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The concentration of magnesium and potassium in sea water, in abalone, and *Sargassum* sp. in rainy season and dry season

Konsentrasi magnesium dan kalium pada air laut, abalon, dan *Sargassum* sp. saat musim hujan dan kemarau

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ABSTRACT

The increasing global demand for high-protein foods has heightened interest in high-quality fishery products such as abalone. This study examined seasonal variations in magnesium (Mg^{2+}) and potassium (K^{+}) concentrations in natural abalone (*Haliotis squamata*) tissues, surrounding seawater, and associated *Sargassum* sp. Sampels were collected during the rainy and dry seasons of 2023 from coastal waters in Pekutatan, Jembrana, Bali. Ion concentrations were measured using atomic absorption spectrophotometry (AAS), and proximate composition was analyzed for both abalone meat and *Sargassum* sp. Results revealed higher Mg^{2+} and K^{+} concentrations in abalone meat and shell during the rainy season. Similarly, *Sargassum* sp. showed greater ion accumulation during the rainy season, while seawater displayed contrasting trends: Mg^{2+} levels were higher in the dry season, whereas K^{+} levels increased during the rainy season. Proximate analysis indicated higher protein (48.03 ± 0.89%) and moisture (21.56 ± 0.90%) contents in abalone meat during the rainy season. In contrast, most nutrient components in *Sargassum* sp. peaked during the dry season, except for ash content, which was highest during the rainy season (48.94 ± 0.63%). These findings suggest that seasonal changes significantly affect ionic uptake and nutritional quality in aquatic organisms through complex environmental-physiological interactions.

Keywords: *Haliotis squamata*, magnesium, potassium, *Sargassum* sp., seasonal variation

ABSTRAK

Meningkatnya permintaan global akan makanan berprotein tinggi telah meningkatkan minat terhadap produk perikanan berkualitas tinggi seperti abalon. Penelitian ini meneliti variasi musiman dalam konsentrasi magnesium (Mg^{2+}) dan kalium (K^{+}) pada jaringan abalon alami (*Haliotis squamata*), air laut di sekitarnya, dan *Sargassum* sp. Sampel dikumpulkan selama musim hujan dan musim kemarau pada tahun 2023 dari perairan pesisir di Pekutatan, Jembrana, Bali. Konsentrasi ion diukur menggunakan spektrofometri serapan atom (AAS), dan komposisi proksimat dianalisis untuk daging abalon dan *Sargassum* sp. Hasil penelitian menunjukkan konsentrasi Mg^{2+} dan K^{+} yang lebih tinggi pada daging dan cangkang abalon selama musim hujan. Demikian pula, *Sargassum* sp. menunjukkan akumulasi ion yang lebih besar selama musim hujan, sementara air laut menunjukkan tren yang kontras: kadar Mg^{2+} lebih tinggi pada musim kemarau, sedangkan kadar K^{+} meningkat pada musim hujan. Analisis proksimat menunjukkan kandungan protein (48.03 ± 0.89%) dan kelembapan (21.56 ± 0.90%) yang lebih tinggi pada daging abalon selama musim hujan. Sebaliknya, sebagian besar komponen nutrisi pada *Sargassum* sp. mencapai puncaknya pada musim kemarau, kecuali kadar abu, yang paling tinggi pada musim hujan (48.94 ± 0.63%). Temuan ini menunjukkan bahwa perubahan musim secara signifikan mempengaruhi serapan ion dan kualitas nutrisi pada organisme akuatik melalui interaksi lingkungan-fisiologis yang kompleks.

Kata kunci: *Haliotis squamata*, kalium, magnesium, *Sargassum* sp., variasi musiman

INTRODUCTION

Various issues in global economic development, such as the increasing demand for protein-rich foods, have led to a rising demand for high-quality fisheries products, including abalone. The demand for abalone, both in live and dried forms, continues to increase and has contributed to the decline of wild abalone populations due to non-selective harvesting practices. Another contributing factor is the limited availability of abalone hatcheries, resulting in continued reliance on wild capture, which further exacerbates population depletion. This product contains high-value bioactive components such as proteins, lipids, and essential minerals (Sharma *et al.,* 2020). In addition to genetic factors, the quality of seafood products is also strongly influenced by environmental characteristics. Aquatic environments undergo seasonal variations driven by temperature, salinity, pH, and other physicochemical parameters (Norouzi & Tavani, 2016).

In response to these environmental changes, the nutritional composition of aquatic organisms may also vary within certain physiological limits. Reduced growth rates due to stress and declining environmental quality such as fluctuations in temperature, salinity, pH, and other factors can increase susceptibility to mortality in aquatic organisms. Climate change has the potential to alter fundamental ecological processes and impact marine and aquaculture systems through sea level rise and shifts in precipitation patterns. The performance of marine aquatic organisms across seasonal transitions, from the rainy to the dry season, reflects phenological differentials among interacting species, which may influence population dynamics through reproductive success and/or increased competition (Visser & Gienapp, 2019; Wann *et al.,* 2019; Zimova *et al.,* 2016).

Climate change exerts significant effects on the physiology, growth patterns, and behavior of aquatic organisms, including abalone, which represents an economically important species in marine aquaculture (Shanks *et al.,* 2020; Émond *et al.,* 2020). The relatively slow growth rate of abalone necessitates evaluation of factors influencing tissue and shell formation, particularly the roles of magnesium (Mg^{2+}) and potassium (K^+) ions. This study was conducted through the analysis of Mg^{2+} and K^+ concentrations in abalone tissues of various size classes, seawater from their natural habitats, and macroalgae as their primary feed source. The objective is to comprehensively understand ionic homeostasis dynamics and intra- and extracellular structural regulation in supporting abalone growth. In addition to abalone, physiological responses to temperature changes have been observed in other marine organisms, providing comparative insights into adaptive mechanisms. Water temperature fluctuations of up to 10°C reflect seasonal differences between winter (approximately 10°C) and summer (approximately 25°C).

Temperature is a critical environmental factor influencing physiological processes and energy metabolism in hybrid Australian abalone (*Haliotis rubra* × *Haliotis laevigata*). Elevated temperatures tend to increase nutritional requirements, including protein intake, which contributes to improved nutritional quality of abalone tissues (Hassan *et al.,* 2023; Rizzo *et al.,* 2024). Silver carp (*Hypophthalmichthys molitrix*) produce two types of proteins depending on the season: heat-stable proteins during summer and thermolabile proteins during winter (Abe *et al.,* 2020). Seasonal variation in biochemical composition is closely associated with age, sex, and reproductive status, and should be considered in environmentally adaptive abalone aquaculture strategies. Energy efficiency in abalone is largely influenced by temperature and feed availability.

Based on the dynamic energy budget model in *Haliotis discus hannai*, elevated temperatures may enhance energy allocation for growth and physiological maintenance (Duan *et al.,* 2021). Furthermore, recent metabolomic studies indicate that carbohydrate utilization as a primary energy source plays a crucial role in abalone adaptation to changing environmental conditions, including low-temperature environments (Venter *et al.,* 2022; Xu *et al.,* 2020). Therefore, understanding the dynamics of abalone energy metabolism requires consideration of seasonal environmental factors that influence growth performance and nutrient utilization efficiency. Minerals, including sodium and potassium used to enhance growth, are primarily derived from abalone feed (Bansemer *et al.,* 2016). Many minerals are supplemented in formulated diets; however, some are considered unnecessary because abalone can absorb certain minerals directly from the surrounding water (Musharraf & Khan, 2018). Therefore, to systematically understand the nutritional quality of abalone, it is essential to consider seasonal variations in nutrient composition.

Magnesium requirements vary among fish species (Evans *et al.,* 2021; Iglikowska *et al.,* 2017). Magnesium uptake from the aquatic environment is generally insufficient to meet metabolic demands, resulting in frequent occurrences of magnesium deficiency across species (Evans *et al.,* 2021). Deficiency symptoms include impaired growth, anorexia, high mortality, lethargy, and reduced bone quality (Lall & Kaushik, 2021). Magnesium also plays a critical role in protein synthesis, and suboptimal levels reduce the efficiency of this process (Wei *et al.,* 2018; Sun *et al.,* 2018). Among macrominerals, potassium (K^+) is the principal intracellular ion involved in various physiological functions, including nerve impulse transmission, maintenance of membrane potential, acid–base balance, and osmoregulation (Chen *et al.,* 2016; Kumar *et al.,* 2020).

Potassium plays a significant role in abalone physiology, not only as the primary intracellular ion but also in enhancing nutrient digestibility. It has been shown to increase pepsin enzyme activity, thereby improving protein and amino acid digestibility (Shi *et al.,* 2020). Aquaculture studies have utilized potassium both as a dietary supplement and as an indicator of specific nutritional requirements. Potassium deficiency negatively affects abalone growth; therefore, optimal levels of potassium and protein intake are required to support optimal growth performance (Latuihamallo *et al.,* 2019; Jia & Liu, 2018). This study aims to analyze the concentrations of magnesium and potassium in the meat and shells of wild abalone, the seawater of their natural habitats, and *Sargassum* sp. as a natural feed source, across both the rainy and dry seasons.

MATERIALS AND METHODS

Sampling method

Sampling of wild abalone and *Sargassum* sp. was conducted by SCUBA diving at a depth of approximately ±2.5 m. Seawater samples were collected by submerging sample bottles into the water column at a depth of approximately ±50 cm. Wild abalone samples were categorized into two size classes with mean shell lengths of 30.813 ± 4.62 mm and 50.313 ± 5.41 mm, collected during the rainy season (November–February) and the dry season (March–May). A total of 40 wild abalone specimens were collected, of which 32 individuals were used for the analysis of Mg^{2+} and K^+ concentrations across both seasons. These samples were divided into two size groups, with mean lengths of 30.813 ± 4.62 mm and 50.313 ± 5.61 mm, respectively.

For mineral analysis using atomic absorption spectrophotometry (AAS), each ion (Mg^{2+} and K^+) was analyzed in 11 individual abalone per season (n = 11 per season per ion), as illustrated in Figures 1a and 1b. The sample types analyzed included wild abalone (*Haliotis squamata*), *Sargassum* sp., and seawater. All samples were collected from the coastal waters of Pekutatan, Mendoyo District, Jembrana Regency, Bali, at coordinates 8°09′13.4″S–114°42′51.9″E, during January 2023 and April 2023. This study was conducted by analyzing the concentrations of magnesium (Mg^{2+}) and potassium (K^+) in abalone tissue and shell, seawater, and *Sargassum* sp. as a natural feed source.

Magnesium and potassium analysis

Analytical methods for Mg^{2+} and K^+

The concentration of Mg^{2+} in abalone tissue, shell, and *Sargassum* sp. samples was determined using the AAS method. The analysis of Mg^{2+} and K^+ concentrations in abalone tissue, shell, and *Sargassum* sp. was conducted at the Dairy Nutrition Laboratory, Department of Nutrition Science and Feed Technology, Faculty of Animal Science, IPB University. Meanwhile, the analysis of Mg^{2+} and K^+ concentrations in seawater was carried out using AAS in accordance with the

Figure 1. a = morphology of abalone, b = tissue (meat) of wild abalone.

Indonesian National Standard (SNI, 2005) at the Department of Chemistry Laboratory, Faculty of Mathematics and Natural Sciences, IPB University. For sample preparation, 1 g of abalone tissue, shell, and *Sargassum* sp. was placed into a 125 mL (or 100 mL) Erlenmeyer flask, followed by the addition of 5 mL concentrated HNO_3. The mixture was allowed to stand for 1 hour at room temperature in a fume hood. Subsequently, the samples were heated on a hot plate at 80°C for 4–6 hours (within the fume hood). The samples were then covered and left overnight in the fume hood.

Afterward, 0.4 mL concentrated H_2SO_4 was added, and the mixture was reheated on a hot plate for 1 hour until the solution became more concentrated. Then, 2–3 drops of a mixed solution of $HClO_4$: HNO_3 (2:1) were added. The samples were heated again until a sequential color change occurred from brown to dark yellow and then to light yellow. Once the color change was observed, heating was continued for an additional 10–15 minutes. The samples were then cooled, followed by the addition of 2 mL distilled water and 0.6 mL concentrated HCl, and reheated for approximately 15 minutes until complete dissolution was achieved. The solution was transferred into a 100 mL volumetric flask.

If precipitates were present, filtration was performed using filter paper or glass wool. The final solution was stored and subsequently analyzed for Mg^{2+} content using AAS. The analytical procedures for Mg^{2+} and K^+ in abalone tissue, shell, and *Sargassum* sp. were identical, with the only difference being the cathode lamp wavelength used in the spectrophotometer. The wavelengths were set at λ = 285.2 nm for Mg^{2+} and λ = 766.5 nm for K^+.

Analysis of Mg^{2+} and K^+ concentrations in seawater

Analytical method for seawater Mg^{2+}

Seawater samples were filtered using a 0.45 μm membrane prior to analysis. This filtration process was applied for both Mg^{2+} and K^+ analyses due to their similar analytical principles. A total of 10 mL of filtered seawater was pipetted into a 100 mL volumetric flask, diluted, and acidified with 0.05 M HNO_3 to the calibration mark. The solution was homogenized, and 10 mL of this solution was pipetted again into another volumetric flask and diluted with 0.05 M HNO_3 to volume. After homogenization, 2 mL of the solution was further pipetted and diluted again with 0.05 M HNO_3.

For K^+ analysis, standard solutions were prepared by adding 0.05 M HNO_3 to the stock solution, followed by homogenization and transfer into a volumetric flask containing a 10 ppm K^+ standard. Calibration curves were prepared for both Mg^{2+} and K^+ with concentrations of 0.0 ppm, 0.1 ppm, 0.2 ppm, 0.6 ppm, and 0.8 ppm. The distinction between Mg^{2+} and K^+ analysis lies in the wavelength settings used in AAS, namely λ = 285.2 nm for Mg^{2+} and λ = 766.5 nm for K^+.

Proximate analysis

Proximate analysis of abalone tissue and *Sargassum* sp. samples was conducted based on standard methods from the Association of Official Analytical Chemists (AOAC, 1990). Moisture content was determined using oven-drying at 105°C until constant weight was achieved. Protein content was analyzed using the Kjeldahl method, which includes digestion with concentrated sulfuric acid, ammonia distillation, and titration, with the result converted into protein content using a factor of 6.25. Lipid content was determined using the Soxhlet extraction method with anhydrous ether as the solvent. Crude fiber was analyzed through sequential digestion using 0.255 N sulfuric acid and 0.313 N sodium hydroxide, followed by drying and weighing of the residue. Ash content was determined through dry ashing in a muffle furnace at 550°C for five hours until a stable white or light-colored ash was obtained. Nitrogen-free extract (NFE) or soluble carbohydrate content was calculated by difference using the formula:

$$\text{NFE (\%)} = \begin{array}{c}100 - (\text{moisture} + \text{ash} + \text{protein} \\ + \text{crude fiber} + \text{lipid})\end{array}$$

All analyses were conducted in duplicate to ensure data validity and reproducibility.

Data analysis

Data analysis was performed using a non-parametric approach with a descriptive-comparative framework, in accordance with the characteristics of the data obtained from sampling without replication and without experimental treatment design. Data were collected from two different seasons, namely the rainy and dry seasons, and included Mg^{2+} and K^+ ion concentrations in abalone tissue, shell, and *Sargassum* sp.. Data tabulation and preliminary processing were conducted using Microsoft Excel 2020. Descriptive statistical analysis and exploration of seasonal differences were performed using SPSS Statistics version 24.

RESULTS AND DISCUSSION

Results

Mg^{2+} and K^{+} concentrations in abalone tissue and shell

The concentration of Mg^{2+} in the soft tissue of wild abalone with size classes of 30.813 ± 4.62 mm and 50.313 ± 5.41 mm was higher during the rainy season compared to the dry season. A similar pattern was observed in the shell matrix, where Mg^{2+} content increased during the rainy season. The same trend was also evident for K^{+} concentrations in both soft tissue and shell across the two size groups, consistently showing higher mineral content during the rainy season than in the dry season (Table 1).

Mg^{2+} and K^{+} concentrations in Sargassum sp. and seawater across seasons

The concentrations of Mg^{2+} and K^{+} in *Sargassum* sp. tended to be higher during the rainy season compared to the dry season, indicating seasonal variation in the accumulation of these ions (Figure 2). In contrast, Mg^{2+} concentrations in seawater were generally higher during the dry season than in the rainy season. Conversely, K^{+} concentrations exhibited a tendency to be higher during the rainy season compared to the dry season (Figure 3).

Proximate analysis of wild abalone tissue

All proximate composition parameters of wild abalone tissue namely moisture, protein, lipid, and crude fiber showed higher values during the rainy season compared to the dry season. In contrast, the nitrogen-free extract (NFE) content was higher during the dry season (Table 2).

Proximate composition of Sargassum sp.

The proximate composition of *Sargassum* sp. indicates that moisture, lipid, crude fiber, and nitrogen-free extract (NFE) contents tend to be higher during the rainy season compared to the dry season. In contrast, ash and protein contents tend to be higher during the dry season (Table 3).

Table 1. Concentrations of Mg^{2+} and K^{+} in the soft tissue and shell of wild abalone during the rainy and dry seasons.

Size of abalone (mm)	Concentration Mg^{2+} (g/kg)			
	Abalone meat		Abalone shell	
	Rainy season	Dry season	Rainy season	Dry season
30.813 ± 4.62	3.215 ± 0.13	0.585 ± 0.04	3.140 ± 0.14	0.256 ± 0.01
50.313 ± 5.41	2.560 ± 0.03	0.509 ± 0.06	0.605 ± 0.01	0.145 ± 0.00
	Concentration K^{+} (g/kg)			
30.813 ± 4.62	10.125 ± 0.18	3.256 ± 0.09	0.413 ± 0.02	0.135 ± 0.01
50.313 ± 5.61	11.625 ± 0.18	2.768 ± 0.13	0.363 ± 0.05	0.090 ± 0.00

Note: abalone size categories are presented, and Mg^{2+} and K^{+} concentrations in tissue and shell are expressed as mean values.

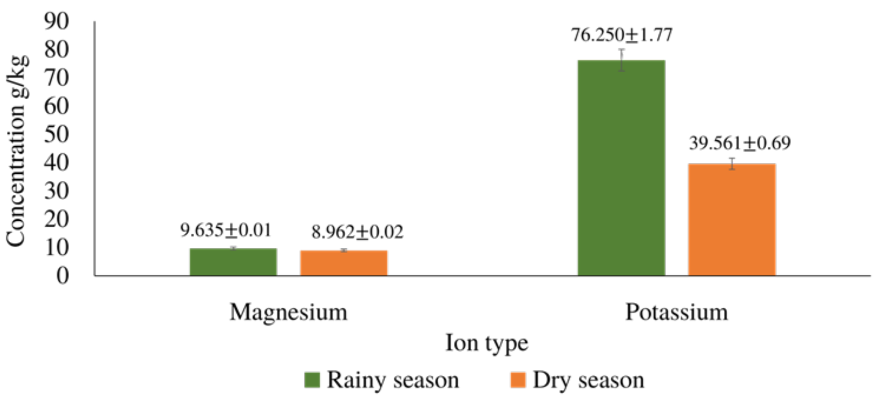

Figure 2. Mg^{2+} and K^{+} concentrations in *Sargassum* sp. during the rainy and dry seasons.

Water quality parameters during the rainy and dry seasons in the coastal waters of Pekutatan Village, Jembrana Regency, Bali

Water quality in the coastal waters of Pekutatan Village across both seasons remained within the optimal range for the growth of abalone and other aquatic organisms, as presented in Table 4.

Discussion

The concentrations of Mg^{2+} and K^{+} ions in the tissue and shell of wild abalone exhibited clear seasonal variation, with higher values observed during the rainy season compared to the dry season. This pattern is likely associated not only with hydrological and physiological processes but also with biological dynamics in the aquatic environment, such as increased growth of phytoplankton and macroalgae (*Sargassum* sp.), which tend to be more intensive during the rainy season. Increased rainfall and terrestrial runoff during this period enhance nutrient availability, thereby stimulating primary productivity, including the growth of phytoplankton and macroalgae (Brandt *et al.*, 2023; Crespo *et al.*, 2022; Adiguna *et al.*, 2021; Muhtadi, 2017). As illustrated in Figure 2, *Sargassum* sp. shows potential for mineral accumulation by absorbing Mg^{2+} and K^{+} from seawater, functioning as a

Table 2. Proximate composition of wild abalone tissue during the rainy and dry seasons.

Season	Proximate composition (%)					
	Moisture	Ash	Protein	Lipid	Crude fiber	NFE
Rainy season	21.56 ± 0.90	8.55 ± 0.30	48.03 ± 0.89	5.14 ± 0.28	0.43 ± 0.26	16.61 ± 2.62
Dry season	19.55 ± 0.68	7.95 ± 0.81	47.04 ± 0.62	4.87 ± 0.16	0.35 ± 0.08	20.25 ± 2.27

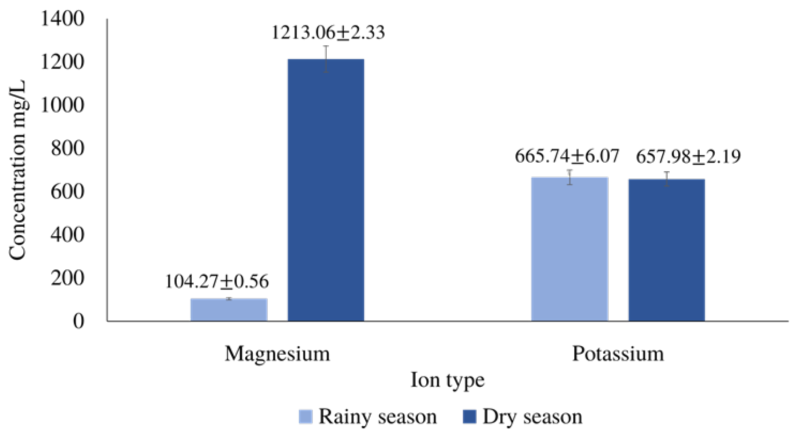

Figure 3. Mg^{2+} and K^{+} concentrations in seawater during the rainy and dry seasons.

Table 3. Proximate composition of *Sargassum* sp. during the rainy and dry seasons.

Season	Proximate composition (%)					
	Moisture	Ash	Protein	Lipid	Crude fiber	NFE
Rainy	11.00 ± 0.09	34.65 ± 0.13	6.92 ± 0.09	0.67 ± 0.08	6.43 ± 0.04	40.33 ± 0.21
Dry	6.56 ± 0.05	48.94 ± 0.63	9.47 ± 0.02	0.56 ± 0.01	3.83 ± 0.05	30.65 ± 0.53

Table 4. Range of water quality parameters during the rainy and dry seasons in the coastal waters of Pekutatan Village.

Season	Parameter			
	Salinity (ppt)	Temperature (°C)	DO (ppm)	pH
Rainy	29-32	25.4-29.3	5.8-6.6	7.8-8.0
Dry	30-35	26.3-32.5	5.7-6.1	8.0-8.2

natural feed source for wild abalone. This process contributes to elevated concentrations of these ions in abalone tissues during the rainy season.

Furthermore, changes in algal structure and biological activity across growth stages and age may also influence ion content within macroalgal tissues. Thus, mineral transfer from algae to abalone represents a key mechanism explaining the seasonal increase in Mg^{2+} and K^{+} concentrations (Hur *et al.,* 2023). Although the data were obtained from a single seasonal cycle, the results provide a clear indication of ion regulation patterns in marine organisms in response to local seasonal fluctuations. Long-term studies are needed to determine whether these dynamics represent short-term adaptive responses or broader ecological trends associated with environmental change. These findings highlight seasonal variability as a potential early indicator of larger-scale ecological shifts.

Changes in oceanographic conditions during the rainy season, such as reduced salinity and fluctuations in sea surface temperature, also influence community structure and the distribution of marine organisms that serve as natural food sources for abalone. Environments that support the growth of algae and phytoplankton not only enhance food availability but also increase the supply of mineral ions within the food web. This reflects the close interaction between ecosystem dynamics and marine animal physiology (Muniz *et al.,* 2021). The physiological response of abalone to environmental conditions is strongly influenced by external factors such as temperature, feed quality, and seasonal variability. According to Volkoff and Rønnestad (2020), the response of aquatic organisms to temperature changes depends on the duration, intensity, and rate of temperature variation. Additionally, Shi *et al.* (2020) demonstrated that abalone can absorb minerals not only through dietary intake but also directly from seawater, consistent with their habitat characteristics.

Seasonal variability in Mg^{2+} and K^{+} concentrations may also reflect differences in metabolic efficiency and feed conversion among individuals. Environmental factors such as thermal stratification, ion distribution in the water column, and seasonal changes in water quality can impose physiological stress, affecting growth rates and mineral accumulation in abalone tissues. Therefore, seasonality serves as an important determinant of mineral bioaccumulation through both dietary pathways and physiological processes. Previous studies by Beever *et al.* (2016), Foden & Young (2016), and Kovach *et al.* (2019) have shown that climate change drives significant variability in physiological and ecological responses among aquatic organisms. This study highlights differences in the nutritional composition of wild abalone (*Haliotis squamata*) between the rainy and dry seasons. These differences are closely linked to variations in the type and mineral content of natural feed available in their habitat. Each aquatic species has specific dietary requirements and feeding preferences influenced by morphological, physiological, behavioral, and environmental factors.

The proximate composition of abalone tissue including protein, lipid, moisture, ash, and minerals such as calcium, phosphorus, magnesium, sodium, and potassium is strongly influenced by the quality and type of feed consumed. Individual age and environmental dynamics also contribute to the accumulation of these components. Feeding success depends on the availability of suitable food and the organism's mobility, with feeding behavior involving a sequence of processes including detection, capture, and ingestion (Assan *et al.,* 2021; Conde-Sieira & Soengas, 2017; Gomes *et al.,* 2022). Seasonal transitions from the rainy to the dry period significantly affect nutrient and mineral uptake dynamics in aquatic organisms. Although this phenomenon is seasonal, the underlying mechanisms are closely related to biological and physiological responses that are also relevant in the context of long-term climate change.

Climate change systematically influences both physical and biological conditions of aquatic environments, including growth patterns, fertilization, and community structure. Lin *et al.* (2021) reported that climate change impacts entire trophic chains in aquatic ecosystems, ultimately affecting productivity and fish availability. Environmental factors such as temperature and solar radiation play key roles in determining nutrient availability, which underpins primary productivity and the sustainability of aquatic populations. Ecologically, seasonal environmental variation is closely associated with the availability and quality of natural feed, which in turn influences the nutritional composition of wild abalone. Macroalgae such as *Ulva lacilunata* and *Codium tomentosum* exhibit significant seasonal changes in mineral, protein, and lipid content (Sousa *et al.,* 2025). Kumar *et al.* (2021) also emphasized the influence of physicochemical factors such as temperature and salinity on the bioactive composition of macroalgae. Consequently, wild abalone feeding on such algae may exhibit higher levels of saturated fatty acids compared to cultured abalone (Li *et al.,* 2024; Liu *et al.,* 2023).

In addition to hydrological and physiological processes, environmental factors such as rainfall intensity, soil erosion rates, land-use patterns in catchment areas, and geological substrate composition also contribute to increased Mg^{2+} and K^{+} concentrations in seawater. One of the primary mechanisms is surface runoff during the rainy season, whereby water transports soil particles, organic matter, and mineral ions from terrestrial environments into aquatic systems via rivers and overland flow. Figure 3 demonstrates that Mg^{2+} and K^{+} concentrations in seawater fluctuate between the rainy and dry seasons, reflecting dynamic environmental processes. These variations are likely influenced by hydrological processes and geothermal activity, although the relative contributions of these factors remain insufficiently quantified. From a geological perspective, the distribution of marine minerals may also be influenced by long-term climate change and bioaccumulation mechanisms in nutrient-poor waters. Environmental pressures, particularly increased temperatures during the dry season, may shift nutrient composition in marine environments, thereby affecting productivity and the distribution of marine biota (Corrias *et al.,* 2020; Lozano & Díaz, 2022).

The concentrations of Mg^{2+} and K^{+} ions in seawater are influenced by multiple components of hydrothermal systems, including rock weathering, current dynamics, and evaporation, especially in tropical marine regions characterized by elevated surface temperatures. These factors collectively contribute to the hydrological and geochemical dynamics of marine systems. Sun *et al.* (2016) noted that the biogeochemical cycles of major cations calcium, magnesium, sodium, and potassium are largely governed by terrestrial weathering, hydrothermal circulation, ion exchange, and sedimentation processes. Protein content in wild abalone tissue was found to be higher during the rainy season compared to the dry season. This difference is likely associated with variations in nutrient composition in the aquatic environment, influenced by age and habitat conditions. Yu *et al.* (2023) reported that protein intake in *Haliotis discus hannai* increases as an adaptive response to elevated temperatures during summer. Therefore, a comprehensive understanding of abalone nutritional quality requires consideration of seasonal nutrient dynamics.

The moisture and carbohydrate content of *Sargassum* sp., the primary natural feed for abalone in the coastal waters of Pekutatan Village, Mendoyo District, Jembrana Regency, Bali, were higher during the rainy season compared to the dry season. In contrast, protein and lipid contents were higher during the dry season. These variations are likely influenced by environmental conditions and algal age. Moisture content can serve as an important indicator in estimating relative protein, energy, and lipid content in algal biomass (Jolaoso *et al.,* 2016). Total ash content in abalone or fish is an important indicator in nutritional evaluation, as it reflects mineral content. Ash represents the inorganic residue remaining after combustion of organic matter and indicates the total mineral composition of a food material. Since minerals are essential nutritional components, ash content can be used to estimate total mineral levels and their contribution to nutritional value (Chung *et al.,* 2024).

Salinity is a critical water quality parameter in both aquaculture systems and natural habitats of abalone, as it influences osmotic balance in aquatic organisms (Zain *et al.,* 2023). During this study, salinity ranged from 29–32 ppt in the rainy season and 30–35 ppt in the dry season. These values are close to the optimal range of 30–35 ppt recommended by Susanto *et al.* (2016), and are consistent with findings by Pebriani and Dewi (2016) and Nahak *et al.* (2023), indicating that abalone can tolerate salinity levels between 31–35 ppt.

Dissolved oxygen is another critical factor affecting the growth and survival of abalone (*Haliotis squamata*). The observed dissolved oxygen levels ranged from 5.8–6.6 mg/L during the rainy season and 5.7–6.1 mg/L during the dry season, remaining within optimal conditions for abalone survival. Iskandar *et al.* (2022) reported that dissolved oxygen levels between 5.1–6.2 mg/L are suitable for abalone culture, consistent with findings by Hayati *et al.* (2018), which indicate that levels above 5 mg/L are optimal for growth and survival. The measured pH of seawater at the sampling site ranged from 7.5–7.9 during the rainy season and 8.0–8.6 during the dry season. These values are within the suitable range for abalone growth. Iskandar *et al.* (2022) reported that the optimal pH range for abalone culture is 7.4–8.3, while Pebriani and Dewi (2016) noted that abalone can tolerate pH levels between 7.5–8.7. Furthermore, Fazil *et al.* (2017) emphasized that seawater pH plays a crucial role in aquatic life and serves as an important indicator of water quality.

CONCLUSION

The results of this study demonstrate that the absorption patterns of Mg^{2+} and K^{+} ions in abalone tissue, shell, and *Sargassum* sp. are influenced by seasonal dynamics within the aquatic ecosystem. These variations are closely associated with the availability of natural food sources and fluctuations in ion concentrations in seawater. The findings indicate the presence of adaptive mechanisms in aquatic organisms in response to environmental changes, resulting in season-specific ion uptake patterns. This pattern reflects dynamic bioaccumulation processes in tropical marine ecosystems and provides new insights into the relationship between environmental variability and mineral physiology in aquatic organisms.

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