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Review

Metal(oid)s in *Ulva* – should we be worried?

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ABSTRACT

Ulva spp. are promising food resources owing to their nutritional richness and beneficial properties. However, it accumulates potentially toxic trace elements, raising health safety concerns and proving useful for biomonitoring studies. In response to this concern, this review, conducted in collaboration with the EU-COST Action CA 20106 network, critically analysed 176 peer-reviewed papers to evaluate metal(oid) accumulation in *Ulva*. This study revealed substantial variability in the essential and non-essential element content due to environmental conditions, geographic regions, morphological forms, and analytical methods used in both wild and cultivated *Ulva*. The analysis was based on gross morphology (tube or foliose) rather than species-level identification. The identification of toxic forms, such as methylmercury and inorganic arsenic, remains limited, highlighting the need for element speciation to more accurate assess safety. Based on these findings, the review identified and outlined key areas requiring attention to ensure the safe and effective use of *Ulva*. Standardised analytical protocols are needed to improve consistency and comparability across studies and to enable accurate detection of toxic element forms. Improved taxonomic resolution, using molecular tools, is essential for distinguishing species-specific accumulation patterns. Expanding research into understudied geographic regions will help capture global variability in environmental influences on trace element uptake. Finally, standardised cultivation parameters are crucial to control elemental composition in farmed *Ulva* and to ensure its suitability for human consumption and commercial applications.

1. Introduction

1.1. *Ulva* – biology, taxonomy, and ecological role of a key marine alga

The *Ulva* Linnaeus genus (Ulvophyceae, Chlorophyta) is a green macroalgae that thrive across diverse marine, estuarine, and freshwater habitats worldwide. Its ubiquitous distribution underscores the notable ability of *Ulva* to adapt to fluctuating environmental conditions, including those strongly influenced by anthropogenic factors, and displays resilience and prolific growth. Over the last decade, *Ulva*, commonly known as sea lettuce, has gained popularity as a nutritious food source owing to its high vitamin, mineral, and antioxidant content. However, similar to other marine organisms, *Ulva* can accumulate metal (oid)s from its environment, which potentially raises food safety concerns, especially regarding cadmium (Cd) and lead (Pb) concentrations in *Ulva* biomass. These metals can be enhanced in the marine

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environment due to industrial discharge, agricultural run-off, and other anthropogenic activities, and are in direct contact with the macrophytobenthos. To ensure the safety of *Ulva* for consumption, it is crucial to monitor and regulate metal content, for example, by setting permissible limits for Cd and Pb in seaweed products, as well as understanding the system biology of this important future crop. Generally, *Ulva* species exhibit two primary morphological forms: a blade-like thalli composed of two-cell layers and tubular or filamentous thalli with a central lumen (Brodie et al., 2007). Previously, these forms were considered distinct genera, namely *Ulva* and *Enteromorpha*. However, molecular data led to their consolidation under the single genus, *Ulva*, as proposed by the author of the genus, Linnaeus (Hayden et al., 2003; Linnaeus, 1953).

However, defining species boundaries within *Ulva* and, hence, defining a clear taxonomy poses challenges owing to limited diagnostic features, morphological variation, and plasticity within the species (Blomster et al., 1998; Steinhagen, Karez, et al., 2019; Xie et al., 2020). Taxonomic revisions, based on natural population diversity and crossing experiments, have revealed substantial variability, and resulted in the synonymy of several names and descriptions of new species (Bliding, 1968; Fort et al., 2022, 2021; Hoeksema & van den Hoek, 1983; Koeman & van den Hoek, 1981; Lagourgue et al., 2022; Steinhagen et al., 2023; Steinhagen, Karez, et al., 2019; Tran et al., 2022). The taxonomic history of *Ulva* encompasses a lengthy list of described and intraspecific taxa, along with numerous nomenclatural and taxonomic proposals (Hayden et al., 2003), underscoring the need of molecular species identification (Tran et al., 2022). Today, AlgaeBase lists over 400 species names and more than two hundred subspecies, varieties, and forms within the *Ulva* genus, with ongoing efforts to verify and clarify their taxonomic statuses (Guiry & Guiry, 2021).

Correct species identification, clear taxonomic boundaries, and genotype performance assessments are of utmost importance for *Ulva* classification. This is particularly notable for some species that can form massive blooms caused by their proliferative character under suitable environmental conditions (Bermejo et al., 2022; Smetacek & Zingone, 2013); for example, 52% of global macroalgal blooms (to 2018) were predominantly or exclusively *Ulva* (Joniver et al., 2021). Eutrophication, driven primarily by anthropogenic nitrogen inputs, is the main cause of these green tides (Bermejo et al., 2019; Perrot et al., 2014; Zhang et al., 2013) and occurs with increasing frequency worldwide (Steinhagen, Weinberger, et al., 2019; Xu et al., 2014).

In Europe, green tides result from fertiliser run-off, increasing nitrate and phosphate levels, particularly in estuaries and coastal embayment's. This leads to large *Ulva* mats, accumulating up to 27 kg wet weight per square metre (Fletcher, 1996). These noxious, aesthetically unpleasant algal masses can persist for years, disrupting fisheries, tourism, and ecosystems (Valiela et al., 1997). The decomposition of algal biomass on the seafloor creates anoxic conditions, alters sediments and macrofaunal communities (Franz & Friedman, 2002), and degrades water quality. Green tides also serve as indicators of broader environmental change (Fletcher, 1996). The increased frequency of green tide occurrences since the 1970s has been attributed to the proliferation of rapidly growing genotypic variants within these regions (Fort et al., 2020).

1.2. Proximate composition of Ulva

Ulva tissue consists of 78–80% water (Da Costa et al., 2020; Lamare & Wing, 2001; Marsham et al., 2007), and the ash fraction varies between 11 and 52% of dry weight (dw) (Foster & Hodgson, 1998; Ortiz et al., 2006) (Table 1). Many studies on naturally harvested *Ulva* have shown that it has a very low total lipid content, 0.3–3.8% of dw (Marsham et al., 2007; Ortiz et al., 2006; Soares et al., 2021). However, *Ulva* contains total lipid content of up to 8% of dw, attributed to genetic and environmental variation (Madibana et al., 2020; Mæhre et al., 2014; Yaich et al., 2011). *Ulva* has a carbohydrate content of 15–62% of dw (Dominguez & Loret, 2019; Ortiz et al., 2006; Wong & Cheung, 2000), which mainly consists of dietary fibre, that is, 14–61% of dw (Dominguez & Loret, 2019; Lu & Chen, 2022; Ortiz et al., 2006; Rasyid, 2017). Barakat et al. (2022) observed that *Ulva* comprised of 31.5% carbohydrate, of which ulvan represented 43.66% of total the carbohydrate content (13.75 g.100 g^{-1} dw), with an ulvan sulphate content of 20.45%. In a further compositional analysis, the total carbohydrate content was 79% of dw (İsmail et al., 2017). Protein concentrations and total phosphorous (P) contents were 6–29% of dw (Smith et al., 2010) and 0.05–5% of dw (Mæhre et al., 2014; Rasyid, 2017), respectively. Finally, nitrogen (N) contents are 1.2–3.2% of dw (Kamer et al., 2004; Van Alstyne, 2016). Protein and N contents have been reported to be even higher in *Ulva* from tank cultivations, for example, reaching contents of 5.9% dw of N (Msuya & Neori, 2008; Nielsen et al., 2012). In addition, *Ulva* possesses significant quantities of antioxidants and vitamins, particularly vitamins A, C, and E, and various B vitamins (El Zokm et al., 2020; Ismail et al., 2017; Nunes et al., 2017; Taboada et al., 2010).

Table 1
Overall nutritional value of naturally collected *Ulva.*

Component	Value
Moisture	78[a*]–80[b]% of ww
Ash	11[c]–52[d]% of dw
Carbohydrate	15[e]–62[c]% of dw
Dietary fibre	14[f]–61[c]% of dw
Total lipid	0.3[c,d]–8[g,h]% of dw
Protein	6[d]–29[b]% of dw
Phosphorus (P)	0.05[f]–5[g]% of dw
Nitrogen (N)	1.2[i]–3.2[j]% of dw

Abbreviations: dw, dry weight; ww, wet weight
[*] Species and location details corresponding to values in the table:
[a] *Ulva lactuca*, New Zealand (Lamare & Wing, 2001)
[b] *Ulva lactuca*, UK (Marsham et al., 2007)
[c] *Ulva lactuca*, Chile (Ortiz et al., 2006)
[d] *Ulva rigida*, South Africa (Foster & Hodgson, 1998)
[e] *Ulva lactuca*, Hong Kong (Wong & Cheung, 2000)
[f] *Ulva lactuca*, Indonesia (Rasyid, 2017)
[g] *Ulva lactuca*, Norway (Mæhre et al., 2014)
[h] *Ulva lactuca*, Tunisia (Yaich et al., 2011)
[i] *Ulva intestinalis*, US (Kamer et al., 2004)
[j] *Ulva lactuca*, US (Van Alstyne, 2016)

1.3. Metal(oid)s in Ulva: composition, regulatory frameworks, and toxicity

Ulva is a valuable mineral source, but can also accumulate potentially toxic metals (Ho, 1990a; Shams El-Din et al., 2014; Simon et al., 2022). There are several indications of when to expect metal content to be elevated in *Ulva,* with studies along the Black Sea coast linking the contamination of *Ulva* tissue with direct human impact (Strezov & Nonova, 2009). Contamination sources, such as industrial waste, sewage effluent, shipyards, harbours, and high ship traffic intensity, have been reported to influence the contents of Cd, copper (Cu), Pb, iron (Fe), and zinc (Zn) in *Ulva* (Malea & Haritonidis, 1999, Ustunada et al., 2011; Rodríguez-Castañeda et al., 2006, Gaudry et al., 2007; Charlier et al., 2012). Other cases included harbour docks with chromate Cu arsenate wood, where accumulations of chromium (Cr), Cu, and arsenic (As) were found (Weis & Weis, 1992), and industrial or urban discharges resulting in high tissue mercury (Hg) concentrations (Coelho et al., 2005; Diop & Amara, 2016; Zhang et al., 2022). Furthermore, agricultural nutrients and metal effluents (Nriagu & Pacyna, 1988) may influence the elemental content of *Ulva* (Diop & Amara, 2016; Mæhre et al., 2014; Wan et al., 2017).

As, Cd, Cr, Cu, Fe, Hg, manganese (Mn), Pb, and Zn are commonly associated with anthropogenic activity (Nriagu & Pacyna, 1988), but in many cases, these pollutants can also occur in *Ulva* from geogenic or natural sources (Rodríguez-Castañeda et al., 2006; Wan et al., 2017). In the rare case of *Ulva*, which occurs in inland freshwater systems with very low salinity, thalli accumulate Ca, Mg, Ni, and Cd to a much greater extent than in marine systems (Rybak et al., 2012a). Additionally, high concentrations of Fe, Zn, and Cd, and low salinity are correlated, which may be a cause of the inverse relationship between ion activity and salinity (Favero et al., 1996).

The elemental composition of *Ulva* is site dependent and follows seasonal patterns (Schintu et al., 2010; Malea et al., 2015; Haritonidis & Malea, 1999, Favero et al., 1996). Trace elements in *Ulva* are generally at a minimum during summer and a maximum in autumn/winter, a pattern also reported for brown (for example, *Laminaria digitata*; Adams et al., 2011), and red algae (for example, *Palmaria palmata*; Hagen Rødde et al., 2004). This has been explained by a dilution effect associated with growth dynamics; an increase in *Ulva* biomass decreases its metal concentration (Haritonidis & Malea, 1999; Villares et al., 2002).

Moreover, the metal content seems to depend on the specific species and phenotypes of *Ulva*, where the bladed species are reported to have a lower metal uptake capacity than the tubular forms (Malea & Haritonidis, 2000).

No regulation has yet been introduced in the EU, specifically for maximum allowable concentrations of As, Pb, and Hg in seaweed for human consumption. However, the EU has established limits for Cd and Pb contents in food supplements, which may not exceed 3 mg kg^{-1} dw^{-1} and Hg 0.1 mg kg^{-1} dw^{-1} (EU, 2017). Although some countries, such as France, have their own legislation regarding metals in seaweed, several organisations, including the WHO and FAO, have defined recommendations and a cautionary approach. For animal feed materials, the maximum levels of total and inorganic As (iAs) are 40 and 2 mg kg^{-1}, respectively; Cd is 1 mg kg^{-1}, Pb is 10 mg kg^{-1}, and Hg is 0.1 mg kg^{-1} (EU (European Commission), 2015, 2017). For food supplements, As is undefined, with other elements, except Cd and Hg, in lower contents than that for feed. The reported levels are listed in Table 2.

Although this review focuses on the European regulatory landscape, it is worth noting that some Asian countries have introduced specific limits for heavy metals in seaweed and related products which are discussed in detail by Guo et al. (2023) and Huang et al. (2025). For example, China has set maximum levels for inorganic arsenic in seaweed-based supplementary foods (0.3 mg kg^{-1}) and aquatic seasonings (0.5 mg kg^{-1}), as well as lead limits for fresh seaweed (0.5 mg kg^{-1}) and seaweed products (1.0 mg kg^{-1}) (Guo et al., 2023). South Korea regulates cadmium and lead in selected species such as laver and sea mustard, while Taiwan has broader regulations covering inorganic arsenic, cadmium, lead, and mercury in seaweed (Guo et al., 2023).

Elevated levels of As have been found in vegetables, fruits, and seafood (EFSA, 2009a; WHO, 2011; Taylor et al., 2017; Mac Monagail & Morrison, 2019). Some marine organisms possess the ability to assimilate elevated levels of As, posing potential harm to humans; thus, the measurement of seafood should include the identification of As species that may potentially endanger consumers (Phillips, 1990; Shiomi et al., 1990; Taylor et al., 2017; Malik et al., 2023). The chemical form of As determines its toxicological and biochemical activities (Chowdhury, 2004; Kaise et al., 1996; Neff, 1997). Inorganic species, namely arsenite and arsenate, exhibit higher toxicity levels than their basic methylated forms, such as methyl As acid (MA) and dimethylarsenic (DMA) (WHO, 2011). More complex organic As (arsenoribosides) do not affect living organisms and are generally considered non-toxic (Oya-Ohta et al., 1996; Pergantis et al., 1997; Pergantis et al., 2000). Attributes of As speciation in macroalgae are also critical for clarifying the cycle of As in marine ecosystems, without health risk appraisal (Francesconi et al., 1994; Zhang et al., 2022). Marine macroalgae, as primary producers, play a crucial role in connecting As present in the water column with various organisms within the food chain. The metabolism of arsenoribosides may serve as a potential origin of low toxicity arsenobetaine in higher organisms (Francesconi & Edmonds, 1996).

Table 2
European maximum levels for priority pollutants in food and feed (EU (European Commission), 2015, 2017).

Metal source	Food (mg kg^{-1} ww^{-1})	Feed (mg/kg relative to a moisture content of 12%)
iAs	0.1–0.3[a]	<2[b]
As	No level defined	40[b]
Cd	3[c]	0.5[d]
Pb	0.3–3[e]	5–10[d]
Hg	0.5–1[f]	0.1–0.5[g]

Abbreviations: ww, wet weight
[a] different rice product;
[b] feed materials derived from seaweed;
[c] food supplements from dried seaweed (mg kg^{-1} DW^{-1});
[d] complementary or complete feed;
[e] leaf vegetables or food supplements;
[f] fishery products;
[g] any feed material or fishery product

Many factors can affect As accumulation and changeover in macroalgae. The crucial factors that need to be considered are the species of macroalgae, concentration of As in the surrounding water, time of harvesting of the algae, concentration of nutrients in the environment, and the temperature of the surroundings (Duncan et al., 2015; Larrea-Marín et al., 2010; Rose et al., 2007; Zhao et al., 2012). Ma et al. (2018) investigated the inorganic, organic, and total As contents of 282 macroalgae species and reported that iAs and total As amounts of algae changed between the classes, and was found to be highest in brown and lowest in green seaweeds (Ma et al., 2018). Excessive exposure to metals, including As, Cd, Hg, Cr, Ni, Pb, Zn, and Fe, is associated with various cancers, organ damage, reproductive issues, and developmental problems. These metals can cause oxidative stress, disrupt cellular processes, and impair vital systems, such as the kidneys, nervous, and cardiovascular systems. A detailed overview of the specific health effects of the above-mentioned metal(oid)s is presented in Table 3.

1.4. Metal(oid)s accumulation through biosorption and uptake in Ulva

Ulva spp. exhibits a notable ability to metal uptake, making them valuable tools for environmental assessment and candidates for bioremediation. The mechanisms, which include surface adsorption, chelation, active transport through ion channels, and detoxification activities, highlight the overall importance of metals in absorption. The interplay of intrinsic and extrinsic factors, physiological and environmental conditions, influences the efficiency and selectivity of metal absorption. For instance, foliose *Ulva* species accumulate substantial levels of metals, such as Cd, Cu, and Pb, from contaminated environments, emphasising their pivotal role in biomonitoring and metal detoxification processes (Rahhou et al., 2023; Romero et al., 2024). From a mechanistic perspective, it is crucial to differentiate between adsorption on algal surfaces, cellular uptake, and sequestration. However, it leads to metal accumulation and a high metal quota in *Ulva*.

1.4.1. Biosorption processes

Biosorption processes include ion exchange, where metal ions replace other cations on the algal surface; complexation, where metal ions form stable complexes with functional groups in the cell wall; and electrostatic interactions between the metal ions and the algae surface. The transformation of biomass into *Ulva* biochar can enhance bioremediation efficiency (Ravindiran et al., 2024). In general, the sorption of Cu^{2+} by *Ulva* follows Langmuir isotherms, suggesting monolayer adsorption onto specific binding sites, indicating a high affinity for Cu at low concentrations. Biosorption kinetics for Pb^{2+} and Cd^{2+} often involve pseudo-second-order kinetics, implying chemisorption as the rate-limiting step (Kumar et al., 2006).

Sorption generally increases with pH, as more metal ions are available in a form that can bind to the functional groups on the *Ulva* cell walls. Abiotic factors, such as high temperatures, have various effects on the sorption capacity, depending on the metal and its concentration.

Table 3
Toxicological profile of priority pollutant metal(oid)s

Metal source	Health effects	Mechanisms of toxicity	References
Arsenic (As) Metalloid Inorganic arsenic (iAs) As (III) As(V) and organic compounds	-Carcinogenic -Genotoxic (iAs and its metabolites) -Skin cancer (basal and squamous cell carcinoma iAs) -Development toxicity -Neurotoxicity -Cardiovascular diseases	-Inhibition of enzyme activity, -Oxidative stress induces DNA base oxidation. -Altered DNA methylation -Impaired DNA repair -Alteration in neurotransmitter homeostasis -Neuroinflammation -Endothelial damage and inflammation increase the risk of plaque formation	EFSA et al., 2024 Watanabe & Hirano, 2013 Thomas et al., 2001 Hughes, 2002 Ratnaike, 2003 Mochizuki, 2019
Cadmium (Cd)	Human carcinogen (Group 1) Enhance the mutagenicity induced by other DNA-damaging agents -Genotoxic -Neurotoxic -Teratogenic -Endocrine function (oestrogenic and androgenic activity).	-Mimics the activity of other divalent metals essential in biological processes -interferes with homeostasis of calcium, zinc, and iron -Disruption of cellular processes -Oxidative stress -Inhibits DNA repair enzymes	(EFSA (European Food Safety Authority), 2009b) Morais et al., 2012 Genchi et al., 2020
Chromium (Cr) Cr III Cr VI	-Carcinogenic (Cr VI) -Respiratory issues -Mutagenic at high concentrations -Genotoxic (Cr VI)	-Oxidative stress -Generation of oxygen radicals -DNA damage -Generation of DNA adducts	EFSA, 2014
Copper (Cu)	-Hepatotoxicity -Nephrotoxicity -Gastrointestinal distress	-Oxidative stress -Disruption of cellular functions -Accumulation of copper in the liver, brain, heart, kidney, and eyes. -Impact on Zn homeostasis -Disturbances in calcium homeostasis	EFSA, 2023
Mercury (Hg) -Elemental mercury (Hg0), -Inorganic mercury -Organic mercury	-Neurotoxicity -Kidney damage -Developmental issues -Cardiotoxicity -Reproductive toxicity -Immunotoxicity	-Disruption of glutaminergic, cholinergic, and dopaminergic neurotransmitter system -Mercury species bind covalently to isolated DNA -Oxidative stress -Inflammation -Lipid peroxidation -Mitochondrial disfunction -Thrombosis	EFSA, 2012 Fernandes Azevedo et al., 2012
Nickel (Ni)	-Carcinogen -Genotoxicity -Co-mutagenic (with alkylating agents or UV light) -Immuno-toxicity -Reproductive and developmental toxicity	-Oxidative stress -Oxidative damage to DNA and lipid peroxidation	EFSA, 2020
Lead (Pb)	-Neurotoxicity, developmental delays -Increases β-amyloid peptide in Alzheimer's disease -Cardiovascular effects -Nephrotoxicity -Lead is a weak indirect genotoxin -Carcinogen -Haematological effects (anaemia)	-May interfere with dopamine, acetylcholine system, and muscarinic receptors -Inhibition of Na/K ATP-se activity -Activation of protein Kinase C -Formation of intranuclear inclusion bodies in the renal proximal tube -Interference with haem biosynthesis enzymes -Increase of erythrocyte destruction - Reactive oxygen species formation -Interference with DNA repair processes	Bolin et al., 2006 EFSA, 2010
Zinc (Zn)	-Adverse gastrointestinal effects -Neurological disease	-Disruption of cellular processes -Oxidative stress -Impaired Cu absorption	Wessels et al., 2021 Dardenne and Bach (2020) Schoofs et al., 2024
Iron (Fe)	-Liver toxicity -Increased risk of diabetes -Cardiovascular issues -Adverse gastrointestinal effects	-Oxidative stress -Disruption of cellular processes -Accumulation of iron in liver in the form of ferritin and haemosiderin	Eaton and Qian (2002). EFSA, 2024

1.4.2. *Metal uptake*

In addition to surface adsorption, which is a passive mechanism, metals can be taken up actively and specifically through H+-ATPses, cation-, or siderophore-transporters, which were also suggested for *U. mutabilis* (deClerck et al., 2018). Here, metallophores can play a crucial role as organic ligands that bind and transport metal ions, typically released by bacteria, fungi, and plants in the environment, as they acquire essential metals or sequester toxic ones from the environment. These metals are often necessary for enzymatic functions, structural roles, and other cellular processes (Kraemer et al., 2015; Kraepiel et al., 2009). The key characteristics of metallophores are defined by (i) their metal ion binding, (ii) metal transport, and (iii) their biological function (Gomes et al., 2024). Metallophores have a high affinity for specific metal ions, such as Fe, Zn, Cu, and Mn. Once a metallophore binds a metal ion through multiple donor atoms, it often interacts with specific receptors on the cell surface to facilitate the uptake of the metal ion or metal complex into the cell. This process can involve active transport mechanisms or passive diffusion (Kraemer et al., 2015). Metallophores play a vital role in metal homeostasis. Several key types have been already described, such as siderophores, zincophores, as well as Cu and molybdenum-binding metallophores (Maret, 2024). Notably, siderophore-producing and alga growth-promoting bacteria are also associated with *Ulva* (Morales-Reyes, Ghaderiardakani, & Wichard, 2022; Wichard, 2016). Those bacteria recruit Fe from the environment via metal complexes, which are also acquired by *Ulva* under Fe-depleted conditions (Morales-Reyes & Wichard pers. comm.; Wienecke et al., 2024). Zincophores, Cu, and Mn-binding metallophores are less common but serve a similar function, providing trace elements for various enzymatic activities and cellular functions, but could also contribute to detoxification.

1.4.3. Detoxification

The resilience of macroalgae in metal-polluted ecosystems is attributed to various mechanisms, including metal exclusion, internal detoxification, metal transformation (Navarette et al., 2019), and the production of extracellular binding polypeptides, such as cysteine-rich metallothionein or potentially metallophores. Cu stress in *Ulva compressa* has been extensively studied, and many detoxification mechanisms have been identified, including the synthesis of phytochelatins, metal-chelating proteins, and metallothioneins (Mellado et al., 2012; Laporte et al., 2016). Furthermore, bacterial metallophores, secreted by symbiotic bacteria, appear to represent an additional mechanism for sequestering external metals and mitigating their toxic effects, including those of Cd, Cu, and Hg (Gomes et al., 2024; Wichard, 2016). Similar detoxification mechanisms have already been intensively studied in bacteria, where cellular processes and the release of metallophores sequester metal ions, rendering them biologically unavailable (Mathivanan et al., 2021; Mohr et al., 2021). Such detoxification mechanisms of bacteria are notable, as they can prevent accumulation through uptake or sorption in *Ulva.*

1.5. Objectives and aim of the review

This review synthesises and critically assesses the current body of literature on the accumulation and availability of metal(oid)s in *Ulva* biomass, with a focus on evaluating metal concentrations across varying geographic regions, sources of biomass (wild-harvested versus cultivated), and different morphological growth forms. This study presents a detailed, state-of-the-art analysis of how environmental factors, cultivation practices, and growth conditions influence metal uptake in *Ulva*. Through a comprehensive review of the literature on metal bioaccumulation in this genus, we seek to reveal key trends, identify knowledge gaps, and outline future research directions essential for advancing environmental monitoring efforts and supporting the dynamic commercial applications of *Ulva* biomass.

Additionally, we discuss the technologies and analytical techniques that are essential for generating comparable datasets across laboratories, which will be critical for establishing standardised protocols, advancing research, and informing regulatory frameworks for the safe and sustainable use of *Ulva* in commercial applications.

2. Methodology

2.1. Literature survey of studies publishing data on metal(oid)s in Ulva

A comprehensive search of the Scopus database was conducted to assess the potential of green

seaweed *Ulva* for microminerals (Cu, Cr, Fe, Ni, and Zn) and toxic minerals (As, Cd, Hg, and Pb). The search was performed using the following keywords and Boolean operators from the Scopus database:

- **Metal(oid)s:** OR iron, copper, zinc, arsenic, lead, cadmium, chromium, mercury, nickel, metal AND
- **Metal(oid)s analysis:** analysis, OR occurrence, incidence, contamination, level, concentration, survey, determination, study, analysis, content, detection, distribution, presence, investigation, accumulation, uptake, monitoring

  AND

- **Seaweed:** *Ulva*

The search yielded 1,092 documents. After applying the exclusion criteria (non-English papers, non-research articles, and documents outside the date range of 1970 to June 2024), 105 references were removed. Of the remaining 987 documents, a review of titles, keywords, and abstracts excluded 759 papers that did not meet the review criteria. Thus, 176 papers were selected for data extraction (Fig. 1).

In accordance with recent taxonomic revisions, where species previously classified under *Enteromorpha* have been merged into the genus *Ulva* based on molecular and phylogenetic studies (Hayden et al., 2003), this study used "*Ulva*" as the primary term for literature search. As such, earlier references, before 1989, using "*Enteromorpha*" may not have been explicitly included unless reclassified under *Ulva* in the original source. However, we retrieved some papers including *Enteromorpha*. This approach was adopted to reflect current taxonomic standard.

2.2. Data visualisation

Data visualisation was performed in R using the ggplot2, ggpubr, tidyr, and dplyr packages.

3. Results

3.1. Identification of Ulva species

Identifying *Ulva* species is difficult because of their morphological similarities and plasticity. Most of the studies used (79%) had *Ulva* identified to the species-level, with the remaining at the genus level. The taxonomic analysis of *Ulva* species was performed based on microscopic, morphological, and more recently, molecular identification. The most widespread method of identification is morphological analysis, which is based on morphological characters and uses taxonomic keys compared with databases or websites, such as Algae Base, and other taxonomic guides. Only one paper reported the use of microscopic analysis (Shams El-Din et al., 2014), while three were in combination with morphological studies (Chakraborty et al., 2014; Coelho et al., 2016; Haghshenas et al., 2020). Recent developments in molecular systematics have made it possible to discriminate among various species. DNA barcoding, for example, using *tuf*A, is a notable tool to assist in the complex taxonomy of *Ulva*. The use of a DNA barcoding database (GenBank) is important for species-level identification. Only three papers used this method in combination with a morphological inspection (Al-Adilah et al., 2021; Li et al., 2023; Olsson et al., 2020).

Conversely, most of the research papers (143) failed to specify the methodology used for sample identification, rendering species-level identification questionable.

Minor investigations, 10 out of 176, encompassed molecular analysis, specifically phylogenetic studies of *Ulva* species. Consequently, we opted to categorise the *Ulva* species based on its morphology into two classifications: the flat, sheet-like foliose, and filamentous tubular form (Fig. 2).

Morphological forms further influence the research focus, with foliose structures consistently dominating publication counts for nearly all elements, such as Cu, Pb, Zn, and Cd. This trend likely reflects the ecological importance and accessibility of foliose forms for studying metal accumulation and interactions. In contrast, tubular and unidentified morphologies have received considerably less attention, suggesting untapped opportunities for future exploration.

Collectively, these findings underscore the shifting priorities in metal research, emphasising the increasing focus on ecological and environmental contexts, the persistence of regional disparities in research effort, and the critical influence of morphology and growth conditions on scientific inquiry. Addressing the gaps in underexplored regions, growth conditions, and morphologies is essential for developing a more comprehensive understanding of metal dynamics and their ecological and industrial implications.

3.2. Metal(oids) content and its variability in different species of Ulva

The metal(oid) content of *Ulva* species, particularly concerning toxic

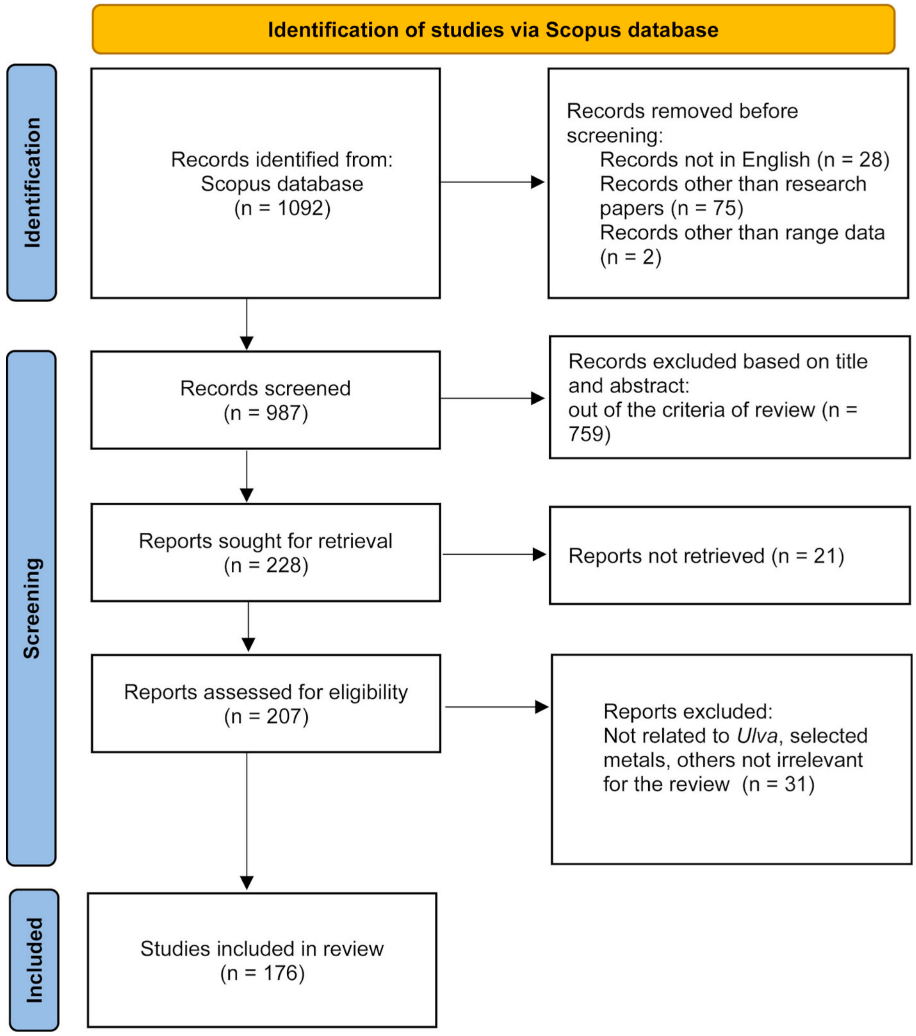

Fig. 1. Flow diagram illustrating the search strategy and selection process for the review.

elements, raises health concerns and necessitates stringent monitoring to ensure compliance with European safety regulation (Commission Regulation (EU), 2023). Effective management and control are essential to maintain these levels within the established safety limits. Additionally, the presence of trace elements in *Ulva* underscores its potential as a valuable source of micronutrients for human nutrition.

The analysis of publication trends for key elements (Cu, Cr, Fe, Ni, Zn, As, Cd, Hg, and Pb) from 1979 to 2024 showed a marked increase in publication activity. This was evident after 2000, particularly for Zn, Pb, and Cd, with a pronounced peak in 2014, reflecting intensified scientific focus and possibly significant breakthroughs or heightened environmental awareness during that time (Fig. 3).

The study areas mentioned in the publications were categorised based on Spalding et al. (2007) to ensure consistency with globally recognised marine biogeographic classifications. Regionally, the Temperate Northern Atlantic stands out as the most extensively studied area, especially for Cu, Zn, Pb, Cd, and Cr, likely due to its historical industrialisation and associated pollution challenges. In contrast, regions such as, Temperate Southern Africa and the Arctic Ocean, have limited research activity, potentially reflecting disparities in industrial pressures, environmental concerns, or regional research capacity (Fig. 4).

When studying the distribution of *Ulva* species, using Spalding's marine ecoregions allows for comparison across ecologically similar coastal zones, regardless of political boundaries. This approach captures shared environmental drivers such as temperature, salinity, and current systems or metall(oid)s. It also avoids fragmentation of ecological units that span multiple countries, enabling more accurate ecological analysis.

The metal(oid) variability in *Ulva* species is complex due to substantial factors, including origin, number, characteristics and preparation of samples, harvest period and area, analytical method and conditions, use of certified reference materials, and expression of results. Samples have been obtained as fresh or dried algae, from different origins (natural, cultivated, or commercial), harvested from different parts of the thalli, in different seasons, and from various areas (polluted or unpolluted, urban or rural in open coast, estuarine systems, and freshwater areas). The analytical methodology and conditions, mostly Inductively Coupled Plasma Mass Spectrometry (ICP-MS) with certain variants (Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES) and Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES)), were very important and may have affected the quantitative results. The presentation of results, whether as mean or range and in the form of figures or tables, can complicate statistical analysis.

Considering the spectrum of microminerals (Cu, Cr, Fe, I, Ni, and Zn) and comparing it with the adequate intake (AI) guidelines established by The European Food Safety Authority (EFSA (European Food Safety Authority), 2017), the proportion of macroalgae consumption aligns with these recommendations. The AI of Cu is 1.6 mg/day for men and 1.3 mg/day for women. If 5 g of freeze-dried weight (fdw) is consumed once a week (Sá Monteiro et al., 2019), approximately 1 g of fdw/day,

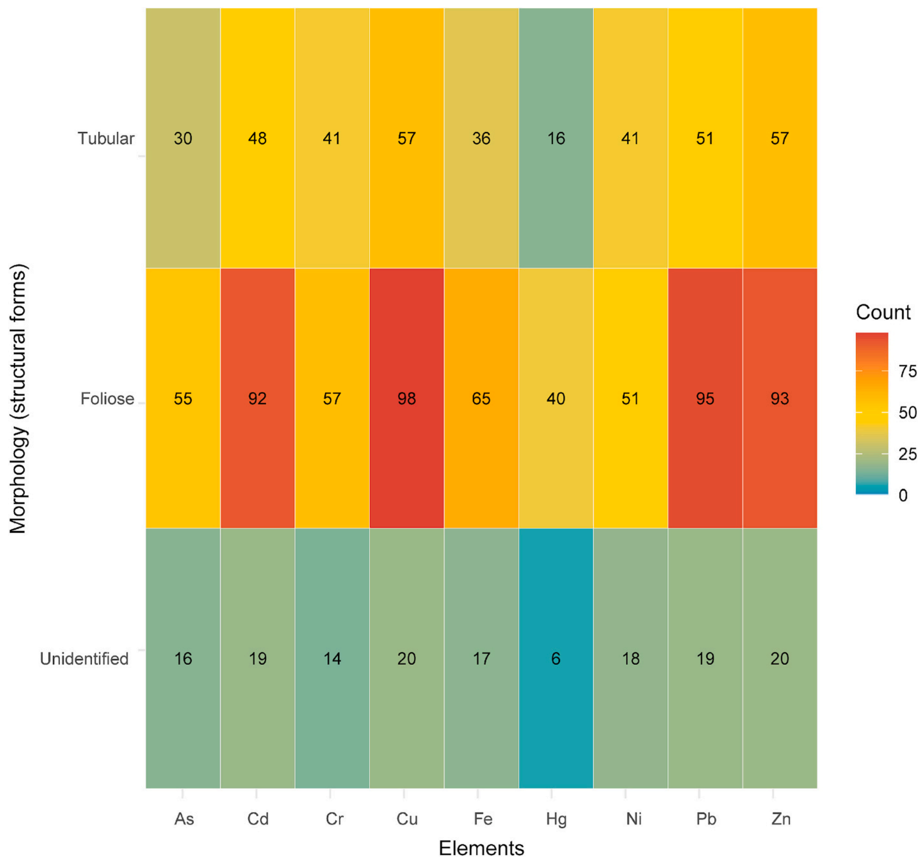

Fig. 2. Trends in publication counts for key elements (Cu, Cr, Fe, Ni, Zn, As, Cd, Hg, and Pb) categorised by morphological forms of *Ulva* (tubular and foliose) to assess variations in research focus across structural types. The plot represents the distribution of the studies, with the numbers inside each bar indicating the total publication count for each element within the two structural forms. The heat map indicates the publication counts, ranging from blue (low) to red (high).

with a maximum concentration of 775.63 mg/kg, this results in an intake of 0.77 mg/day. This intake constitutes approximately 48.5% of the AI for men and 59.7% for women, indicating that even a small daily amount of *Ulva* can significantly contribute to the recommended Cu intake levels.

According to the European food safety regulations and guidelines, there is no specific maximum level (ML) for toxic minerals in seaweed. However, updated ML, for Cd (3 mg/kg), Hg (0.1 mg/kg), and Pb (3 mg/kg) in food supplements, and iAs (0.1–0.3 mg/kg) in cereals and cereal based products have been established by the European legislation (Commission Regulation (EU), 2023). Based on these MLs, the minimum values of the As, Cd, Hg, and Pb concentration ranges were below the MLs, but the maximum value exceeded these MLs. The IARC classifies As, Cd, Ni, and Cr as carcinogenic (Group 1), Pb as probably carcinogenic (Group 2A), and methylmercury (MeHg) as possible carcinogenic (Group 2B). This classification is of concern and requires the monitoring and control of *Ulva* species for human consumption on a case-by-case basis.

3.3. *Metal(oid) content in wild and cultivated Ulva species: the rearing water quality matters*

Cultivated species occurred in a controlled environment, using a closed system, while wild species grew in open systems (polluted or unpolluted, urban or rural in open coast, and estuarine system or freshwater areas) with its consequent possible contamination. There are substantial data on *Ulva* composition; however, to the best of our knowledge, no comparison has been made between wild and aquaculture types.

The metal(oid) content of *Ulva* is influenced by the chemical composition of the surrounding water, including factors, such as salinity, nutrient levels, pH, and the overall presence of pollutants and dissolved organic material. The ability of *Ulva* to absorb and store metals and minerals makes it an important bioindicator of water quality and a potential resource for bioaccumulation in marine ecosystems. Therefore, the metal pollution of the rearing water is significant when assessing suitable conditions for *Ulva* cultivation.

An examination of growth conditions revealed a strong research bias toward wild environments, with Cu, Zn, and Pb being the most frequently studied elements. This emphasis underscores the priority of understanding metal dynamics in natural ecosystems, while cultivated and commercial conditions remain significantly underexplored, highlighting a critical gap in research related to controlled and industrial applications (Fig. 5)

Most of the *Ulva* samples studied were of wild origin (90%), and only 8% were cultivated and 2% were commercial samples. The commercial samples reported the presence of metals in *Ulva sp.* from Italy and the USA (Filippini et al., 2021; Todorov et al., 2022) and *U rigida* from Spain (Besada et al., 2009; Llorente-Mirandes et al., 2011).

The most studied nomenclature for cultivated *Ulva* was *Ulva* sp., as the cultivators could only definitively identify the genus level. Among the identified cultivated species, *Ulva lactuca* was the most common, followed by *U. fenestrata, U. intestinalis*, *U. prolifera,* and *U. rigida.* The archaically named *Enteromorpha*-type was the least reported name used in this study. All these cultivated species were harvested in eight countries, mainly from Portugal, Sweden, and Spain.

The range content of microminerals of cultivated *Ulva* species was for: Cu (6.97–121.11 μg/g), Cr (3.92–28130 μg/g), Fe (45.6–2024 μg/g), Ni (2.96–8560 μg/g), and Zn (35.98–212.22 μg/g). The highest concentrations of these microminerals were as follows: *Enteromorpha*-type

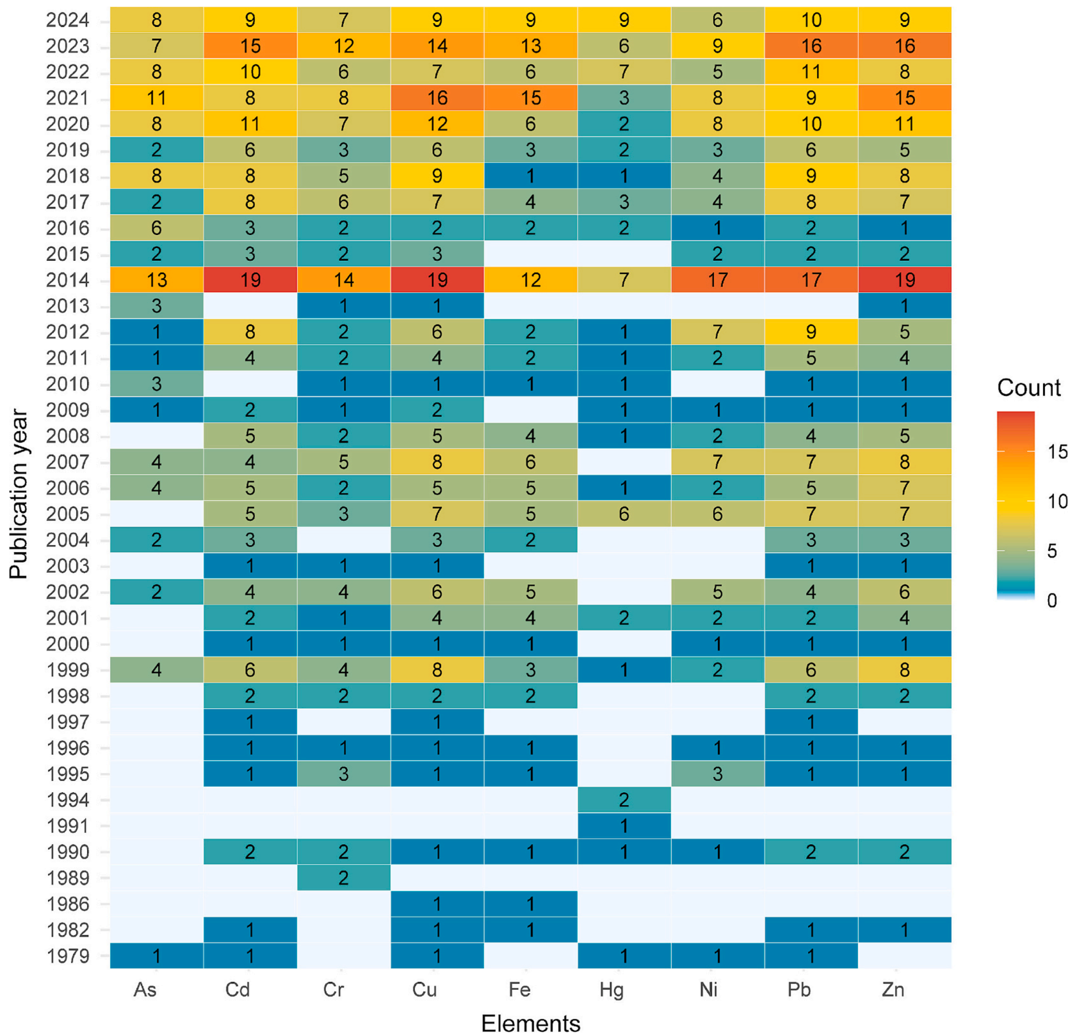

Fig. 3. Trends in publication counts for key elements (Cu, Cr, Fe, Ni, Zn, As, Cd, Hg, and Pb) from 1979 to 2024. The plot shows the distribution of studies across years, with the values in each cell representing the number of publications focused on a specific element each year. The heat map indicates the publication count, ranging from blue (low) to red (high).

from Australia, 14.87–121.11 μg/g for Cu; *Ulva sp.* from Spain, 28130 μg/g for Cr; *Enteromorpha*-type from Australia, 320–2024 μg/g for Fe; *U. lactuca* from Norway, 10–80.7 μg/g for I; *Ulva sp.* from Spain, 8560 μg/g for Ni; and *Enteromorpha*-type from Australia, 55.66–212.22 μg/g for Zn (Arcos Limiñana et al., 2023; Gosavi et al., 2004; Roleda et al., 2021).

The concentration ranges of toxic minerals in cultivated *Ulva* species were as follows: As, 0.13–10.73 μg/g; Cd, 0.05–1.11 μg/g; Hg, 0.00082–0.21 μg/g; and Pb, 0.05–8.89 μg/g (for full information see supplementary material). The highest concentrations of these toxic minerals were observed in Enteromorpha-type from Australia, with As ranging from 5.43 to 10.73 μg/g, Cd from 0.36 to 1.11 μg/g, and Pb from 3.58 to 8.89 μg/g. Additionally, the highest Hg concentration (0.21 μg/g) was detected in *U. fenestrata* from Sweden (Gosavi et al., 2004; Stedt, Gustavsson, et al., 2022; Stedt, Steinhagen, et al., 2022).

Despite the concentration variability of the metal(oid) content of cultivated species, the maximum value of metal(oid)s is lower than that of wild species owing to better control of water management and monitoring. However, the minimum value of metal(oid)s is much higher than that of the wild ones. However, it is difficult to compare these values because the number of studies on cultivated species is less than that on wild species. In addition, the cultivation growth conditions are different in all studies (Tub water (TUB), Salt brine (SALT), Land-based integrated multi-trophic aquaculture (LB-IMTA), and Sea-based integrated multi-trophic aquaculture (SB-IMTA).

3.4. Hg and As speciation in Ulva species

Hg and As are highly toxic metals, but their toxicity varies significantly depending on their chemical species.

A total of 79% of the analytical results determined total As, whereas 8% had total and iAs. Only two papers focused on the speciation of As (including total As, iAs, and arsenate; organoarsenicals: MA, DMA, TMAO, TETRA, AB, AC; arsenosugars: Glu-sug, PO4-sug, SO3-sug, SO4-sug; and other forms of As). Only two papers analysed iAs (Locatelli & Torsi, 2002; Misheer et al., 2006).

The metal speciation of Hg in *Ulva* involves the uptake and accumulation of various mercury forms, including inorganic mercury (Hg^{2+}), MeHg (CH_3Hg), and potentially elemental mercury (Hg^0). The toxicity of these forms varies, with MeHg being the most toxic and bioaccumulative form. *Ulva* can store mercury in various forms within its tissues (Da Costa et al., 2020; Henriques et al., 2019), and its ability to sequester or detoxify mercury depends on the species biochemical processes, such as the production of sulphur-rich ligands and peptides.

The analysis of Hg represents 29% of the data. Most studies investigated total Hg, whereas only one analysed the total and organic forms of Hg (Coelho et al., 2005).

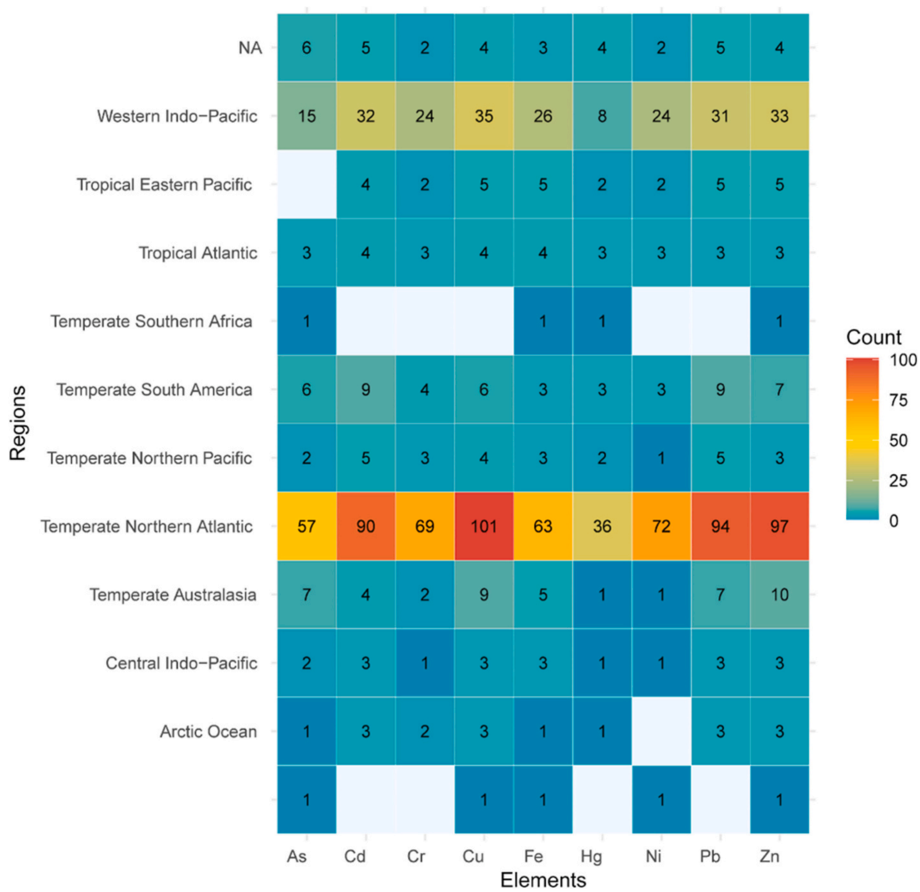

Fig. 4. Trends in publication counts for key elements (Cu, Cr, Fe, Ni, Zn, As, Cd, Hg, and Pb) across different marine regions, categorised based on Spalding et al. (2007). The plot displays the distribution of the studies, with the values in each cell representing the number of publications focused on a specific element within a given region. The heat map indicates publication counts, ranging from blue (low) to red (high).

4. Discussion

Over the past few decades, *Ulva*, commonly known as sea lettuce, has gained popularity as a food and feed ingredient owing to its rich nutritional profile and sustainable cultivation potential. This edible seaweed is an excellent source of proteins, vitamins, and minerals and offers health benefits due to its high fibre and antioxidant content (Holdt & Kraan, 2011). *Ulva* can be consumed fresh, dried, or cooked, making it a versatile supplement for a balanced diet.

Ulva cultivation provides a sustainable alternative to wild harvesting, reducing the ecological impact and ensuring product safety, particularly concerning metal(oid) accumulation under controlled conditions. However, wild-grown *Ulva* poses a concern because of its ability to accumulate toxic metals, necessitating regular monitoring. Data from this review indicate that cultivated *Ulva* generally contains lower levels of heavy metals than wild-harvested samples, making it a safer choice for food and feed applications (Holdt & Kraan, 2011; Kim et al., 2024).

Despite these advantages, the ability of *Ulva* to absorb metals is paradoxical. Although it plays a beneficial role in wastewater bioremediation by taking up and detoxifying metals in polluted environments, this same characteristic can pose risks if the accumulated metals enter the food chain. Thus, stringent assessment and regulatory measures are required to balance the environmental benefits of *Ulva* with food safety concerns, favouring tank-cultivated *Ulva* biomass over wild harvest.

Using axenic *Ulva* cultures or microbiome-manipulated systems can help clarify the role of bacteria in metal detoxification and trace metal acquisition, highlighting the complex symbiotic relationship between *Ulva* and its microbiome (Wichard, 2016). This topic needs to be investigated further to include microbial interactions that may influence metal uptake and detoxification mechanisms in *Ulva* cultivation.

Currently, published research focuses primarily on wild *Ulva* samples, whereas studies on cultivated or commercial varieties remain limited. Moreover, despite reviewing 176 peer-reviewed articles, *Ulva* species identification remains uncertain owing to substantial taxonomic ambiguity and methodological variability across studies. This inconsistency challenges the ability to draw definitive conclusions and underscores the need for standardised *Ulva* identification protocols in future research.

Beyond scientific uncertainty, species misidentification also creates barriers to regulatory approval and market access. Roleda and Heesch (2021) demonstrate that commercially available *Ulva* products are often incorrectly labeled, a situation that risks non-compliance with EU food/feed regulations and reduces consumer trust. Current food safety legislation often restricts *Ulva* use to a small number of historically accepted species. However, Roleda and Heesch (2021) argue for a shift toward function-based regulatory criteria, focusing on chemical composition and proven safety, rather than strict taxonomic boundaries. This approach could support more sustainable and scalable integration of *Ulva* into food and feed systems.

A comprehensive approach integrating controlled cultivation, species identification, microbiome research, and regulatory monitoring will be essential for maximising the benefits of *Ulva* while mitigating potential risks. Standardised methodologies for metal analysis, risk assessments, and safety evaluations must be implemented to ensure its sustainable use in food, feed, and environmental applications. By addressing these research gaps, *Ulva* can be safely integrated into commercial markets as a nutritious and environmentally beneficial

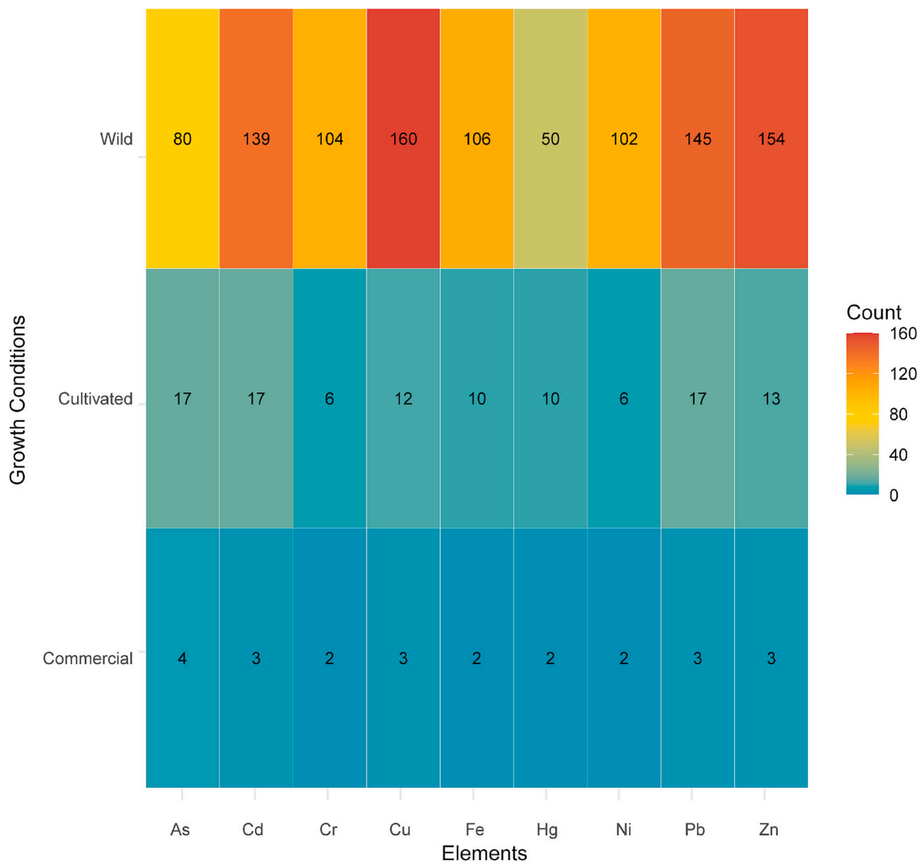

Fig. 5. Trends in publication counts for key elements (Cu, Cr, Fe, Ni, Zn, As, Cd, Hg, and Pb) across the three growth conditions: wild, cultivated, and commercial. The plot illustrates the distribution of studies, with the values in each cell representing the number of publications focused on a specific element under each growth condition. Colour intensity reflects publication counts, ranging from blue (low) to red (high).

resource.

This review highlights the potential of *Ulva* as a source of essential elements, such as calcium, magnesium, Fe, Cu, and Zn, while also addressing the risks associated with its accumulation of toxic metals, including As, Cd, Cr, Hg, Ni, and Pb. Furthermore, the role of metallophores, biogenic ligands that facilitate metal ion uptake, is crucial for understanding metal homeostasis and detoxification. These metallophores, produced by the microbiome of *Ulva*, provide insights into fundamental biological mechanisms and their applications in environmental and aquaculture sciences (Vega-Gomez et al., 2024).

4.1. Methodological differences

This review examines the various methodologies employed that affect the comparability of results. Differences in sampling techniques, analytical methods, reference materials, and the environmental conditions of the *Ulva* samples (*e.g.*, wild versus cultivated) contribute to discrepancies in metal accumulation data, complicating the overall understanding of *Ulva*'s metal absorption process.

4.2. Environmental and geographical influence

This study underscores the impact of environmental and geographical factors on metal accumulation in *Ulva*. Samples from industrialised or polluted regions generally show high concentrations of toxic metals, emphasising the importance of careful site selection for tank cultivation and monitoring the incoming water flow to minimise health risks.

Accurate species identification in *Ulva* is unreliable because it is solely based on morphological characteristics. Molecular genetics, particularly DNA barcoding, is essential for reliable species-level identification. The studies reviewed indicate that *Ulva* has potential as a nutrient source, but significant risks are associated with toxic metal accumulation. The challenges of uncertain species identification and methodological inconsistencies have tempered these findings.

For the food industry, every batch of *Ulva*—whether wild-harvested or cultivated—must be analysed to ensure its safety for use within legislative parameters, providing a healthy product for consumers.

4.3. Metal accumulation

Ulva species can accumulate both essential and toxic metals, making them a subject of interest for various applications. Essential elements, such as Fe and Zn, which are critical for *Ulva* growth and human health, are found in varying concentrations among species. The presence of essential nutrients for human health highlights the potential of *Ulva* as a nutrient source, although the variability reduces its usefulness. However, the presence of toxic elements, such as As, Cd, and Pb, raises concerns regarding food safety for human consumption or the use in animal feed. This necessitates nutritional analysis, especially metal analysis per batch, as a safety assessment to mitigate these risks.

4.4. Non-toxic metal levels

Ulva is a valuable source of essential metals, such as magnesium, calcium, Fe, and Zn, in varying concentrations across species and regions. For example, *E. compressa* from India and *U. clathrate* from Saudi Arabia show high levels of these minerals and metals, indicating their potential use in dietary supplements. However, the high level of variability must be considered when using *Ulva* for nutritional purposes which homogenising batches can mediate.

4.5. Toxic metal levels

Some *Ulva* species with toxic metals pose environmental and health risks. For example, *U. compressa* and *U. fasciata* from Egypt show elevated levels of Cd and Pb, suggesting localised pollution and the need for targeted environmental assessments. These levels sometimes exceed the established safety limits, posing considerable risks for human consumption and animal feed without proper processing. Hence, it is important especially for food and feed applications to source, if wild-harvested, from pristine areas. This risk considerably less with cultivated *Ulva,* as the inflow water of tank systems can be pre-assessed and monitored.

4.6. Species-specific trends in metal accumulation

Certain *Ulva* species exhibit higher concentrations of specific metals, indicating their potential for bioaccumulation studies and environmental monitoring. For instance, *E. compressa* from India shows high levels of Zn and moderate levels of Cu. Additionally, *U. australis* from Australia has notably high Zn levels, reflecting species-specific trends in metal accumulation.

4.7. Geographical variations in metal levels

Metal concentrations in *Ulva* vary across countries (see Fig. 4 and Supplementary material), influenced by regional environmental conditions and pollution sources, such as oil refineries or tanneries. For example, Indian samples exhibited high levels of Fe and Zn, whereas Saudi Arabia samples showed elevated levels of Cr and Ni. Nevertheless, gaps in the datasets for certain metals in some countries limit comprehensive comparisons, highlighting the need for more uniform data collection coupled with proper species identification.

4.8. Environmental monitoring

The capacity of *Ulva* to accumulate essential and toxic metals makes it a promising bioindicator for environmental pollution. Certain species, such as *Ulva compressa* and *Ulva fasciata,* have demonstrated significant metal uptake abilities, making them useful for bioremediation and environmental monitoring. The variability in metal concentrations across species and countries suggests that *Ulva* can be an effective bioindicator for monitoring environmental pollution on a circumglobal scale for assessing marine ecosystem health.

4.9. Risk assessments and safety protocols

Developing robust health risk assessments and safety protocols is imperative. Especially under the EU feed regulations (S.I. No. 22/2020) - European Union (Food and Feed Hygiene) Regulations 2020; Feed Materials Regulation (EU) 68/2013; Feed Additive Regulation (EC) 1831/2003; Feed Contaminants Directive 2002/32/EC; Pesticide Residues Regulation (EC) 396/200; and food regulations (Novel Food Regulation (EU) 2015/2283 Food Additive Regulation (EC) 1333/2008 Food Contaminants Regulation (EC) 1881/2006 Pesticide Residues Regulation (EC) 396/2005 Seaweed Contaminants Recommendation COM 2018/464 Fishery and Agriculture Products Labelling Regulation (EU) 1379/2013 Nutrition and Health Claim Regulation (EC) No 1924/200). Therefore, these assessments must be executed to develop, market, or sell food and feed products in the EU. The risks posed by toxic metals will be addressed by performing these assessments. It will also advance the research and exploration of new processing methods to mitigate these risks, ensuring that *Ulva* remains a safe and valuable dietary choice for humans and animals.

4.10. Research gaps and recommendations for research and regulation

Current research shows a significant focus on wild samples, whereas studies on cultivated or commercial varieties remain limited. Research should prioritise controlled systems that standardise growth conditions and metal uptake mechanisms. Additionally, the limited investigation into Hg and As speciation within *Ulva* highlights a crucial knowledge gap, emphasising the need for further exploration to assess consumption safety and environmental impact.

Standardising methodologies for sampling, analysis, and data reporting is essential for improving the comparability of results across studies. Inconsistencies in measurement techniques hinder meaningful comparisons, emphasising the need for a unified methodological framework. Advanced analytical techniques, such as isotope ratio analysis and metal speciation studies, should be used to understand the sources, bioavailability, and toxicity of metals in *Ulva* products. These techniques will enhance safety evaluations and provide insights into metal accumulation dynamics.

Expanding research efforts to underrepresented *Ulva* species and geographical regions is crucial to better understand species-specific metal uptake and environmental influences. Longitudinal studies should be conducted to monitor seasonal and temporal variations in metal accumulation in order to identify the safest sources for cultivation and harvest. Additionally, health risk assessments must be prioritised to evaluate the safety of *Ulva* for human and animal consumption. This includes toxicological studies on heavy metal bioavailability, potential synergistic effects, and acceptable intake limits.

Accurate species identification remains a major challenge owing to taxonomic ambiguity. Future studies should use molecular genetics, including DNA barcoding, to enhance classification and allow for better cross-study comparisons. Understanding microbiome interactions is also necessary, as *Ulva*-associated bacteria play a critical role in metal detoxification and nutrient assimilation. Investigating these microbial communities will provide insights into natural detoxification mechanisms and their applications in aquaculture and environmental sustainability.

Different *Ulva* species, although often morphologically indistinguishable, may exhibit markedly different chemical profiles and elemental compositions, with direct implications for their nutritional value and safety in food and feed applications (Roleda & Heesch, 2021). This variability underscores a major research and regulatory gap: the lack of routine molecular- level species identification. Misidentification remains a persistent issue, as exemplified by the historical mislabeling of *Ulva lactuca*, which has since been reclassified in Europe as *U. fenestrata*. Such taxonomic confusion complicates safety assessments, traceability, and standardization of products. Given that species-specific differences can influence palatability, bioavailability, and metal accumulation, future studies and regulations should mandate molecular identification protocols to improve quality control, ensure consumer safety, and support accurate labeling in commercial applications.

Legislative and regulatory frameworks need to be strengthened to ensure the safe commercial use of *Ulva*. Policymakers should establish clear guidelines for metal thresholds in *Ulva*-based products, ensuring compliance with food and feed safety standards. Risk management strategies, such as rigorous monitoring and processing methods, should be implemented to mitigate contamination risks and optimise the nutritional benefits of *Ulva*.

By addressing these research priorities, *Ulva* can be safely integrated into food, feed, and environmental applications while maximising its potential benefits as a bioremediation tool and nutrient source. Developing robust health risk assessments, improving species identification, and enhancing cultivation and processing techniques will allow for the responsible utilisation of *Ulva* in various industries, ensuring both sustainability and consumer safety.

5. Conclusions

The dual role of *Ulva* species as both valuable nutritional resources and bio accumulators of potentially toxic metal(oid)s. While *Ulva* offers promising opportunities for food and feed applications due to its protein, fatty acid, mineral, and antioxidant content, its capacity to absorb heavy metals from the environment requires careful assessment.

In response to the central question of this review, whether we should be worried about metal(oid)s in *Ulva*, our findings indicate that concern is justified mainly for wild-harvested biomass, especially from polluted environments. However, when cultivated under controlled and monitored conditions, *Ulva* can be safely used in food and feed, provided that metal levels are routinely assessed and regulatory standards are upheld.

Our synthesis of 176 peer-reviewed studies reveals significant variability in elemental composition across species, geographic regions, and cultivation systems. Notably, cultivated *Ulva*, particularly from controlled systems, consistently exhibits lower levels of toxic elements compared to wild samples, reinforcing its suitability for safe use in food and feed when properly managed.

A key challenge identified is the lack of species-level identification, which complicates both scientific interpretation and regulatory oversight. Even morphologically similar *Ulva* species can vary considerably in their chemical profiles, which affects both safety and nutritional assessments.

This necessitates the implementation of mandatory molecular identification protocols and enhanced taxonomic precision in research and commercial production.

Furthermore, the presence of metallophores and the influence of the *Ulva*-associated microbiome suggest underexplored pathways for natural detoxification, with implications for both food safety and bioremediation strategies.

To unlock the full potential of *Ulva* in circular food systems, future efforts must prioritise:

- Molecular taxonomy to ensure traceability and safety
- Standardised methodologies for metal analysis and risk assessment
- The use of controlled cultivation systems
- Development of functional criteria in legislation beyond species-based approval

By addressing these critical knowledge and regulatory gaps, *Ulva* can be responsibly integrated into sustainable aquaculture, and the broader food, feed, and nutraceutical sectors.

CRediT authorship contribution statement

Liliana Vargas-Murga: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Ömerhan Dürrani:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Jessica Adams:** Writing – review & editing, Writing – original draft, Conceptualization. **Sophie Steinhagen:** Writing – review & editing, Writing – original draft, Conceptualization. **Gamze Turan:** Writing – review & editing, Writing – original draft, Conceptualization. **Edlira Aruçi:** Writing – review & editing, Writing – original draft, Conceptualization. **Liam Morrison:** Writing – review & editing, Writing – original draft, Conceptualization. **Thomas Wichard:** Writing – review & editing, Writing – original draft, Conceptualization. **Stefan Kraan:** Writing – review & editing, Writing – original draft, Conceptualization. **Muki Shpigel:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodchem.2025.145941.

Data availability

The authors declare that the data supporting the findings of this study are available within the paper and its Supplementary Information files.

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