nM ZnPT₂. Zinc pyrithione was expected to photodegrade within the following day; hence, the same concentration of ZnPT₂ was added for three consecutive evenings. After addition of ZnPT₂, the water in the enclosure was stirred, and four 1-L subsamples were removed for analysis. Internal standard was added to each of the four replicates before extraction on SPE and analysis. Background samples of surrounding water showed no trace of ZnPT₂ or CuPT₂.

RESULTS AND DISCUSSION

The analytical method has a detection limit of 2 and 1 μM for ZnPT₂ and CuPT₂, respectively, and a linear range of one order of magnitude (Fig. 1). With a preconcentration factor of 1,000, the detection limit for seawater is 2 and 1 nM for ZnPT₂ and CuPT₂, respectively. Recovery of 250 nM in seawater is 85% ± 4% for ZnPT₂ and 90% ± 5% for CuPT₂.

Recovery of ZnPT₂ from seawater containing various ratios of deionized water

A relationship between the ratio of seawater and the recovery of ZnPT₂ was found. The relationship was negative log-linear (Fig. 2). No trace of ZnPT₂ was found in 100% seawater, and a maximum recovery of 49% ± 6% (n = 3) was obtained from 0.01% seawater in deionized water. In addition, the concentration of CuPT₂ increased with the ratio of seawater. A maximum formation of CuPT₂ was found in 100% seawater, in which a concentration of 12 ± 1 nM (accounting for 48% of the added ZnPT₂) was detected. In media containing 1% seawater or less, a small amount of CuPT₂ was found.

The results show that the components of seawater influence the stability of ZnPT₂. Zinc pyrithione could not be recovered more than 49%, even in very dilute seawater matrices. However, the concentrations of chloride and sodium in the dilute seawater are still approximately twice the concentration of ZnPT₂, which suggests that complexes such as NaPT and Cl⁻ZnPT might be formed (where PT₂ represents the pyrithione ligand). Calculations of the speciation of ZnPT₂ in aqueous solutions (deionized water) of pH 7 at three different nominal ZnPT₂ concentrations (0.1, 1, and 10 μM) have been accomplished by Doose et al. [7]. Those authors found that only at the highest concentration (10 μM) was ZnPT₂ present at a ratio (53%) similar to the one found in the present study. At lower concentrations, ZnPT₂ will be present only as 0.59 and 14% of the nominal concentrations 0.1 and 1 μM, respectively. The nominal concentration used in the present experiment was 25 nM; hence, according to Doose et al., ZnPT₂ would not be found in a concentration greater than the limit of detection. However, the present experiment was conducted in seawater, and the naturally occurring ions will displace the equilibria obtained by Doose et al. The seawater conditions in the present experiment tend to stabilize the presence of nondissociated ZnPT₂.

When copper was present at high-enough concentrations (100 and 10% seawater), CuPT₂ also was formed, as shown in the present study. The small amounts of CuPT₂ found in the diluted seawater samples could be caused by copper impurities on the surface of the glass bottles or the analytical equipment.

Recovery of ZnPT₂ from seawater containing various concentrations of Cu²⁺

No trace of ZnPT₂ was observed in any of the following experiments with addition of copper(II) to the media. Hence, the focus here will be on the formed CuPT₂.

Copper(II) chloride was added in excess to seawater samples to a concentration of 15 μM copper(II). Zinc pyrithione
was then added to a nominal concentration of 25 nM, and 45% ± 4% \( (n = 3) \) was recovered as CuPT\(_2\). These results did not differ markedly from the recovery of ZnPT\(_2\) from seawater, in which 48% of the added ZnPT\(_2\) was recovered as CuPT\(_2\) from 100% seawater. To prevent unwanted complexation reactions between zinc(II) or pyrithione and organic material or inorganic salts in the seawater, a similar experiment was carried out in deionized water to which CuCl\(_2\) was added. The recovery of ZnPT\(_2\) as CuPT\(_2\) in this experiment was 55% ± 5% \( (n = 3) \). A complete transfer into CuPT\(_2\) was not observed. Hence, the high concentration of either chloride or copper(II) possibly prevented a total transchelation into CuPT\(_2\).

To determine the possible influence of chloride, CuCl\(_2\) was substituted by Cu(NO\(_3\))\(_2\) at the same concentration in deionized water. Recovery of ZnPT\(_2\) as CuPT\(_2\) was 51% ± 2% \( (n = 3) \), only slightly less than that recovered when chloride was used. The results indicated that a high concentration of copper(II) and the presence of inorganic ligands disturbed the stability of 1:2 metal:pyrithione complexes. The excess amount of copper(II) compared to pyrithione (PT\(^-\)) prevented a total transchelation into the CuPT\(_2\) complex. Instead, the 1:1 copper:pyrithione (CuPT\(^+\)) may have been formed, which is stabilized with the other inorganic ligands (Cl\(^-\) or NO\(_3\)^-):

\[
nZnPT_2 + mCu^{2+} \rightarrow nZn^{2+} + nCuPT^+ + n/2CuPT_2
\]

where \( m \gg n \). Because of a high expected polarity of CuPT\(^+\), this compound would not be retained on the SPE column and, therefore, would be lost before HPLC analysis of the sample. The theory that CuPT\(^+\) was formed because of excess Cu\(^{2+}\) and then verified further. Equimolar concentrations of Cu(NO\(_3\))\(_2\) and ZnPT\(_2\) were added to a salt solution, and recovery of ZnPT\(_2\) as CuPT\(_2\) was 94% ± 3% \( (n = 3) \).

When Cu(NO\(_3\))\(_2\) was present in excess in salt solution, only 67% ± 6% \( (n = 3) \) was recovered as CuPT\(_2\), indicating that the concentration of Cu\(^{2+}\) displaced the equilibrium toward CuPT\(^+\).

Ranke and Jastorff [8] speculate on the existence of a 1:1 CuPT\(^+\) complex from speciation of ZnPT\(_2\) in seawater. Their calculations are based on the stability constant for the formation of the 1:1 ZnPT\(^+\) complex (log \( K_c \) = 5.8) from Galvin et al. [9]. This stability constant also is used as the 1:1 formation constant for CuPT\(^+\). Thereby, Ranke and Jastorff conclude that the fraction of the 1:1 CuPT\(^+\) complex would be considerably smaller than the fraction of ZnPT\(_2\) because of the small amount of free Cu\(^{2+}\) compared to Zn\(^{2+}\). However, Sun et al. [10] published the 1:1 stability constant for the complexes of pyrithione with copper and zinc, among others, and the stability of the copper complex (CuPT\(^+\)) clearly is more than 10\(^6\)-fold higher than that of the corresponding zinc complex (ZnPT\(^+\)). Hence, a considerable amount of CuPT\(^+\) may be expected to form, as shown in the present article.

**Antifouling paint–leaching experiment**

To evaluate the fate of ZnPT\(_2\) leached from antifouling paints, a leaching experiment was performed. The objective was to evaluate fate only, not to determine the actual leaching rate.

From the Alu-Safe paint, containing no copper, ZnPT\(_2\) was detected only within the first hour when leached into seawater. The concentration of ZnPT\(_2\) in the first sample was 4 ± 2 nM. A formation of CuPT\(_2\), however, was apparent throughout the experiment, starting at a high concentration of 21 ± 2 nM \( (n = 3) \) in the first sample, which thereafter was reduced through-out the experiment, ending at 0.9 ± 0.2 nM \( (n = 3) \) after 1 d of leaching (Fig. 3). The concentration of CuPT\(_2\) measured after the first day of the experiment remained constant in all samples at approximately 1 nM until the end of the experiment after 4 d (data not shown). The results suggested that the fate of ZnPT\(_2\), from the paint, not containing copper, was determined by the presence of Cu\(^{2+}\) and other ligands in the seawater and the leaching rate from the paint.

The other antifouling paint tested, Mille Ocean, contained CuO in addition to ZnPT\(_2\) as an active biocide. No trace of ZnPT\(_2\) was found during the entire 12-d experiments. Instead, a high concentration of CuPT\(_2\) was found, being highest at the beginning of the experiment, with up to 19 ± 8 nM \( (n = 3) \) after 4 h, thereafter being reduced to an almost constant concentration of approximately 6 nM after 4 d (Fig. 4).

Copper present in antifouling paints as CuO is oxidized to Cu\(^{2+}\) when released to the surrounding water [11]; hence, the presence of CuO in antifouling paints will increase the copper concentration in the water immediately adjacent to the painted surface. An increase in copper concentration in the water will thereby increase the transchelation of ZnPT\(_2\) into CuPT\(_2\). This can explain why ZnPT\(_2\) was not observed in the dimensions: 612.0x792.0

**Fig. 3.** Measured concentrations (mean ± standard deviation) of zinc pyrithione (ZnPT\(_2\)) and copper pyrithione (CuPT\(_2\)) in seawater exposed to a surface with Alu Safe (Hempel’s Marine Paints, Lyngby, Denmark) antifouling paint in the dark. Each sample was exposed for 1 h \( (n = 3) \). Bars indicate standard deviations.

**Fig. 4.** Measured concentrations (mean ± standard deviation) of zinc pyrithione (ZnPT\(_2\)) and copper pyrithione (CuPT\(_2\)) in seawater exposed to a surface with Mille Ocean (Hempel’s Marine Paints, Lyngby, Denmark) antifouling paint in the dark. Each sample was exposed for 1 h \( (n = 3) \).
Photodegradation

After a 1-h exposure, the samples were extracted and analyzed. Recovery of CuPT$_2$ from the samples placed outdoors was 3% $\pm$ 1% ($n = 2$). One sample was removed according to the Grubbs test for outliers ($p < 0.05$) [12]. Samples placed indoors showed no photodegradation and a recovery of 94% $\pm$ 5%, suggesting that photodegradation was dependent on light intensity.

A photodegradation experiment also was performed in the field (Isefjorden). Bottles containing 25 nM CuPT$_2$ in seawater were immersed in the water column at four different depths for 1 h. Photodegradation was observed 0.5 m below the surface, where CuPT$_2$ recovery was 60% $\pm$ 15% ($n = 3$) (Fig. 5). Recoveries obtained at depths of 1, 2, and 3 m in the field photodegradation experiment were not significantly different from those of nonexposed samples ($p < 0.05$). The recoveries obtained at depths of 1 m and below were similar to the recovery of CuPT$_2$ from seawater containing 25 nM CuPT$_2$ when not exposed to light (recovery, 95% $\pm$ 6%; $n = 3$) (Fig. 1b). Hence, photodegradation was absent at 1 m or more below the surface.

The water in Isefjorden contained high amounts of CDOM, which reduces the penetration of sunlight (especially UV light). The calculated light absorption because of CDOM showed that CDOM alone would cause a reduction in light at 380 nm to 31 and 9.5% of surface intensities at a depth of 1 and 2 m, respectively. Although CDOM is the dominant UV light-attenuating constituent in these waters, particulates (detritus and phytoplankton pigments) also absorb UV light. With chlorophyll $a$ concentrations of approximately 5 $\mu$g/L, light intensities at a depth of 1 m can be estimated to be 20% of the incident light (C. Stedmon, personal communication, National Environmental Research Institute, Roskilde, Denmark). This most likely explains the low photodegradation of CuPT$_2$ in seawater exposed to sunlight in Isefjorden compared to the total photodegradation observed for samples exposed to direct sunlight outside the laboratory.

Calculated photodegradation half-lives were estimated from both zero-order and first-order degradation reactions, because only two points (0 and 62 min) were obtained from the experiment. By indirect estimation of the photodegradation, Maraldo and Dahllof [1] have found that the photodegradation of CuPT$_2$ and ZnPT$_2$ follows a zero-order reaction. However, the investigation of the photodegradation of another antifouling biocide (dichlofluanid) follows a first-order reaction [13]. Therefore, both zero-order and first-order degradation half-lives were determined in the present experiment. The degradation half-lives were found to be 209 $\pm$ 76 min (zero order) and 122 $\pm$ 25 min (first order) at a depth of 0.5 m; these half-lives are longer than those reported previously [1,2]. For comparison, calculated photodegradation half-lives for a depth of 1 m also were determined, although the concentration found was not statistically different from that of a nonexposed sample. Photodegradation half-lives at 1 m were 738 $\pm$ 70 min (zero order) and 490 $\pm$ 20 min (first order) (Fig. 5, brackets).

A photodegradation half-life of less than 2 min has been obtained for ZnPT$_2$ by direct analysis in artificial seawater placed in full sun outdoors in quartz tubes. When exposed to a xenon light source, degradation half-lives were 17.5 min for ZnPT$_2$ and 29.1 min for CuPT$_2$ exposed in artificial seawater [2]. In a third study, ZnPT$_2$ and CuPT$_2$ were exposed to natural sunlight in natural or sterile seawater in Scott Duran glass bottles. Estimated degradation half-lives are between 7 and 9 min for both compounds [1]. The photodegradation experiments referred to earlier all have in common that they were exposed directly to the light source, being separated only by a glass or quartz container. Hence, the degradation half-lives of the earlier experiments may be valid only in surface waters.

Large-scale experiment

Four 1-L samples for measurements were taken out daily immediately after addition of ZnPT$_2$ and stirring of the approximately 3,000-L enclosure (Fig. 6). Zinc pyrithione was added on days 1, 2, and 3. Only a low concentration of ZnPT$_2$ was measured at day 1; this concentration was not significantly different from zero. On day 2, the concentration increased to 15 $\pm$ 3 nM ($n = 4$), and on day 3, the concentration increased further, to 35 $\pm$ 4 nM ($n = 4$). A stable concentration of CuPT$_2$ was determined on days 1, 2, and 3 at approximately 11 to 12 nM.

After the first addition of ZnPT$_2$ (day 1) (Fig. 6), CuPT$_2$ accounted for approximately 20% of the ZnPT$_2$ concentration. The result was lower compared to the results obtained in the controlled transchelation experiments. The water in Isefjorden
contains more organic matter, both in the form of algae and dissolved organic matter, compared to the 0.2-μN-filtered seawater used for transchelation experiments that originated from the open Skagerak waters. This indicates that organic ligands caused some of the ZnPT₂ removal.

After the second addition of ZnPT₂ (day 2) (Fig. 6), 15 ± 3 nM (n = 4) ZnPT₂ was found, and the same concentration of 12 ± 2 nM (n = 4) CuPT₂ was still present. This suggested that the available copper(II) was recirculated during day 1 and that other potential ligands capable of disrupting ZnPT₂ had been reduced from day 1 to day 2, leading to a significant concentration of ZnPT₂ at day 2. The amount of organic matter, measured as chlorophyll a, also decreased from day 1 to day 2, from 5 to less than 1 μg/L, because of the toxic effect of ZnPT₂ and subsequent sedimentation of dead organic material. The results were further confirmed after the third addition (day 3) (Fig. 6), because the concentration of CuPT₂ also was unchanged on day 3 and the concentration of ZnPT₂ increased further, to 35 ± 4 nM (n = 4).

CONCLUSION

The present study shows that when ZnPT₂ is added to seawater, either through direct addition or when leached from paint, it is partly transchelated into CuPT₂, a more toxic and stable complex. However, the concentration of CuPT₂ formed only accounts for approximately half the nominal ZnPT₂ concentration because of the presence of ions and organic matter in the water. Zinc pyrithione itself is thereby only detectable in natural waters at concentrations sufficiently large to overcome the competition from naturally occurring complexation agents. Furthermore, the potential photodegradation of CuPT₂ in seawater containing high amounts of organic matter is much lower than that shown earlier in laboratory studies. It is thereby necessary to measure concentrations and effects of CuPT₂, as well as those of ZnPT₂, when assessing the effects of use of ZnPT₂-based antifouling paints, even though CuPT₂ is not an active ingredient of the paints.

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