REVIEW ARTICLE

Potential Photochemical Interactions of UV Filter Molecules with Multi-chlorinated Structure of Prymnesins in Harmful Algal Bloom Events

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Abstract: Harmful algae blooms (HABs) involving *Prymnesium parvum* (Golden algae) is a worldwide fish killing event, seriously threatening the aquaculture industry and aquatic ecosystems. HABs frequently occur in natural reservoirs such as natural lakes which receive large numbers of visitors throughout the year. As a result, large amounts of Ultra-Violet (UV) chemical filters (the active ingredient of sunscreen products) are released to the lake due to swimming or sun-bathing, which add synergic environmental stresses on the Lake ecosystem. *Prymnesium parvum* is associated with the production of potent toxins (prymnesins) known for fish kills around the world. The molecular structure of prymnesins possesses both chlorine and nitrogen groups which can actively participate in photochemical reactions with organic and inorganic UV filter molecules. Consequently, reactive oxygen species (ROS) and chlorinated toxins can be potentially formed, leading to fish kill and dangerous biomagnification of reactive molecules in humans through dietary consumption of seafood. In this brief review, we discussed some possible mechanisms for the formation of toxic compounds due to the presence of UV filters and chlorine-containing compounds, using a lake in central Texas as an example. While the properties of various biotoxins released by *P. parvum* in a HAB event have been investigated, this is the first time that the environmental concern of the toxic behavior of reactive UV filters in a HAB event has been highlighted. Significant new insights are needed for the connections between harmful algae blooms and the accumulation of UV filters in water bodies so that appropriate policies can be established to protect the marine environment.

1. INTRODUCTION

Sunscreen and personal care products such as creams, moisturizing lotions and lipsticks contain a diverse group of organic UV filters and inorganic nanoparticles (*i.e.* TiO_2, CeO_2). [1-3]. These UV filters are added to protect human health against the harmful effects of the UV light radiation (320–400 nm for UVA and 290–320 for UVB) [4]. UV filters display many properties of Priority Organic Pollutants (POPs) (*i.e.* high lipophilicity, moieties of aromatic rings, biological recalcitrance [4],). They typically reach the aquatic ecosystem directly from the washing-off of the human skin during swimming and bathing or indirectly via mistreatment of the wastewater [5-9].

Many previous studies reported the toxic behavior of certain UV filters (*i.e.* benzophenone (BP) and ethylhexyl methoxy cinnamate (EHMC)) on aquatic biota by disrupting the estrogenic activity or the reproductive system of fish [10, 11]. Due to their extensive applications and continued release into the aquatic ecosystem, organic UV filters are considered as pseudo-persistent chemical contaminants, and their unknown environmental fate has raised public concerns about their potentially toxic effects [12]

High concentrations (up to 19,000 ng/L) of the UV filters have been reported in surface water and wastewater [13]. For example, high concentration of 4-Methylbenzylidene camphor (4-MBC) has been detected at Norwegian beaches[14] and several other UV filters including 4-methylbenzylidene camphor (4-MBC), 2-ethylhexyl 4-dimethylaminobenzoate (OD-PABA) in the range of 412-933 ng/L were detected in rivers and lakes in South Korea and Spain [10, 15]. Available data on the occurrence of UV filters in the USA is relatively limited and calls for more research. Bratkovics *et al* (2015) found the concentration of octocrylene (OC) was greater than 3700 ng/L and the concentration of oxybenzone was as high as 2200 ng/L in South Carolina's coastal water, in a positive correlation with tourist activities along the state's coastal marine environment [16]. In another study, Sharifan *et al* (2016) estimated that the annual release of UV filters along the coastal lines of Texas (367 miles/590 km) could be over 300 kg year $^{-1}$ on an average basis for the UV filters of OC and EHMC [2]. In a similar study, Poiger *et al* (2004) estimated the release of EHMC upto 224 kg in the Lake Zurich in Swiss during summer time [6].

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Due to their high octanol–water partition coefficients (log K_{ow}), (2 to 15) [17], UV-filters can be accumulated in fish and be biomagnified in humans through the seafood chain [18, 19]. For example, as high as 17 µg/g of OC in zebrafish (*Danio rerio*) [11] and 1800 ng/g of 4-methylbenzylidene camphor (4-MBC) in brown trout (*Salmo trutta fario*) have been reported [12].

High release of these UV filters is attributed to the increasing numbers of tourists in water bodies including beaches, lakes, and springs. Annually, more than 6 million swimmers and beachgoers visit the water bodies of Texas [2]. As a result, significant amounts of organic and inorganic UV filters enter the surface water in the Gulf of Mexico, springs and natural lakes in Texas [2].

Natural water reservoirs in Texas have been threatened by anthropogenic activities due to large petroleum refineries and oil wells (*i.e.* emission and wastewater discharge), massive agricultural activities (*i.e.* pesticide release) and mining extractions (*i.e.* toxic wastewater) as well as natural phenomena involving frequent HABs events. For the first time in 1985, the state of Texas documented the presence of the *p. parvum* (golden alga) bloom along the Pecos River [20].

This phenomenon has affected 33 reservoirs in Texas along major river systems, including the Brazos, Canadian, Rio Grande, Colorado, and Red River [21], and has resulted in the death of more than 27 million fish [22] and caused tens of millions of dollars in damage [23].

The release of UV filters to the brackish and freshwater reservoirs, which are threatened by seasonal HABs, may exacerbate environmental stresses on the ecosystem. However, the potential synergistic effects of UV filters in HABs are presently unknown. The *P. parvum* species is notorious for killing large numbers of fish during HAB period [20, 24]. Despite its harmful biological effects, the characteristics of the toxic component(s) produced by transformation of *P. parvum* have not been distinctively determined [25, 26].

Emerging evidences indicate the possible formation of new toxic compounds through photocatalytic reactions of UV filters in an aqueous system, leading to massive fish kill, serious damage to the molecular structures of essential large molecules such as deoxyribonucleic acid (DNA) or proteins in human bodies [27, 28]. This article highlights the potential toxicity caused by photochemical interactions of UV filters
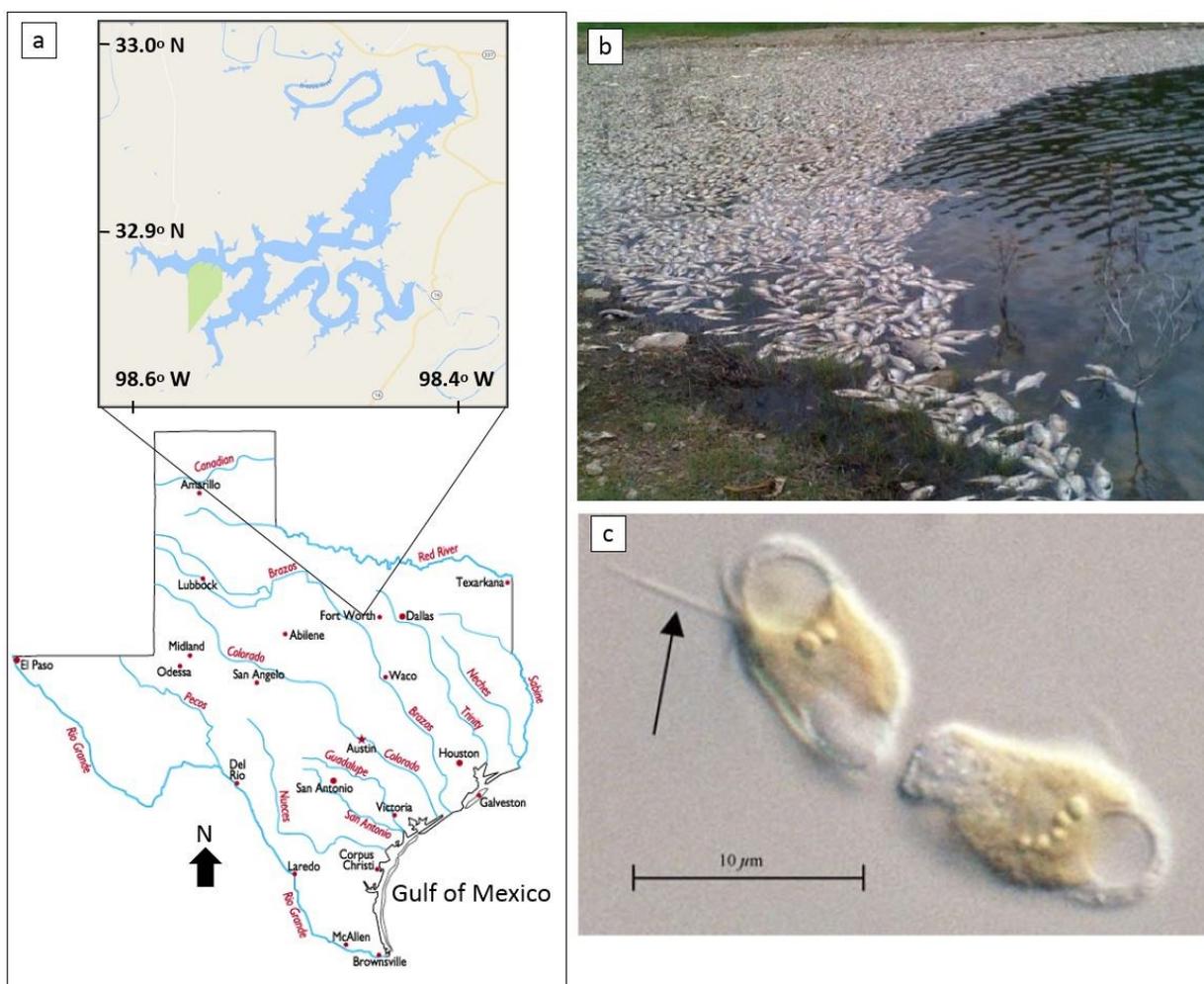

Fig. (1). a) Lake Possum Kingdom, Texas, USA (modified from worldatlas.com), b) a scene of massive dead fish in Possum Kingdom Lake (Source NBCDFW [34]), c) light micrograph of two *P. parvum* cells. (Source Manning &Claire [29]).

in exposure to multi-chlorine-biotoxin of *P. parvum*, and discusses the potential chemical mechanisms for the interactions of these chemicals and shed light on new research needs to protect the coastal and marine ecosystem.

2. AFFECTED AREA

HABs occurrence of *P. parvum* is a common phenomenon in a broad range of water qualities from freshwater of natural lakes to brackish estuarine around the world [29]. Several vectors have been considered as transferring factors of *P. parvum* bloom such as polluted bilge and encystment [29], which could massively aggravate the ecological threats.

To demonstrate the ecological importance of this phenomenon, the Possum Kingdom Lake (PKL) in Texas is used as an example. PKL is a reservoir on the Brazos River in Texas with a capacity of 893 x 106 m^3 and the surface area of 80 km^2 (Fig. **1**) [20]. The maximum and mean depths of the Lake are 60 and 11 m, respectively [30]. There are several reasons to use PKL as an example. Firstly, blooms of *P. parvum* occur regularly in PKL [20, 31, 32]. Secondly, it has easy access from several metropolitan areas in Texas such as the Dallas and Fort Worth metropolitan area. Thirdly, it possesses a long shoreline (500 km [20]), which hosts 19 swimming sites and more than 300 hotel rooms and cabins, indicating the high capacity of PKL in receiving a large number of swimmers and beachgoers throughout a year [33]. Therefore, there is a high potential of synergic effects of chemical interaction of UV filter molecules and long chain molecules of *P. parvum* in PKL that has not been closely examined.

3. TOXICITY APPROACH

P. parvum is a unicellular alga [35]. Its length ranges from 8–15 μm and its width from 4–10 μm and have two flagella (Fig **1**) [29]. *P. parvum* blooms occur when the cell density exceeds 10^7 cells. L^{-1}, which turns the color of the surface water into golden [20, 36]. This class of algae is associated with the production of a variety of sublethal to lethal biotoxins known as prymnesins that represent a combination of potent ichthyotoxic, cytotoxic and hemolytic chemicals [21, 35, 37]. The synthesis of these biotoxic from *P. parvum* and corresponding chemistry behind their toxicity mechanisms is not fully understood [38].

It is postulated that environmental variables such as the water salinity, light intensity, temperature, and pH play a critical role in the toxicity of prymnesins [29]. Also, some evidence has shown the critical role of toxic metabolites (*i.e.* saturated and unsaturated fatty acid amides) during *P. parvum* bloom [39]. Based on the available information in the literature, it is possible that prymnesins themselves may not be the culprit for the toxic effects associated with *P. parvum*. Instead, the secondary metabolites formed during the HAB events may be a more important factor dictating the toxicity of prymnesins. Therefore, the presence of UV filter and their interactions with prymnesins may affect the toxicity levels of prymnesins.

It has been suggested that a mixture of unknown proteolipids structures, waxy lipid molecules, saponins, proteinaceous molecules, and proteophospholipids are linked to defined structure of prymnesins and primarily are responsi-

ble elements for the toxicity of *P. parvum* [25]. The biologically and chemically active functional groups increase the concentrations of the chemically active surface (*i.e.* amin groups with negative charges) in the potential derivatives of the prymnesins [39]. For example, Bertin *et al* (2012) suggested a loss of $H_2C=C-NH_2-OH^+$ due to the McLafferty rearrangement in the transformation of *P. parvum* is associated with forming parent amine $^-NH_3$ in different metabolites [40]. The nitrogen containing groups in each organic molecule originated from prymnesins may serve as a precursor for the formation of chlorine based toxins such as chloropicrin [41-43].

It is well accepted that dissolved natural organic matter and chlorine species exist in water, hence the required precursor for initiating a photochemical reaction with released UV filters is a point of concern. Due to varying photo-instability of organic UV filters, they play a critical role in the formation of a variety of aromatic-based compounds with a potential active surface (positively and negatively charged) as a result of photochemical reactions in exposure to sunlight [44, 45]. For example, the breakdown of organic octocrylene (OC) and p-aminobenzoic acid (PABA), two UV filters in the presence of sunlight can generate reactive oxygen species (ROS) [46-48]. Similarly, some inorganic UV filters (*e.g.* TiO_2 nanoparticles) are the most frequent and photoreactive components in sunscreen formula and can produce a very high concentration of ROS, causing major damage to the DNA structure by modifying the nucleotide bases [49].

The molecular structures of prymnesins consisting of high weight cyclic polyethers prymnesin-1 ($C_{107}H_{154}Cl_3NO_{44}$) or prymnesin-2 ($C_{96}H_{136}Cl_3NO_{35}$) (Fig. **2**), and their metabolites (*i.e.* myristamide) [25, 50] possess both chlorine and nitrogen containing functional groups [25]. The nitrogen-containing groups can potentially react with chemically excited UV filter molecules in exposure to sunlight and form fragile polymer matrices [51]. These phenolic-like structure matrices, depending on the exposure time and water pH, are considered to be oxidative in the presence of nitrogen groups of organic molecules and inorganic nanoparticles such as TiO_2 [52]. This fact could intensify the creation of precursors for the chlorine-based toxins.

The two toxins, prymnesin-1 and prymnesin-2 exhibit extremely potent ichthyotoxicity and hemolytic activity [35]. These characteristics are linked to their gross structural features: chlorine atoms and an amino group, an unbranched single chain of 90 carbons except for a single methyl group, a joined polycyclic ether ring (ABCDE-ring), four separate 1,6-dioxadecalin units (FG-, HI-, JK- and LM-rings), conjugated double and triple bonds, and glycosidic [35]. The composition of this complex form of the prymnesin indicates a high tendency to form a variety of saturated and unsaturated derivatives [53]. Due to the moiety head ending of chlorine, the presence of amino groups, and the variation in the degrees of chlorination in the ladder structure of the prymnesin [54], the probability of the reactions with excited molecules of organic UV filters may increase [45]. There is also a high chance of enhancement of photochemical transformations by inorganic UV filters (*e.g.* TiO_2) [49]. These chemical reactions can be critical in the toxic behavior of prymnesin, which has not been closely examined in ecotoxi-
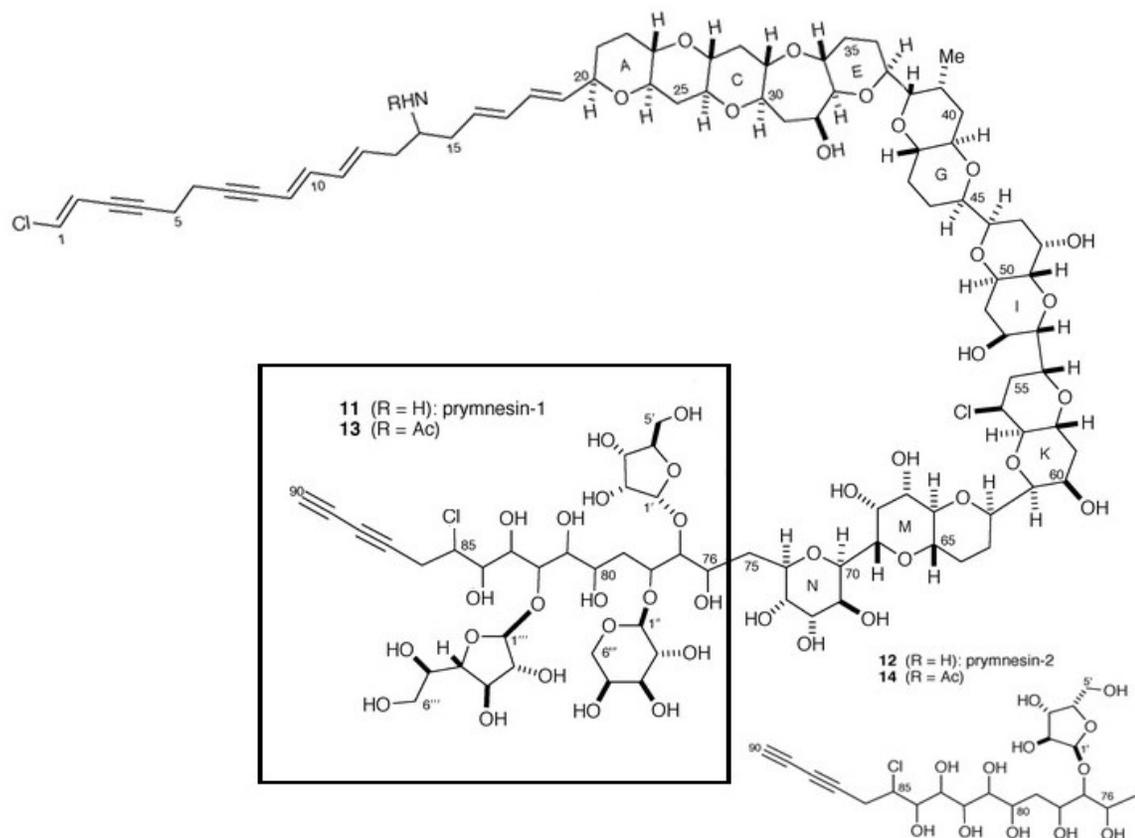
Fig. (2). Putative stereochemistry of the toxic polyketides, prymnesin-1, and prymnesin-2 are modified from Murata *et al* (2000) [50].

cological studies. Fig. **3** illustrate this mechanism conceptually.

Due to the high concentrations of prymnesin with chlorinated structure during the killing events, highly reactive chlorine-containing species may exist in water. The negative charges on mineral surfaces in marine biotic and abiotic composition supports the notion that high concentrations of active chlorine species (ACS) including chlorine-containing molecules in different oxidation states (*i.e.*chlorine atoms (Cl•), chlorine molecules (Cl_2), dichloro radical anions ($Cl_2•^−$), hypochlorous acid (HOCl) and hypochlorite anions ($ClO^−$)), may exist in water, possibly formed through the oxidation of chloride anion $Cl^−$ [55] that could potentially attack the available positive functional groups in the water and form a variety of multi chlorinated-compounds.

A series of abiotic and biotic reactions in marine sediment may lead to the chlorination of organic compounds by inorganic chlorines such as high molecular weight Cl_{org} (chlorohumus, chlorinated humic- and fulvic acids) and naturally occurring low-molecular weight Cl_{org} (aromatic Cl_{org} (chlorophenol analogs) and aliphatic Cl_{org}) [56]. Subsequently, chlorinated compounds in water potentially participate a photochemical interaction with organic UV filters and create toxic or endocrine disrupting compounds [45]. For example, Chai *et al* (2017) identified the chlorinated structure of octyl dimethyl-p-aminobenzoate (ODPABA) in exposure to chlorine as transformation by-

products, which can disrupt the activity of human estrogen receptor α (ERα) [57]. Also, scientists suggested that the reaction of ODPABA and octyl-p-methoxycinnamate (OMC) with hypochlorite leads to the formation of mutagenic and toxic chemicals in exposure to sunlight [45, 58]. Researchers showed benzophenone-type UV filters (BPs) can generate toxic transformation products in reaction with the residue of chlorine in water [59, 60]. During the biochemical transformation of prymnesin as effective natural organic matter (NOM), a direct correlation between UV absorption and activation of chlorine-based toxins in the presence of chlorinated molecules possibly exist, which potentially leads to the formation of chlorine based toxins such as trihalomethanes (THMs) and haloacetic acids (HAAs) [42, 61-63].

4. ENVIRONMENTAL VARIABLES

Environmental factors are site specific and in a HAB event, they can affect the levels of toxicity and distribution of different biotoxins associated with prymnesins. Therefore, in this section, the roles of main environmental factors affecting the toxicity of prymnesins (UV Filter, nutrient availability, light, temperature, pH) are briefly discussed below.

5. UV FILTERS

Organic UV-filters comprise a heterogeneous group of molecules characterized by conjugated aromatic moiety, which can absorb UV-A and UV-B radiation[45]. The reported concentration of this class of chemicals is proportion-
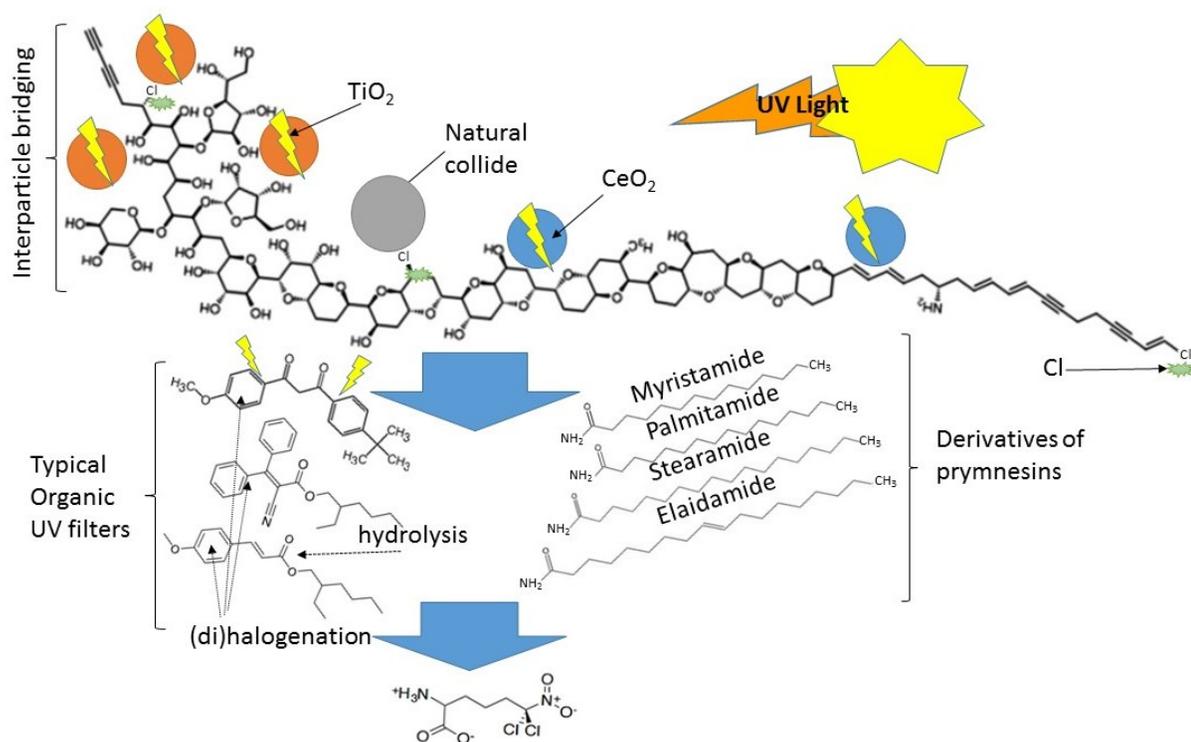
Fig. (3). The proposed mechanisms of toxicity on the reaction of ENPs and organic UV filters with long chain molecule of prymnesin. The derivatives of prymnesins were modified from Bertin *et al* (2012) and the long molecular chains of prymnesin were taken from (Henrikson *et al* (2010). The possible halogenations of the proposed UV filters were suggested by Lambropoulou*et al* (2014) [64] and the compounds responsible for toxicity were extracted from McCurry *et al* (2016) [41].

al to numbers of visitors to natural reservoirs [2]. The photo-instability of the organic and inorganic UV filters vary with the specific conditions in the aquatic environment, meaning that UV filters exhibit different behaviors in different water sources [45]. For example, TiO_2 is an engineered nano-material, which not only formulated in sunscreen compositions but also has been frequently reported in the discharge of various industries such as textiles [65]. It is believed to actively aggregate with NOM including existing alga in a HAB event [65]. This may provoke the photocatalytic characteristics of TiO_2 in such a reaction which result in the creation of chlorinated toxins. This fact was previously described in Fig. **3**. Table **1** shows the physicochemical characteristics of four widely used organic UV filters. The chemical structures of these compounds mostly contain one or two aromatic rings and corresponding aliphatic chains, which exhibit various unsaturation levels [17].

6. NUTRIENT AVAILABILITY

The nutrient availability was demonstrated as a substantial factor affecting the growth rate of *P. parvum* in a HAB event, which greatly affects the toxin formations and release by this organism [29]. Agricultural effluents are a rich source of nitrogen (*i.e.* nitrate or nitrite) and phosphorus (phosphate) which was suggested as a eutrophication vector that significantly increases the *P. parvum* populations [29, 66].

In addition, mistreatment of municipal wastewater that discharges to the receiving waters may contain a

considerable amount of nutrients as well as high concentration of UV filters. In some cases, the average removal efficiency of the wastewater treatment plant (WWTP) for certain UV filters (*i.e.* 2-ethylhexyl salicylate (EHS), BP3, EHMC) has been reported from 40 to 60 % [10]. For example, Krzeminski *et al* (2017) found the concentration levels of BP3 and OC as high as 1099 and 763 ng/L in a WWTP effluent, respectively [67]. In another study, the total concentration of UV filters was reported to be upto 850 ng/Lin the effluent of WWTP [10].
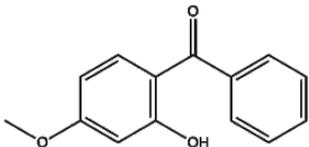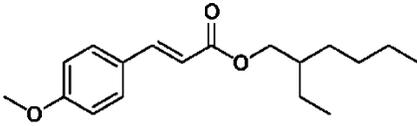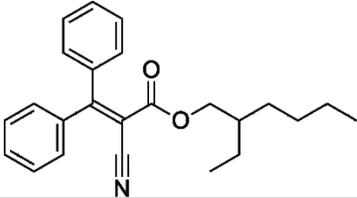
7. LIGHT

The light intensity has been suggested as a factor affecting the toxicity levels of prymnesin [29]. Some research documented the positive correlation between the properties of light (*i.e.* intensity) and the growth rate of *P. parvum* as well as the corresponding ichthyotoxicity levels [68, 69]. Similarly, the light factor is strongly correlated with the photo-instability of UV filters in aqueous systems [45, 70, 71]. Therefore, it is possible that light might be a stimulating factor in the photochemical reaction of UV filters with chemical metabolites of prymnesin.

8. TEMPERATURE

As a eurythermal species, *P. parvum* can tolerate a wide range of temperatures [29]. This range of temperature is believed to be concomitant with the release of UV filters to natural water bodies due to high water recreational activities.

Table 1.   **Chemical name, water solubility, Log K_{ow} and molecular structures of typical UV filters [1].**

Name	Log K_{ow}**	Solubility** (at 25 °C) (g l^{-1})	molecular weight* (g/mol)	Structure**
Benzophenone-1 (BP1)	3.17	0.39	182	
Ethylhexyl methoxycinnamate (EHMC)	5.8	0.15	290	
Octocrylene (OC)	7.3	0.02	361	
Ethylhexyl-dimethyl-PABA (OD-PABA)	6.15	4.7×10^{-3}	277	

* *Source*: https://pubchem.ncbi.nlm.nih.gov.
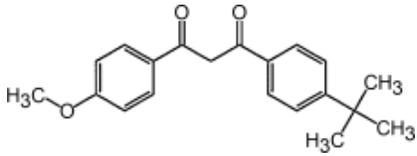
** Source: Molins-Delgado, D., *et al* (2016) [1]

This co-occurrence was consistent with a summer bloom reported in Finland where the temperature is at its highest level [72]. A positive correlation between kinetic chemical reaction and presence of such natural organic matter and concentration of active ingredient in sunscreen products exist, which potentially leads to the creation of chlorinated toxins [61-63, 73]. This fact strengths the hypothesis of the critical role of temperature in photochemical reactions of chlorine and nitrogen active surface of prymnesin derivatives in water.

9. PH

The toxicity of prymnesin substantially varies in different pH. For example, low pH in the aqueous phase is associated with hemolysis and high pH with ichthyotoxicity activities [29]. It means that at different pH different metabolites may form and consequently, different reactions can take place. Due to a variety of UV filters and their site-specific conditions, the effects of pH on this class of chemical are not well understood.

In addition to the aforementioned factors, the increase of NO_3^- and ClO_4^- in water are the additional sources of chemically reactant components [74], which may actively react with existing UV filters. Also, ClO_4^- may be formed through an oxidative reaction of chloro-oxyanions and UV-mediated photo-oxidation, which may behave as a chemically reactive compound in such water [74] where has a wide exposure to UV radiation.

This study clearly demonstrates that molecular activation and synthesis of chlorin-based toxins in response to UV filters are highly likely, and the complicated processes involved in these chemical transformations most likely differ with the surrounding environmental conditions. This process can be more complicated and potentially synergistic in response to corresponding environmental factors (*i.e* a combination of hot temperature, intense sunlight and acidic pH water). These environmental differences may explain the different observations concerning the toxicity of prymnesin under different environmental conditions.

Due to these deleterious environmental impacts, application of sunscreen products is currently prohibited in a few popular tourist coastal areas around the world such as marine Ecoparks in Mexico [75, 76], Japan [77] and in some semi-enclosed transitional systems [75].

10. CONCLUSION

An understanding of the toxic behavior of UV filters is critically important in the protection of surface water. This review revealed that aquatic lives in aquatic ecosystems such as PKL can be critically threatened through different confounding factors. The photochemical reaction of released UV filters (organic and inorganic) with transformation products of prymnesins (containing nitrogen or chlorine group) are possibly associated with the production of lethal biotoxins in lakes around the globe. This phenomenon affects the ecolog-

ical performance of many aquatic ecosystems and synergistically increases the toxicity to fish. This emerging environmental concern needs to be investigated.

Information on the concentration levels of UV filters is geographically limited mostly to some countries in Asia and Europe. Therefore, there is a need to advance and deepen studies in different regions of the USA to better understand the magnitude and environmental behavior of these emerging contaminants. Research on this issue will direct environmental policies towards protection of the reservoirs such as zoning of aquatic areas.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable.

HUMAN AND ANIMAL RIGHTS

No Animals/Humans were used for studies that are base of this research.

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The author (editor) declares no conflict of interest, financial or otherwise.

REFERENCES

[1]   D. Molins-Delgado, P. Gago-Ferrero, M.S. Díaz-Cruz, D. Barceló, Single and joint ecotoxicity data estimation of organic UV filters and nanomaterials toward selected aquatic organisms. Urban groundwater risk assessment, Environmental Research 145 (2016) 126-134.

[2]   H. Sharifan, D. Klein, A. Morse, UV Filters are an Environmental Threat in the Gulf of Mexico: A Case Study of Texas Coastal Zones, Oceanologia 58(4) (2016).

[3]   C. Karunakaran, P. Navamani, P. Gomathisankar, Particulate sol–gel synthesis and optical and electrical properties of CeO2/TiO2 nanocomposite, Journal of the Iranian Chemical Society 12(1) (2015) 75-80.

[4]   M. Vila, M. Celeiro, J.P. Lamas, C. Garcia-Jares, T. Dagnac, M. Llompart, Simultaneous in-vial acetylation solid-phase microextraction followed by gas chromatography tandem mass spectrometry for the analysis of multiclass organic UV filters in water, Journal of Hazardous Materials 323, Part A (2017) 45-55.

[5]   C.-B. Park, J. Jang, S. Kim, Y.J. Kim, Single- and mixture toxicity of three organic UV-filters, ethylhexyl methoxycinnamate, octocrylene, and avobenzone on Daphnia magna, Ecotoxicology and Environmental Safety 137 (2017) 57-63.

[6]   T. Poiger, H.R. Buser, M.E. Balmer, P.A. Bergqvist, M.D. Muller, Occurrence of UV filter compounds from sunscreens in surface waters: regional mass balance in two Swiss lakes, Chemosphere 55(7) (2004) 951-63.

[7]   D.L. Giokas, A. Salvador, A. Chisvert, UV filters: From sunscreens to human body and the environment, Trac-Trends in Analytical Chememistry 26(5) (2007) 360-374.

[8]   C. Plagellat, T. Kupper, R. Furrer, L.F. de Alencastro, D. Grandjean, J. Tarradellas, Concentrations and specific loads of UV filters in sewage sludge originating from a monitoring network in Switzerland, Chemosphere 62(6) (2006) 915-25.

[9]   W.H. Li, Y.M. Ma, C.S. Guo, W. Hu, K.M. Liu, Y.Q. Wang, T. Zhu, Occurrence and behavior of four of the most used sunscreen UV filters in a wastewater reclamation plant, Water Research 41(15) (2007) 3506-3512.

[10]   K.I. Ekpeghere, U.-J. Kim, S.-H. O, H.-Y. Kim, J.-E. Oh, Distribution and seasonal occurrence of UV filters in rivers and wastewater treatment plants in Korea, Science of The Total Environment 542, Part A (2016) 121-128.

[11]   N. Blüthgen, N. Meili, G. Chew, A. Odermatt, K. Fent, Accumulation and effects of the UV-filter octocrylene in adult and embryonic zebrafish (Danio rerio), Science of The Total Environment 476–477 (2014) 207-217.

[12]   M.M.P. Tsui, H.W. Leung, T.-C. Wai, N. Yamashita, S. Taniyasu, W. Liu, P.K.S. Lam, M.B. Murphy, Occurrence, distribution and ecological risk assessment of multiple classes of UV filters in surface waters from different countries, Water Research 67 (2014) 55-65.

[13]   P. Gago-Ferrero, M.S. Díaz-Cruz, D. Barceló, UV filters bioaccumulation in fish from Iberian river basins, Science of The Total Environment 518–519 (2015) 518-525.

[14]   K. Fent, A. Zenker, M. Rapp, Widespread occurrence of estrogenic UV-filters in aquatic ecosystems in Switzerland, Environmental Pollution 158(5) (2010) 1817-1824.

[15]   I. Ozáez, M. Aquilino, G. Morcillo, J.-L. Martínez-Guitarte, UV filters induce transcriptional changes of different hormonal receptors in Chironomus riparius embryos and larvae, Environmental Pollution 214 (2016) 239-247.

[16]   S. Bratkovics, E. Wirth, Y. Sapozhnikova, P. Pennington, D. Sanger, Baseline monitoring of organic sunscreen compounds along South Carolina's coastal marine environment, Marine Pollution Bulletin 101(1) (2015) 370-377.

[17]   M. Silvia Díaz-Cruz, M. Llorca, D. Barceló, D. Barceló, Organic UV filters and their photodegradates, metabolites and disinfection by-products in the aquatic environment, Trac-Trends in Analytical Chememistry 27(10) (2008) 873-887.

[18]   S. Kim, K. Choi, Occurrences, toxicities, and ecological risks of benzophenone-3, a common component of organic sunscreen products: A mini-review, Environment International 70 (2014) 143-157.

[19]   Ż. Broniowska, B. Pomierny, I. Smaga, M. Filip, B. Budziszewska, The effect of UV-filters on the viability of neuroblastoma (SH-SY5Y) cell line, NeuroToxicology (2016).

[20]   D.L. Roelke, R.M. Errera, R. Kiesling, B.W. Brooks, J.P. Grover, L. Schwierzke, F. Ureña-Boeck, J. Baker, J.L. Pinckney, Effects of nutrient enrichment on Prymnesium parvum population dynamics and toxicity: results from field experiments, Lake Possum Kingdom, USA, Aquatic Microbial Ecology 46(2) (2007) 125.

[21]   R. Sallenave, Toxic golden algae (Prymnesium parvum), in: S.U.o.N. Mexico (Ed.) Consumer and Environmental Sciences, Department of Extension Animal Sciences and Natural Resources, New Mexico State University, Las Cruces, 2010, p. 8.

[22]   D. Sager, L. Fries, L. Singhurst, G. Southard, Guidelines for golden alga Prymnesium parvum management options for ponds and small reservoirs (public waters) in Texas, Texas Parks and Wildlife Department, PWD RP T3200–1404 (1/2007), Austin (2007).

[23]   B.W. Brooks, J.P. Grover, D.L. Roelke, Prymnesium parvum: an emerging threat to inland waters, Environmental Toxicology and Chemistry 30(9) (2011) 1955-1964.

[24]   C.-O. Oh, R.B. Ditton, A time series approach to estimating the economic impacts of exogenous events on a local economy, (2007). In: Burns, R.; Robinson, K., comps. Proceedings of the 2006 Northeastern Recreation Research Symposium; 2006 April 9-11; Bolton Landing, NY. Gen. Tech. Rep. NRS-P-14. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 240-247.

[25]   J.C. Henrikson, M.S. Gharfeh, A.C. Easton, J.D. Easton, K.L. Glenn, M. Shadfan, S.L. Mooberry, K.D. Hambright, R.H. Cichewicz, Reassessing the ichthyotoxin profile of cultured Prymnesium parvum (golden algae) and comparing it to samples collected from recent freshwater bloom and fish kill events in North America, Toxicon 55(7) (2010) 1396-1404.

[26]   E. Mariussen, G.N. Nelson, F. Fonnum, A toxic extract of the marine phytoflagellate Prymnesium parvum induces calcium-dependent release of glutamate from rat brain synaptosomes, Journal of Toxicology and Environmental Health, Part A 68(1) (2005) 67-79.

[27]   S. Ramos, V. Homem, A. Alves, L. Santos, A review of organic UV-filters in wastewater treatment plants, Environment International 86 (2016) 24-44.

[28]   N. Serpone, D. Dondi, A. Albini, Inorganic and organic UV filters: Their role and efficacy in sunscreens and suncare products, Inorganica Chimica Acta 360(3) (2007) 794-802.

[29]   S.R. Manning, J.W. La Claire, Prymnesins: toxic metabolites of the golden alga, Prymnesium parvum Carter (Haptophyta), Marine drugs 8(3) (2010) 678-704.

[30]   R.M. Errera, D.L. Roelke, R.L. Kiesling, B.W. Brooks, J.P. Grover, L. Schwierzke, F. Ureña-Boeck, J.W. Baker, J.L. Pinckney, Effect of imbalanced nutrients and immigration on Prymnesium parvum community dominance and toxicity: results from in-lake microcosm experiments, Aquatic Microbial Ecology 52(1) (2008) 33.

[31]   C. Oh, R. Ditton, Estimating the economic impacts of golden alga (Prymnesium parvum) on recreational fishing at Possum Kingdom Lake (Texas), Report of Texas A&M University to Texas Parks and Wildlife Department, PWD RP T3200–1168 (10/30/2005), Austin (2005).

[32]   G.M. Southard, L.T. Fries, A. Barkoh, Prymnesium parvum: The Texas Experience1, Wiley Online Library, 46(1) (2010) 14-23.

[33]   TPWD, Possum Kingdom State Park, 2016. http://tpwd.texas.gov/state-parks/possum-kingdom. (Accessed 03/16/2016 2016), https://www.possumkingdomlake.com (Accessed 03/09/2017).

[34]   J. Ault, North Texas Lake Recovering Since 2010 Golden Alga Fish Kill, 2015. http://www.nbcdfw.com/news/local/North-Texas-Lake-Recovering-Since-2010-Golden-Alga-Fish-Kill-298327701.html. (Accessed 03/17/2016 2016).

[35]   M. Sasaki, N. Takeda, H. Fuwa, R. Watanabe, M. Satake, Y. Oshima, Synthesis of the JK/LM-ring model of prymnesins, potent hemolytic and ichthyotoxic polycyclic ethers isolated from the red tide alga Prymnesium parvum: confirmation of the relative configuration of the K/L-ring juncture, Tetrahedron Letters 47(32) (2006) 5687-5691.

[36]   D.L. Roelke, G.M. Gable, T.W. Valenti, J.P. Grover, B.W. Brooks, J.L. Pinckney, Hydraulic flushing as a Prymnesium parvum bloom-terminating mechanism in a subtropical lake, Harmful Algae 9(3) (2010) 323-332.

[37]   V.M. Lundgren, D.L. Roelke, B.W. Brooks, E. Granéli, S.L. Davis, T. Baty, W.C. Scott, Prymnesium parvum invasion success into coastal bays of the Gulf of Mexico: Galveston Bay case study, Harmful Algae 43 (2015) 31-45.

[38]   D.L. Roelke, A. Barkoh, B.W. Brooks, J.P. Grover, K.D. Hambright, J.W. LaClaire II, P.D. Moeller, R. Patino, A chronicle of a killer alga in the west: ecology, assessment, and management of Prymnesium parvum blooms, Hydrobiologia 764(1) (2016) 29-50.

[39]   M.J. Bertin, D.C. Voronca, R.W. Chapman, P.D.R. Moeller, The effect of pH on the toxicity of fatty acids and fatty acid amides to rainbow trout gill cells, Aquatic Toxicology 146 (2014) 1-11.

[40]   M.J. Bertin, P.V. Zimba, K.R. Beauchesne, K.M. Huncik, P.D.R. Moeller, Identification of toxic fatty acid amides isolated from the harmful alga Prymnesium parvum carter, Harmful Algae 20 (2012) 111-116.

[41]   D.L. McCurry, A. Quay, W.A. Mitch, Ozone Promotes Chloropicrin Formation by Oxidizing Amines to Nitro Compounds, Environmental science & technology 50(3) (2016) 1209-1217.

[42]   X. Yang, C. Shang, P. Westerhoff, Factors affecting formation of haloacetonitriles, haloketones, chloropicrin and cyanogen halides during chloramination, Water Research 41(6) (2007) 1193-1200.

[43]   S.W. Krasner, W.A. Mitch, D.L. McCurry, D. Hanigan, P. Westerhoff, Formation, precursors, control, and occurrence of nitrosamines in drinking water: a review, Water Research 47(13) (2013) 4433-4450.

[44]   C. Puglia, E. Damiani, A. Offerta, L. Rizza, G.G. Tirendi, M.S. Tarico, S. Curreri, F. Bonina, R.E. Perrotta, Evaluation of nanostructured lipid carriers (NLC) and nanoemulsions as carriers for UV-filters: Characterization, in vitro penetration and photostability studies, European Journal of Pharmaceutical Sciences 51 (2014) 211-217.

[45]   H. Sharifan, D. Klein, A.N. Morse, UV filters interaction in the chlorinated swimming pool, a new challenge for urbanization, a need for community scale investigations, Environmental Research 148 (2016) 273-6.

[46]   K.M. Hanson, E. Gratton, C.J. Bardeen, Sunscreen enhancement of UV-induced reactive oxygen species in the skin, Free Radical Biology and Medicine 41(8) (2006) 1205-1212.

[47]   A. Cantrell, D.J. McGarvey, T.G. Truscott, Photochemical and photophysical properties of sunscreens, Comprehensive Series in Photosciences 3 (2001) 495-519.

[48]   M. Sendra, D. Sánchez-Quiles, J. Blasco, I. Moreno-Garrido, L.M. Lubián, S. Pérez-García, A. Tovar-Sánchez, Effects of TiO2 nanoparticles and sunscreens on coastal marine microalgae: Ultraviolet radiation is key variable for toxicity assessment, Environment International 98 (2017) 62-68.

[49]   A. Ivask, O. Bondarenko, N. Jepihhina, A. Kahru, Profiling of the reactive oxygen species-related ecotoxicity of CuO, ZnO, TiO2, silver and fullerene nanoparticles using a set of recombinant luminescent Escherichia coli strains: differentiating the impact of particles and solubilised metals, Analytical and Bioanalytical Chemistry 398(2) (2010) 701-716.

[50]   M. Murata, T. Yasumoto, The structure elucidation and biological activities of high molecular weight algal toxins: maitotoxin, prymnesins and zooxanthellatoxins, Natural product reports 17(3) (2000) 293-314.

[51]   L. Ávár, K. Bechtold, Studies on the interaction of photoreactive light stabilizers and UV-absorbers, Progress in Organic Coatings 35(1–4) (1999) 11-17.

[52]   H. Yee Low, H. Ishida, Structural effects of phenols on the thermal and thermo-oxidative degradation of polybenzoxazines, Polymer 40(15) (1999) 4365-4376.

[53]   B.M. Trost, Y.H. Rhee, A flexible approach toward trans-fused polycyclic tetrahydropyrans. A synthesis of prymnesin and yessotoxin units, Organic letters 6(23) (2004) 4311-4314.

[54]   S.A. Rasmussen, S. Meier, N.G. Andersen, H.E. Blossom, J.Ø. Duus, K.F. Nielsen, P.J. Hansen, T.O. Larsen, Chemodiversity of Ladder-Frame Prymnesin Polyethers in Prymnesium parvum, Journal of Natural Products 79(9) (2016) 2250-2256.

[55]   O.P. Mishra, A.V. Popov, R.A. Pietrofesa, M. Christofidou-Solomidou, Gamma-irradiation produces active chlorine species (ACS) in physiological solutions: Secoisolariciresinol diglucoside (SDG) scavenges ACS - A novel mechanism of DNA radioprotection, Biochimica et Biophysica Acta (BBA) - General Subjects 1860(9) (2016) 1884-1897.

[56]   S.T. Forczek, M. Pavlík, J. Holík, L. Rederer, M. Ferenčík, The natural chlorine cycle – Formation of the carcinogenic and greenhouse gas compound chloroform in drinking water reservoirs, Chemosphere 157 (2016) 190-199.

[57]   Q. Chai, S. Zhang, X. Wang, H. Yang, Y.F. Xie, Effect of bromide on the transformation and genotoxicity of octyl-dimethyl-p-aminobenzoic acid during chlorination, Journal of Hazardous Materials 324, Part B (2017) 626-633.

[58]   M. Nakajima, T. Kawakami, T. Niino, Y. Takahashi, S. Onodera, Aquatic fate of sunscreen agents octyl-4-methoxycinnamate and octyl-4-dimethylaminobenzoate in model swimming pools and the mutagenic assays of their chlorination byproducts, Journal of Health Science 55(3) (2009) 363-372.

[59]   J. Li, L.-y. Ma, L. Xu, Transformation of benzophenone-type UV filters by chlorine: Kinetics, products identification and toxicity assessments, Journal of Hazardous Materials 311 (2016) 263-272.

[60]   W. Liu, D. Wei, Q. Liu, Y. Du, Transformation pathways and acute toxicity variation of 4-hydroxyl benzophenone in chlorination disinfection process, Chemosphere 154 (2016) 491-498.

[61]   A. Eaton, Measuring Uv-Absorbing Organics - a Standard Method, Journal of American Water Works Association 87(2) (1995) 86-90.

[62]   J. Xiao, Q. Yue, B. Gao, Y. Sun, J. Kong, Y. Gao, Q. Li, Y. Wang, Performance of activated carbon/nanoscale zero-valent iron for removal of trihalomethanes (THMs) at infinitesimal concentration in drinking water, Chemical Engineering Journal 253 (2014) 63-72.

[63]   Q. Han, H. Yan, F. Zhang, N. Xue, Y. Wang, Y. Chu, B. Gao, Trihalomethanes (THMs) precursor fractions removal by coagulation and adsorption for bio-treated municipal wastewater: Molecular weight, hydrophobicity/hydrophily and fluorescence, Journal of Hazardous Materials 297 (2015) 119-126.

[64]   D.A. Lambropoulou, L.M. Nollet, Transformation products of emerging contaminants in the environment: Analysis, processes, occurrence, effects and risks, John Wiley & Sons 2014.

[65]   A.P. Gondikas, F.v.d. Kammer, R.B. Reed, S. Wagner, J.F. Ranville, T. Hofmann, Release of TiO2 nanoparticles from sunscreens into surface waters: a one-year survey at the old Danube recreational Lake, Environmental science & technology 48(10) (2014) 5415-5422.

[66]   A.M. Michalak, E.J. Anderson, D. Beletsky, S. Boland, N.S. Bosch, T.B. Bridgeman, J.D. Chaffin, K. Cho, R. Confesor, I. Daloğlu, Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions, Proceedings of the National Academy of Sciences 110(16) (2013) 6448-6452.

[67]   P. Krzeminski, C. Schwermer, A. Wennberg, K. Langford, C. Vogelsang, Occurrence of UV filters, fragrances and organophosphate flame retardants in municipal WWTP effluents and their removal during membrane post-treatment, Journal of Hazardous Materials 323, Part A (2017) 166-176.

[68]   K. Reich, I. Parnas, Effect of illumination on ichthyotoxin in an axenic culture of Prymnesium parvum Carter, The Journal of Protozoology 9(1) (1962) 38-40.

[69]   A. Larsen, S. Bryant, U. Båmstedt, Growth rate and toxicity of Prymnesium parvum and Prymnesium patelliferum (Haptophyta) in response to changes in salinity, light and temperature, Sarsia 83(5) (1998) 409-418.

[70]   T. Leijtens, G.E. Eperon, S. Pathak, A. Abate, M.M. Lee, H.J. Snaith, Overcoming ultraviolet light instability of sensitized TiO2 with meso-superstructured organometal tri-halide perovskite solar cells, Nature communications 4 (2013).

[71]   J.F. Nash, P.R. Tanner, Relevance of UV filter/sunscreen product photostability to human safety, Photodermatology, photoimmunology & photomedicine 30(2-3) (2014) 88-95.

[72]   T. Lindholm, P. Öhman, K. Kurki-Helasmo, B. Kincaid, J. Meriluoto, Toxic algae and fish mortality in a brackish-water lake in Åland, SW Finland, Hydrobiologia 397(0) (1999) 109-120.

[73]   M. Zare Afifi, E.R. Blatchley Iii, Effects of UV-based treatment on volatile disinfection byproducts in a chlorinated, indoor swimming pool, Water Research 105 (2016) 167-177.

[74]   W.A. Jackson, J. Böhlke, B.J. Andraski, L. Fahlquist, L. Bexfield, F.D. Eckardt, J.B. Gates, A.F. Davila, C.P. McKay, B. Rao, Global patterns and environmental controls of perchlorate and nitrate co-occurrence in arid and semi-arid environments, Geochimica et Cosmochimica Acta 164 (2015) 502-522.

[75]   R. Danovaro, L. Bongiorni, C. Corinaldesi, D. Giovannelli, E. Damiani, P. Astolfi, L. Greci, A. Pusceddu, Sunscreens cause coral bleaching by promoting viral infections, Environmental Health Perspectives 116(4) (2008) 441-7.

[76]   D. Gregg, R. Greiner, The direct impact of recreation on water quality in the Great Barrier Reef Marine Park, Great Barrier Reef Marine Park Authority 2008.

[77]   H. Nakata, S. Murata, J. Filatreau, Occurrence and concentrations of benzotriazole UV stabilizers in marine organisms and sediments from the Ariake Sea, Japan, Environmental science & technology 43(18) (2009) 6920-6926.