

Review

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Posted Date: 15 August 2025

doi: 10.20944/preprints202508.0839.v1

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Review

Artificial Sweeteners in Aquatic Ecosystems: Occurrence, Sources and Effects

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Abstract

The growing consumption of synthetically manufactured sugar substitutes, coupled with the lack of adequate national and international regulations, has led to the presence of various compounds, in different environmental matrices. Within this group, artificial sweeteners, despite their prevalence in mass consumption products, are one of the least studied pollutants. The high consumption of artificial sweeteners, together with the low efficiency of wastewater treatment plants, facilitates their detection in various aquatic ecosystems at concentrations ranging from ng to $\mu\text{g L}^{-1}$. These concentrations have shown to generate adverse effects on the organisms that inhabit these aquatic ecosystems. The main objective of this review is to provide updated information on the global consumption of sweeteners, reported concentrations in various environmental matrices, and, in particular, the effects of exposure to these compounds on aquatic organisms.

Keywords: artificial sweeteners; aquatic ecosystems; river; marine ecosystems; waste waters

1. Introduction

High-intensity artificial sweeteners, synthetically manufactured sugar substitutes, were introduced to the market in 1983 [1] and their production and consumption have continued to increase. The most widely used sweeteners worldwide are acesulfame-k, aspartame, cyclamate, neotame, saccharin, and sucralose, which are mainly used in beverages and foods, contributing minimal or no calories [2]. Their use is aimed at reducing calorie intake in people with diabetes, athletes, and those seeking to control their weight [3–5]. These compounds, which have been introduced into the environment for several years, have acquired the status of emerging contaminants as their detection in the environment has only been possible thanks to advances in highly sensitive analytical techniques [6,7]

These compounds, like other emerging contaminants, are approved for use worldwide. Despite being recognized as safe for human consumption within the recommended average acceptable daily intake (ADI), concerns have grown about their persistence in aquatic systems and their potential chronic effects in non-target organisms and, as an example, cyclamate is restricted in certain countries, such as the United States and Japan [8]. Although there are regulatory agencies around the world, such as the European Food Safety Authority (EFSA), the US Food and Drug Administration (FDA), and the National Institute for Food and Drug Surveillance (INVIMA) in Colombia, the great use of such compounds lies in the excessive consumption of the population, which has increased over time, driven by factors such as disease, trends, and social stereotypes. As an example, global consumption

in 2017 was estimated at approximately 159,000 metric tons, with the highest levels of consumption reported in Asia, Oceania, and the United States [9]

The high consumption of artificial sweeteners, coupled with their low absorption rate in the human body, favors their release into wastewater [9]. Due to the limited efficiency of conventional treatment systems, these compounds are not completely eliminated and are consequently discharged into different environmental matrices in concentrations ranging from ng to $\mu\text{g L}^{-1}$ [10]. While some sweeteners such as aspartame degrade relatively quickly [11] others, such as sucralose and acesulfame-K, resist purification processes and remain in aquatic ecosystems resulting in a high persistence [12,13].

The presence of these compounds in aquatic ecosystems could pose a risk to the organisms that inhabit them. Although there are several studies that demonstrate the effects of exposure to these compounds, most focus on acute effects at high concentrations (mg L^{-1}) [14,15], which probably do not reflect their real effects on the environment. As a result, sublethal effects originating from molecular alterations derived from chronic exposure to environmentally relevant concentrations are often unnoticed.

The main objective of this review is to provide updated information on the global consumption of sweeteners, reported concentrations in various environmental matrices and, in particular, the effects of exposure to these compounds on aquatic organisms reported to date.

2. Bibliographic Search

The literature search was conducted using online scientific databases such as Google Scholar, PubMed, Scopus, and ScienceDirect, using keywords such as artificial sweeteners, aquatic ecosystems, river, marine ecosystems, and waste waters. Publications between 1985 and 2025 were considered; however, only 7 articles prior to 2010 were selected, with the aim of contextualizing the historical evolution of the study of these compounds. Most of the works analyzed correspond to the period 2015–2025 and were included according to the following criteria: (I) evaluation of the use and consumption of artificial sweeteners in different countries; (II) analysis of the routes of entry of these compounds into the environment; (III) identification of limitations in wastewater treatment plants; (IV) reports of concentrations in aquatic ecosystems; and (V) use of aquatic organisms in exposure tests. In total, 85 articles were selected that met at least one of these criteria.

3. Use and Consumption

Artificial sweeteners are commonly used in a wide variety of food and beverage products, such as sugar-free foodstuff, nutritional and energy drinks, carbonated beverages, and artificial juices. In addition, these compounds are used in personal care products, such as toothpaste and mouthwashes. Among the most widely consumed sweeteners are acesulfame K (ACE-K), aspartame (ASP), cyclamate (CYC), neotame (NEO), saccharin (SAC), and sucralose (SUC).

Global consumption of artificial sweeteners has increased significantly over the years, reaching 159,000 metric tons in 2017, with an estimated market value of \$2 billion [9]. In 2017, China led global consumption, accounting for 32% of the total, followed by Asia and Oceania, which together represent 23%, the United States with 23%, Europe with 12%, and Africa with 7% [16]. This geographical landscape reflects an uneven distribution of consumption, influenced by factors such as the availability of these products, local regulations, and cultural preferences regarding food and health.

More recently, in 2021, global sweetener market revenue reached approximately \$21.3 billion and is estimated to increase to \$28.9 billion by 2026 [17], highlighting the growing interest and expansion of their use in various industries. This is mainly attributed to the demand for low-calorie products created through effective marketing campaigns, the growing acceptance of sweeteners as a health-beneficial option, and technological innovations in the production of next-generation sweeteners.

ASP was the global market leader in 2017, with an estimated consumption of 18.5 thousand metric tons, followed by saccharin with 9.7 thousand metric tons, ACE-K with 6.8 thousand metric tons, and sucralose with 3.3 thousand metric tons [9]. The consumption of these compounds varies considerably between different countries, reflecting both consumer preferences and local regulations in each region. For example, SUC was approved for human consumption in the United States in 1998 and has since then authorized in more than 80 countries with a global growth rate of approximately 5.1% per year from 2008 to 2015 [18]. In 2004, sales of SUC in the United States exceeded \$172 million [19], and in 2014, its consumption reached 1,500 tons per year in the United States, 400 tons in Europe, and 1,090 tons in China [20], reflecting its remarkable acceptance in the global market.

SAC, which has also been approved by various regulatory agencies around the world is consumed in more than 90 countries, establishing itself as one of the most widely used sweeteners globally [21]. On the other hand, Bahndorf and Kienle (2004) reported in 2001 that global consumption of ACE-K was 2,500 tons, with America leading consumption at 47%, followed by Europe at 34%, and Asia at only 15%, while Africa and Oceania accounted for just 4% [22]. In the United States, in 2008, 1,103 and 974 products containing ACE-K and ASP, respectively, were reported [23]. In contrast, in countries such as Switzerland and Germany, CYC is the most widely consumed artificial sweetener [24]. On the other hand, China is the leading consumer and producer of artificial sweeteners in Asia, with ACE-K and SUC standing out as the market leaders [25]. In Korea, ASP and SAC production reached 838 and 348 tons in 2011, respectively, with per capita consumption of 8.38 mg/day and 17.4 mg/day for ASP and SAC, respectively [26].

Finally, it is estimated that global consumption of these compounds will continue to grow [27], reflecting the continued expansion and growing demand for these products worldwide.

4. Sources of Artificial Sweeteners in Aquatic Ecosystems

The environmental cycle of sweeteners begins with their industrial production and extends to their arrival in aquatic ecosystems, as shown in Figure 1. These compounds are incorporated into a wide variety of food products, beverages and personal care products. Once consumed, sweeteners are not completely metabolized by humans [28,29], leading to their excretion through urine and feces (Figure 1). The resulting waste enters the sewer system and can be discharged directly into surface waters or aquatic ecosystems or after being treated in wastewater treatment plants (WWTPs).

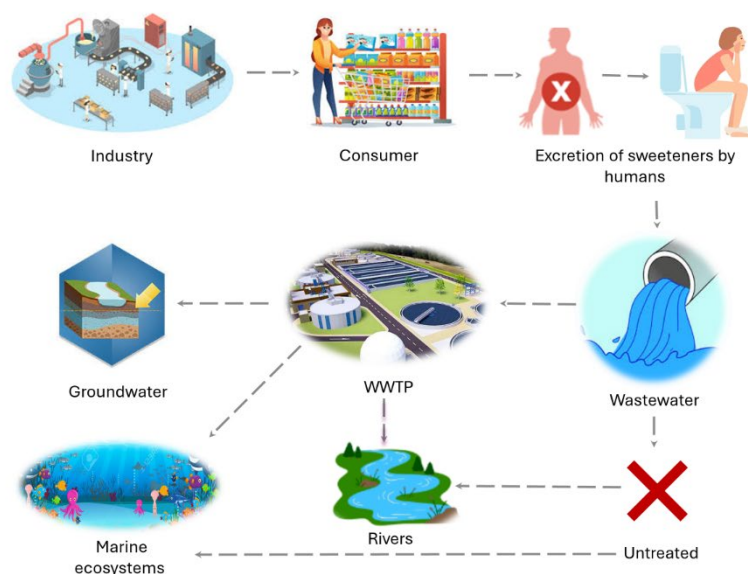


Figure 1. Sources of artificial sweeteners in aquatic ecosystems.

The most commonly used conventional treatments in WWTPs worldwide include activated sludge, anaerobic digestion, and sequencing batch reactors [7]. However, there are more advanced

alternatives, such as membrane bioreactors, bioelectrochemical systems, and constructed wetlands, which offer more effective solutions for the removal of these compounds [7].

Other alternatives, such as the use of UV light in combination with periodate for the removal of NEO, electro-Fenton processes for the removal of SUC, and upflow anaerobic sludge blanket (UASB) reactors for the degradation of CYC, have been shown to achieve removal rates of up to 97% [30,31], 96.1% [32], and 99.6%, respectively [33].

These advances underscore the importance of incorporating innovative technologies into WWTPs to remove artificial sweeteners and other emerging contaminants from waste waters before their reintroduction into surface and marine environments. Research on anaerobic reactors, electro-Fenton processes, and UV-based methods has not only shown high removal efficiencies but has also provided valuable insights into the kinetics and toxicity of these processes, facilitating their optimization.

5. Concentrations of Sweeteners in Environmental Matrices

The reported concentrations of artificial sweeteners in various environmental matrices range from ng to $\mu\text{g L}^{-1}$ [34]. Analysis reveals interesting patterns that suggest variations depending on the type of matrix and the efficiency of wastewater treatment. Globally, the highest concentrations of artificial sweeteners have been found in wastewater, followed by surface water and, finally, seawater [13], while their detection in marine environments has been limited. Only a few studies have documented their presence in seawater, with concentrations ranging from 5.23 ng L^{-1} to $50.2 \mu\text{g L}^{-1}$ [35].

Table 1. Concentrations of artificial sweeteners in different countries and aquatic environments.

Sweeteners	Country	Aquatic environmental	Concentrations ($\mu\text{g L}^{-1}$)	References
Cyclamate	Germany	WWTP influent	190	[36]
		WWTP influent	250	[37]
	Korea	Groundwater	0.155	[38]
		Surface water	120	[39]
	Canada	Groundwater	0.003	[40]
		WWTP influent	26.7–78.3	
		Coastal waters	0.01–0.08	[41]
		Spain	WWTP effluent	0.03–0.06
	Surface water		0.08	[42]
	Neotame	China	WWTP effluent	19.2
WWTP influent			0.03	[43]
WWTP effluent			0.03	[43]
WWTP effluent			10	[12]
Surface water			9.3	[12]
Aspartame	Vietnam	Drinking water	6.94	[44]
		WWTP effluent	3.1	[45]
	China	Surface water	0.21	[39]
		River sediments	0.3	[43]
		Spain	WWTP influent	0.07
WWTP effluent	0.09		[41]	

Saccharin	Switzerland	WWTP effluent	0.01	[42]
		WWTP effluent	0.1	[9]
		WWTP influent	0.1	
	USA	WWTP influent	1.6	[26]
		WWTP effluent	1.8	
		WWTP influent	0.13	[33]
	Germany	WWTP influent	40	[36]
	Australia	WWTP effluent	7.1	[46]
		Coastal waters	0.21	[47]
	China	WWTP effluent	0.42	[39]
		Seawater	50.2	[33]
		WWTP effluent	9.1	[48]
	Spain	WWTP influent	18.4	
		Seawater	0.00523	[35]
India	WWTP influent	303.0	[26]	
USA	WWTP effluent	15.1	[26]	
	WWTP influent	1.4	[26]	
Vietnam	Surface water	1.3	[45]	

Table 1. Cont

Acesulfame	Switzerland	WWTP effluent	16.2	[42]
	Australia	Groundwater	0.34	[49]
		Groundwater	34	[50]
	Germany	WWTP influent	22.9	[51]
		WWTP influent	40	[36]
	Brazil	WWTP effluent	13	[33]
	Canada	Surface water	0.227	[52]
		Groundwater	0.653	[51]
	Korea	Groundwater	0.0329	[38]
	China	Surface water	2.78	[53]
		Surface water	2.9	[51]
	Spain	WWTP effluent	155	[42]
	Italy	WWTP effluent	2,500	[13]
	Norway	Surface water	25	[54]
	Nigeria	WWTP effluent	16	[55]
	Czech Republic	WWTP influent	22.67	[56]
	Switzerland	Groundwater	0.524	[57]
		Groundwater	4.7	[24]
	Singapore	WWTP effluent	29.9	[51]
		135.76	[58]	

			10.51	[59]
	USA	WWTP effluent	50	[60]
	Norway	Surface water	8	[61]
	Sweden	Surface water	3.5	[61]
	Korea	WWTP influent	1.5	[62]
	Brazil	WWTP influent	31	[33]
	China	WWTP effluent	1.9	[46]
	China	WWTP effluent	1.5	[43]
		WWTP influent	1.0	[43]
Sucralose	Spain	WWTP influent	5.3	[48]
		WWTP effluent	18.1	[48]
	Italy	River	0.344	[61]
	Switzerland	WWTP effluent	4.5	[63]
		WWTP influent	4.5	[24]
	USA	Surface water	1.8	[62]
		Drinking water	2.4	[64]
			650	[26]
		WWTP effluent	30	[63]
			1.8	[47]
<i>Table 1. Cont</i>				
			0.9	[65]
			1	[60]
		WWTP influent	1.9	[64]
			27.7	[26]

Among the sweeteners reported here, SUC and ACE-K stand out for having the highest concentrations in the aquatic environment [65] due to their widespread use and high persistence [66]. For example, ACE-K reaches levels of up to 2,500 $\mu\text{g L}^{-1}$ in wastewater effluents in Italy [13]. On the other hand, SUC, although detected in WWTP effluents at lower concentrations of around 10.8 $\mu\text{g L}^{-1}$ [66], shows significant persistence in water bodies such as rivers and lakes, with values of up to 9.6 $\mu\text{g L}^{-1}$ [12]. In contrast, NEO has concentrations in the order of 0.03 $\mu\text{g L}^{-1}$ in wastewater influents and effluents in China [43] suggesting greater efficiency in its removal or lower use globally.

In the case of CYC, marked differences are observed between matrices. While in WWTP influents values can reach up to 250 $\mu\text{g L}^{-1}$ [37], in groundwater the levels are considerably lower, with only 0.003 $\mu\text{g L}^{-1}$ [40], reflecting the lower mobility of this compound to deeper layers or its greater degradation in certain environments. In contrast, ASP has higher concentrations, with 3.1 $\mu\text{g L}^{-1}$ in Vietnam [45], followed by 1.8 $\mu\text{g L}^{-1}$ in the US [26]. It is important to note that although aspartame is one of the most widely consumed artificial sweeteners worldwide, its presence in aquatic ecosystems tends to be limited, probably due to its low environmental persistence. On the other hand, saccharin has been found in remarkably high concentrations, such as 303 $\mu\text{g L}^{-1}$ in WWTP influents in India [26] or 50.2 $\mu\text{g L}^{-1}$ in seawater in China [33].

Finally, it is essential to understand that the presence of these compounds in aquatic matrices is influenced by the amount consumed, the type of treatment used in wastewater treatment plants, and the chemical persistence of each sweetener in the receiving environment. While conventional waste water-treatments may be more effective at removing certain compounds such as CYC, others such as

SUC and ACE-K seem to resist degradation processes and remain in the environment. As a result, aquatic ecosystems can act as long-term reservoirs for these emerging pollutants, posing a potential risk to aquatic organisms.

6. Effects

Whilst there is substantial evidence of the adverse effects of artificial sweeteners on freshwater organisms, covering a wide range of biological responses, research in marine environments is still limited and fragmented. Despite detection of these compounds in seawater, especially in coastal areas, little is known about their impact on marine species. This gap highlights an urgent need for targeted studies to understand their potential eco-logical risks in saltwater ecosystems.

Several studies have shown that sweeteners can induce measurable biological responses even at extremely low concentrations, similar to those detected in aquatic environments [67]. These alterations range from sublethal responses, such as changes in physiological and behavioral biomarker activity, to lethal effects in acute toxicity tests, indicating a potentially significant ecotoxicological impact [68,69].

A notable observation is that compounds such as SUC and ACE-K had the highest number of studies and a wide range of effects, concentration levels as low as ng L^{-1} [67]. This highlights their potential to induce long term cumulative sublethal effects if they persist in the environment. In contrast, SAC and CYC showed a smaller range of studied effects, with less diversity in the parameters evaluated, although this does not necessarily imply lower toxicity, but rather indicate a lack of knowledge and further research needs into the potential effects of these compound in natural environment.

Among the most relevant effects are alterations in physiology (oxidative stress, apoptosis, DNA damage) [70] in the nervous system (alteration of acetylcholinesterase activity, hyperlocomotion, loss of coordination [67,71], as well as in behavior (increased anxiety, decreased learning and memory capacity) [72], and vital functions such as reproduction, feeding, and swimming [67,73]. These effects, although in some cases non-lethal, can compromise the viability of populations and affect the ecological stability of aquatic ecosystems.

It should be noted that chronic tests offer a more complete view of environmental toxicity, revealing cumulative and long-term effects that acute tests do not always detect. Long term monitoring of biomarkers such as lipid peroxidation (LPO), superoxide dismutase (SOD), hydroperoxide content (HPC), protein carbonyl (PCC), sirtuin 1 (SIRT1), and acetylcholinesterase (AChE) allow us to infer the activation of antioxidant defense mechanisms, which could indicate a situation of sustained cellular stress, with the potential to trigger adverse effects on higher organizational levels such as the development, reproduction, and survival of organisms [67,71,74,75].

Freshwater fishes, such as *Danio rerio* and *Cyprinus carpio*, have demonstrated their utility for identifying behavioral and molecular alterations [72], while invertebrates, such as *Daphnia magna* and *Nitocra spinipes*, are suitable for assessing effects on reproduction, feeding, mobility, and acute or chronic toxicity parameters [69,73]. In combination, this diversity of organisms allows for a more robust assessment of the potential impact of sweeteners at different trophic levels.

Despite the relevance of these findings, there is a significant shortage of studies applying mass molecular analysis techniques, such as proteomic, transcriptomic, and genomic approaches. This gap limits deep understanding of the molecular mechanisms by which sweeteners affect aquatic organisms and restricts the development of predictive models of toxicity at the cellular and physiological levels. Furthermore, most experimental studies have focused on evaluating a single sweetener at a time, without considering the possible synergistic, additive, or antagonistic effects that could arise from combined exposures. This limitation represents a significant gap in knowledge, given that these compounds frequently coexist in complex mixtures in the environment.

Finally, it is important to note that, unlike other emerging pollutants such as antibiotics, many sweeteners do not exhibit obvious acute toxicity in the environment [7]. However, their sublethal and chronic effects, especially on sensitive organisms, highlight the need to reassess their permissible

limits in aquatic environments. Furthermore, their widespread presence in WWTP effluents and their persistence suggests that their efficient removal in treatment plants still represents a technical and environmental challenge to be addressed.

Table 2. Main reported effects of artificial sweeteners on aquatic organisms.

Sweeteners	Organisms	Concentration		Assay	Effects	References
		n	$\mu\text{g L}^{-1}$			
	<i>Danio rerio</i>	50		Biomarker assay	Increased HPC and LPX activity	[16]
		10,000		Light/dark preference test (LDP)	Increased anxiety	[72]
		10,000		Test NTDT	Increased anxiety	[72]
		10,000		CPP behavioral testing	Impaired learning and memory capacity	[72]
		>1,000,000		Acute toxicity test LC50 - 96h	Mortality	[51]
		24		Toxicity test IC50 -24h	Effects on swimming and feeding	[67]
Ace-K	<i>Cyprinus carpio</i>	0.05		Biomarker assay	Increased HPC and SOD activity	[76]
	<i>Carassius auratus</i>	100		Biomarker Assay	Increased SOD activity	[75]
	<i>Daphnia magna</i>	100		In vivo cardiac toxicity assay	Increased cardiac	[77]
		24		Toxicity test IC50-24h	Swimming impairment	[67]
		28		Toxicity test IC50-24h	Affecting feeding activity	[67]
		1,600,000		Acute Toxicity Test LC50 - 48h	Mortality	[56]
		0.1		Biomarker assay	Decreased AChE activity	[67]
Aspartame	<i>Daphnia magna</i>	0.1		Biomarker assay	Increased AChE activity	[67]
	<i>Danio rerio</i>	0.49		In situ hybridization assay	Inhibition of neutrophil production	[78]
		20		Teratogenicity test	Cartilage malformation	[71]
	<i>Danio rerio</i>	20		In vitro Toxicity Assay	Decreased in locomotor activity	[71]

		60	Western Blot Technique	Decreased expression of SIRT1 and FOXO3a proteins in neurons.	[71]
Cyclamate	<i>Danio rerio</i>	100	Biomarker assay	Increased AChE activity	[68]
<i>Table 2. Cont.</i>					
	<i>Daphnia magna</i>	1,000	Chronic toxicity test 21-d	Difficulty in reproduction	[73]
		1,000	Light/dark preference tests (LDP)	Alteration of neurotransmitter homeostasis in the brain.	[79]
Saccharin	<i>Danio rerio</i>	100,000	Acute Toxicity Test EC50-48h	Immobilization	[80]
		1,000	Light/dark preference test (LDP)	Excessive increase during swimming	[81]
		100	Biomarker assay	Increased dopamine	[68]
		0.05	Biomarker assay	Increased in LPX, HPC, and PCC activity	[74]
	<i>Danio rerio</i>	0.05	qRT-PCR molecular technique	Over-expression of Nrf1a and Nrf2a genes	[74]
Sucralose		116.5	Acute Toxicity Test LC50-96h	Mortality	[74]
		0.05	Comet assay	DNA damage	[70]
			Tunnel test	Apoptosis	[70]
	<i>Cyprinus carpio</i>	0.05	Biomarker assay	Increased in HPC, LPX, PCC and SOD activity	[82]
	<i>Gammarus zaddachi</i>	500	Biomarker assay	Increased AChE and LPX activity	[83]
		5,000	Toxicity test 14-d	Increased respiration	[84]
		20.1	Biomarker assay	Increased AChE activity	[67]
	<i>Daphnia magna</i>	5	Toxicity Test (Toximeter II)	Increased swimming	[84]
		0.1	Biomarker assay	Increased AChE activity	[83]

	175	Toxicity test IC50-24h	Abnormal swimming	[67]
	235	Toxicity test IC50-24h	Alteration in feeding activity	[67]
<i>Nitocra spinipes</i>	0.5	Acute Toxicity Test LC50-96h	Mortality	[84]
<i>Calanus glacialis</i>	0.05	Toxicity test 72-h	Decrease in egg production	[85]

Ache: Acetylcholinesterase; **CAT:** Catalase; **SOD:** Superoxide dismutase; **FOXO3a:** Forkhead box protein O3a; **HPC:** Hydroperoxide content; **LPX:** Lipid peroxidation; **Nrf1a:** Nuclear respiratory factor 1a; **Nrf2a:** Nuclear respiratory factor 2a; **PCC:** Protein carbonyl; **SIRT1:** Sirtuin 1; **Test CPP:** Conditioned Place Preference; **Test NTD:** Novel tank diving test.

7. Conclusions

The growing global consumption of artificial sweeteners, driven by demand for low-calorie products and health concerns, has contributed to their classification as emerging pollutants due to their persistent presence in various environmental matrices. Their low metabolism rate and the limited effectiveness of conventional wastewater treatments have facilitated the accumulation of artificial sweeteners in the environment, with sucralose and ACE-K being the most commonly detected compounds. Even in cases where certain sweeteners degrade relatively quickly, their continuous introduction into the environment through domestic and industrial discharges gives them a pseudo-persistent character, which exacerbates their potential ecological impact and reinforces the need for their monitoring and control. Although their concentrations are usually low ($\text{ng}-\mu\text{g L}^{-1}$), multiple studies have shown that they can cause physiological, neurological, reproductive, and behavioral effects in aquatic organisms, even at levels close to those found in the environment, which represents a significant ecological risk. However, most of this research has been conducted in freshwater ecosystems, while studies in marine environments are scarce and fragmentary, preventing an adequate characterization of the environmental risk in the latter. Therefore, there is an urgent need to promote research aimed at evaluating the behavior, persistence, and ecotoxicological effects of these compounds in marine and coastal ecosystems. Similarly, it is important to strengthen environmental regulation, implement advanced water treatment technologies, and promote mechanistical studies based on high throughput molecular approaches to better understand their long-term impact on population dynamics.

Author Contributions: Conceptualization, R.F, V.P, C.G. and S.O.; methodology, R.F., V.P., S.O., H.J.B.-A. and G.A., writing—original draft preparation, R.F., C.G, V.P., S.O., H.J.B.-A., M.H. and G.A., writing—review and editing, R.F., G.A., M.H. and. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by Simón Bolívar University, the University of Cádiz and Institute of Marine Sciences of Andalusia (ICMAN - CSIC)

Data availability statement: The data supporting the reported results can be obtained by contacting the first author directly.

Acknowledgments: This work was supported by Simón Bolívar University.

Conflicts of interest: The authors declare that they have no conflicts of interest.

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