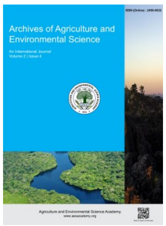
Archives of Agriculture and Environmental Science 9(1): 29-35 (2024)
https://doi.org/10.26832/24566632.2024.090105

e-ISSN: 2456-6632

This content is available online at AESA

Archives of Agriculture and Environmental Science

Journal homepage: journals.aesacademy.org/index.php/aaes



ORIGINAL RESEARCH ARTICLE

CrossMark

Variation in heavy metals concentrations among seaweed species from Mkwiro seaweed farm, Kwale County, Kenya

Paul Leniko Lanyasunya[1], Eric C. Njagi[2*], Joel Gichumbi[2] and Fredrick O. Ogolla[3]

[1]Department of Environmental Sciences, Chuka University, P.O. Box 109-60400, Chuka, KENYA
[2]Department of Physical Sciences, Chuka University, P.O. Box 109-60400, Chuka, KENYA
[3]Department of Biological Sciences, Chuka University, P.O Box109-60400, Chuka, KENYA
[*]Corresponding author's E-mail: echomba@chuka.ac.ke

ARTICLE HISTORY

Received: 28 November 2023
Revised received: 22 January 2024
Accepted: 13 February 2024

Keywords

Contamination
Essential elements
Heavy metals
Kwale county
Pollution
Seaweed

ABSTRACT

This study, conducted at the Mkwiro seaweed farm in Kwale County, Kenya, aimed to assess the concentrations of heavy metals (Cd and Pb) and essential elements (Na, Fe, Ca, and K) in selected edible seaweed species. The study used a cross-sectional, descriptive research design and probability sampling method to collect data. Seaweed samples of three selected species, Cottonii (*Kappaphycus alvarezii*), Sea lettuce (*Ulva lactuca*), and Bubble-green seaweed (*Boergesenia forbesii*) were collected in quadrants and subjected to chemical analysis. Statistical analyses were conducted using R Studio version 4.3.2, with a significance level set at α=0.05. The Kruskal-Wallis test revealed significant differences in lead concentrations among seaweed types (χ^2 (2) = 7.01, p = 0.03). Cadmium concentrations did not show significant differences (χ^2 (2) = 3.88, p = 0.14). For calcium concentrations, ANOVA indicated no significant effect of seaweed type (F (2,33) = 0.6381, p = 0.5347). Iron concentrations differed significantly among seaweed types (χ^2 (2) = 23.35, p = 0.00000849), with *B. forbesii* having the highest median concentration. Potassium and sodium concentrations did not significantly vary among seaweed types (p > 0.05). The study uncovers elevated cadmium levels in seaweed, indicating potential contamination risks. However, concentrations of essential elements were lower. To address these findings, it is recommended to initiate regular monitoring and pollution control measures in seaweed farms. Additionally, diversifying cultivation with low-metal species can enhance product safety and quality.

Citation of this article: Lanyasunya, P. L., Njagi, E. C., Gichumbi, J., & Ogolla, F.O. (2024). Variation in heavy metals concentrations among seaweed species from Mkwiro seaweed farm, Kwale County, Kenya. *Archives of Agriculture and Environmental Science*, *9*(1), 29-35, https://dx.doi.org/10.26832/24566632.2024.090105

INTRODUCTION

Seaweeds, also referred to as macroalgae, are pivotal photosynthetic marine organisms sourced either from natural stocks or through cultivation methods (Lezcano *et al.*, 2018). By 2019, an overwhelming 97% of global mariculture production was attributed to cultivated seaweeds, with the remaining fraction stemming from natural stocks (Zhang *et al.*, 2022). Notably, Asian countries, primarily led by China and Indonesia, collectively contribute around 98% of the world's total seaweed production (Rogel-Castillo *et al.*, 2023). In recent years, European nations have displayed a growing interest in seaweed cultivation and utilization (Campbell *et al.*, 2019). However, unlike the predominant cultivation methods prevalent in Asian nations, most of Europe's macroalgae production comes from natural seaweed beds (Zhang *et al.*, 2022). In stark contrast, Africa lags behind in both the production and utilization of macroalgae (Msuya *et al.*, 2022), contributing to only 0.4% of the world's total production (Rogel-Castillo *et al.*, 2023). Nevertheless, in the warm waters of Tanzania, Madagascar, and South Africa, some commonly farmed seaweeds include *Kappaphycus* spp., *Eucheuma* spp., *Ulva spp.*, and *Gracilaria* spp. Seaweeds hold immense economic importance, with approximately 221 macroalgae species serving various purposes (Fernandes, 2020). Among these, about 145 species are employed for food, while approximately 110 species contribute to phycocolloid production (Chennubhotla *et al*., 2013). At an industrial scale, macroalgae serve as crucial sources of phycocolloids—algins, agars, and carrageenans—integral to gelling, thickening, and stabilizing processes in the food, pharmaceuticals, and cosmetics industries (Mantri *et al*., 2019; Häder, 2021). Phycocolloids play diverse roles, softening baked goods, facilitating water-oil emulsions for separation, and are integral in ice cream sauce production in the food and beverage sector (Busetti *et al*., 2017; Kim, 2012). Moreover, in the paper industry, alginate, derived from phycocolloids, is used for surface sizing, providing a continuous film surface (Bixler and Porse, 2011). Edible seaweeds possess rich nutrient profiles encompassing magnesium (Mg^{+2}), sodium (Na^{+}), calcium (Ca^{+2}), potassium (K^{+}), chloride (Cl^{-}), proteins, and carbohydrates (Circuncisão *et al*., 2018). Their chemical and nutritional compositions are influenced by various factors, such as species diversity and environmental conditions, including habitat, light exposure, water temperature, and salinity (Wong and Cheung, 2000).

Seaweeds, integral components of aquatic ecosystems and economically significant, exhibit a propensity for high bioconcentrations of heavy metals such as mercury, cadmium, arsenic, and lead from seawater (Chen *et al*., 2018). These heavy metals, even in minimal concentrations, pose a severe threat upon entry into living organisms, with their impact intensifying significantly at higher concentrations (Ankit and Korstad, 2022). Lead, for instance, induces irreversible brain damage, affecting human kidneys, reproductive systems, and the nervous system (Fatima *et al*., 2019). Similarly, cadmium, recognized as carcinogenic, triggers liver damage, blood-related complications, renal issues, and bone degeneration (Obasi and Akudinobi, 2020). Regulatory bodies like the French Agency for Food, Environmental, and Occupational Health and Safety (ANSES) establish upper limits (UL) for heavy metals in edible seaweeds, setting lead at 5.0 mg/Kg and cadmium at 0.5 mg/Kg, based on dry weight (ANSES, 2020). Moreover, variations in heavy metal concentrations exist not only between different seaweed species but also within species, indicating site-specific variations (ANSES, 2020). The rise in heavy metal contamination in aquatic environments, in tandem with industrialization, raises significant environmental concerns owing to the high toxicity of these elements, even in trace amounts, and their persistent bio-accumulative nature (Filippini *et al*., 2021; Ankit and Korstad, 2022; Pasumpon *et al*., 2023). A multitude of sources contribute to heavy metal presence in marine settings, including rock weathering, industrial discharge, sewage discharge, offshore oil exploration, agricultural runoff, marine transportation, and recreational activities (El-Sorogy *et al*., 2018; Shah *et al*., 2021). Within aquatic ecosystems, heavy metals tend to accumulate in aquatic life and ascend the food chain, a process known as bioaccumulation, biomagnification, and bioconcentration (Ahmad *et al*., 2020). The uptake and concentration of heavy metals within seaweed species are markedly affected by distinct seaweed varieties and their geographic locales (Hashim and Chu, 2004; Baghazadeh *et al*., 2020). These pivotal factors substantially contribute to the divergence observed in heavy metal content among various seaweed types, underscoring the critical significance of factoring in both the specific species and geographical location during assessments of heavy metal levels.

Despite the economic and ecological importance of seaweeds, particularly in the Kenyan coastal regions, there remains a dearth of information regarding the variations in heavy metal concentrations among cultivated species, notably those sourced from the Mkwiro Seaweed Farm. Gaining insight into the specific concentrations of heavy metals in these seaweeds holds significant potential to ensure their safe utilization and bridge this research gap. This study sets out to assess the levels of essential and non-essential metals present in seaweeds cultivated at the Mkwiro Seaweed Farm along the Kenyan coast. Through a comprehensive evaluation of heavy metal concentrations in these seaweeds, the research aims to deepen the understanding of contamination risks. This information will assist policymakers in devising strategies for the secure cultivation and utilization of seaweed, i.e., the selection of species with lower metal concentrations.

MATERIALS AND METHODS

Area of study

This study was conducted at Mkwiro seaweed farm [(Figure 1) 04° 39.513" S, 039° 23.790" E] in Kwale County, along the Kenyan south coast region. Mkwiro, with an approximate of about 1000 inhabitants (van Hoof and Steins, 2017), is a primarily subsistence fishing village located 2 kilometers off the Kenyan coast. Wasini Island in general supports an array of biodiversity which includes mangrove wetlands, coastal forests, estuaries, white sandy beaches and sand dunes, coral reefs, and seagrass beds that support a host of marine and coastal species. Kenyan coastline is characterized by Northeast Monsoon (NEM) and the Southeast Monsoon [(SEM) Nyamora *et al*., 2018 which affect the physical and chemical conditions of sea water (Church and Obura, 2004). The sites are sheltered from strong wave action and tidal currents by a fringing reef (Kimathi *et al*., 2018). Generally, reef communities here are dominated by Porites spp. assemblages in calm waters and Acropora spp. assemblages in high energy environments (McClanahan and Obura, 1984).

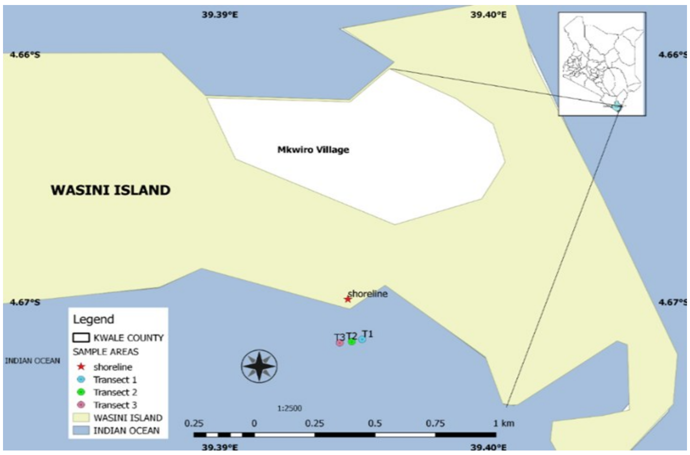


Figure 1. *Map representation of the study area, Mkwiro seaweed farm, in Kwale County, Kenya.*

Additionally, Mkwiro seaweed farm plays a vital role in the local economy, providing livelihoods to surrounding communities' members. The farm is managed by self-help groups consisting of 74 women and 6 men with the help of important stakeholders including local NGOs, Kwale County government and the government of Kenya through the Kenya Marine and Fisheries Policy and Legislation Act, 2016, Integrated Coastal Zone Management (ICZM) policy, 2013 and Maritime Zones Act, 2012. Fisheries Research Institute. The farm adheres to several policy frameworks including thein seaweed cultivation. This location was chosen for the study due to its significance in the regional seaweed industry and its potential impact on the environment and local communities.

Plate 1. *Layout-out of line transects as set at Mkwiro seaweed farm in Kwale Count, Kenya.*

Study design

This study employed a cross-sectional, descriptive research design. This design provides a snapshot of the conditions being studied at a specific point in time (Spector, 2019). To ensure a representative sample, we used probability sampling, following the recommendations of Melsasail *et al.* (2018) This approach involves the random selection of elements from a defined population, minimizing bias and allowing for generalization of findings (Trochim and Donnelly, 2001). These design choices helped in ensuring the validity and reliability of our study's results. The use of random sampling also helps minimize potential selection bias, as it guarantees that each seaweed species has an equal chance of inclusion.

Data collection

Seaweed samples of three selected species, namely Cottonii (*Kappaphycus alvarezii* (Doty) Doty ex P.C. Silva), Sea lettuce (*Ulva lactuca*), and Bubble-green seaweed (*Boergesenia forbesii*), were collected in triplets per quadrant. The following steps were followed to ensure proper handling and processing of the samples.

Sample collection

Three 100-meter-long line transects, namely T1 (04° 39.513 S, -039° 23.790E), T2 (04° 40.527 S, -039° 23.717E), and T3 (04° 40.515 S, -039° 23.415E), were systematically placed 500 meters apart, each with quadrats at 25-meter intervals (Plate 1). Seaweed species including Cottonii (*Kappaphycus alvarezii* (Doty) Doty ex P.C. Silva), Sea lettuce (*Ulva lactuca*), and Bubble-green seaweed (*Boergesenia forbesii*) were purposefully sampled. Triplets of samples were collected from each quadrant using a clean stainless-steel pair of scissors. To eliminate any unwanted materials, each sample was cleaned with seawater, transferred into a dry polythene specimen bag, and properly labeled.

Sample transportation and preparation

All collected samples were promptly transferred to a cooler box packed with ice and transported to Chuka University laboratory in Tharaka-Nithi County within 24 hours. In the laboratory, the seaweed samples were thoroughly washed with ultrapure water and subsequently dried in an oven (Mermert) for 24 hours at Chuka University. The dried samples were then ground into a fine powder before undergoing digestion via the conventional wet acid digestion method. The resulting digested samples were carefully stored in well-labeled specimen bottles prior to chemical analysis.

Chemical analysis

In the chemical analysis process, stock solutions of cadmium (Cd), lead (Pb), iron (Fe), sodium (Na), Calcium and Potassium (K) were prepared by dissolving precise amounts of analytical grade metal salts, sourced from Merk suppliers, in ultrapure water Milli-Q, USA). These solutions were then stored in securely sealed, labeled containers in controlled laboratory conditions. Subsequently, the 1000 ppm stock solutions underwent serial dilution to achieve concentrations, used as working standards. Calibration curves were generated by analyzing these working standards, encompassing a range of concentrations suitable for the anticipated levels of heavy metals and essential elements in the seaweed samples. The analysis of heavy metals (Cd, Pb) and essential element iron (Fe) were analyzed using a PG-990 (PG Instruments Ltd) Atomic Absorption Spectrophotometer in flame mode (FAAS) at Kenya Plant Inspectorate Services (KEPHIS) in Nairobi as described by Ghasemi *et al.* (2021). This instrument offered measurements of metal concentrations in solution through the absorption of specific wavelengths of light emitted by a flame. The essential elements sodium (Na), calcium (Ca) and potassium (K) were chemically analyzed using PerkinElmer Inductively Coupled Plasma Mass Spectrometer [(ICP-MS) NexION 2000B, USA] at KEPHIS in Nairobi using procedure used by Grainger *et al.* (2020).

Calibration and analysis

Before each analysis, the instrument was calibrated using the working standards to establish a linear relationship between absorbance or ion intensity and concentration. The prepared seaweed sample solutions were then introduced into the respective instrument, with optimized settings for maximum sensitivity and accuracy. Readings from the instruments were recorded and used to calculate the concentrations of the target heavy metals and essential elements in the seaweed samples.

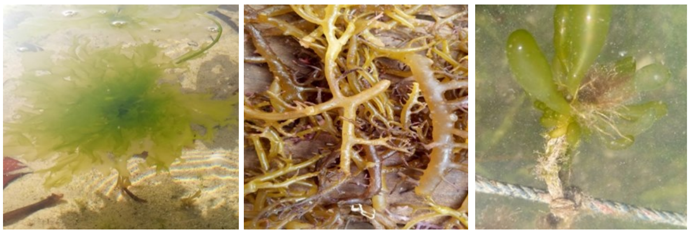
To prevent any potential contamination, all glassware and equipment utilized in the analysis were thoroughly cleaned and rinsed with ultrapure water. Additionally, procedural blanks consisting of ultrapure water without sample were included in the analysis to monitor and correct for any background levels of the elements.

Statistical analysis

To evaluate the impact of seaweed types on heavy metal and essential element concentrations, a set of statistical analyses was used. Firstly, a Kruskal-Wallis test was conducted to assess potential differences among the seaweed types. This non-parametric test was chosen given its suitability for comparing multiple groups where the data does not meet normal distribution assumptions. For instance, when concentrations of Fe, Na, Pb, and Cd did not meet the normality assumption, a Kruskal -Wallis test was applied. Prior to this, an adjustment was made using Holm's method to account for multiple comparisons and maintain the overall significance level at α=0.05. Next, for the analysis of calcium concentrations in the three types of seaweeds, a one-way analysis of variance (ANOVA) was performed. ANOVA was used in comparing means across multiple groups, where the data was found to meet normality and homogeneity of variance assumptions. To ensure the appropriateness of the ANOVA, normality assumptions were assessed using the Shapiro-Wilk test (significance level at α = 0.05). This test provided a reliable assessment of whether the data follows a normal distribution. Additionally, Levene's test was used to examine the homogeneity of variances across the groups. This step was necessary to ensure that the variance within each group was consistent. All statistical analyses were performed using R Studio version 4.3.2, a widely used statistical software known for its robust capabilities in data analysis and visualization.

RESULTS AND DISCUSSION

The collected seaweed species, including *U. lactuca*, *K. alvarezii* (Cottonii), and *B. forbesii*, exhibited distinctive characteristics in their morphology and growth patterns. The *U. lactuca* displayed an erect growth pattern with translucent, tubular thalli, showcasing variations in color and attachment to the substrate. The *K. alvarezii*, identified as a red alga, featured densely entangled branches with pinkish-white tips. The *B. forbesii* demonstrated limited diversity, primarily linked to size variations corresponding to different developmental stages. This species was predominantly located in low-tide zones, gradually increasing in numbers toward subtidal areas. The clavate shape and upright growth pattern of *B. forbesii*, along with its attachment to the sea floor using a disc-shaped rhizomatous base or synthetic ropes in the seaweed farm, distinguished it in terms of morphology. The stipes of *B. forbesii* were compressed and stood vertically, supporting large vesicles with various upright, inflated, cartilaginous, and flexible air bladders, presenting a unique yellowish-orange hue (Plate 2).



Ulva lactuca *Kappaphycus alvarezii* *Boergesenia forbesii*

Plate 2. *Representative Sea weeds observed at Mkwiro seaweed farm in Kwale Count, Kenya.*

Effect of seaweed species on the concentration of heavy metals

The obtained results from the Kruskal-Wallis tests examining lead and cadmium concentrations among different seaweed species exhibit interesting variations. The test revealed a statistically significant effect (χ^2 (2) = 7.01, p = 0.03, adjusted using Holm's method) in lead concentrations among the seaweed types. Lead concentration in *B. forbesii* was significantly higher (*Median* = 0.57) and was significantly different from *K. alvarezii* (Figure 2). The differences observed among the seaweed species in their metal concentrations may have stemmed from their inherent properties in absorbing or retaining certain metals. It's worth noting that the lead levels observed in this study were comparatively lower than those reported by Baghazadeh *et al.* (2020) in a study conducted along the South coast of Iran. These observed discrepancies may be attributed to differences in geographical locations and varying environmental conditions, which are documented to influence heavy metal concentrations in seaweeds (Shah *et al.*, 2021). Furthermore, these variations may be associated with differences in anthropogenic activities, including industrial discharge, as well as the presence of natural sources of heavy metals. On the other hand, cadmium concentrations showed no significant (χ^2 (2) =3.88, p=0.14, adjusted using Holm's method), differences among the seaweed types. However, *B. forbesii* had slightly higher concentrations of cadmium (*Median* = 0.87167 ppm) as compared to *K. alvarezii* and *U. lactuca* respectively (Figure 3). The recorded concentrations of Cd align with previous studies (Huerta-Diaz, 2007; Chen *et al.*, 2021) from the Central West Coast of the Gulf of California and China. Nevertheless, our outcomes differ from Rajaram *et al.* (2020), who observed varying Cd concentrations among seaweed species along the Palk Bay in Southeastern India. Notably, the Cd levels we found were lower in comparison to Janadeleh and Jahangiri's (2016) findings regarding seawater contamination in the territorial waters of the Kingdom of Bahrain which again may be attributed to differences in the in anthropogenic effects.

Effect of seaweed species on the concentration of essential elements

Minerals refers to inorganic substances present all body fluids and tissues. There are basically necessary in the maintenance of some physiochemical life essential processes (Riaz *et al.*, 2020). Marine macroalgae can accumulate minerals from their surrounding and contain about 10 – 20 times much the minerals

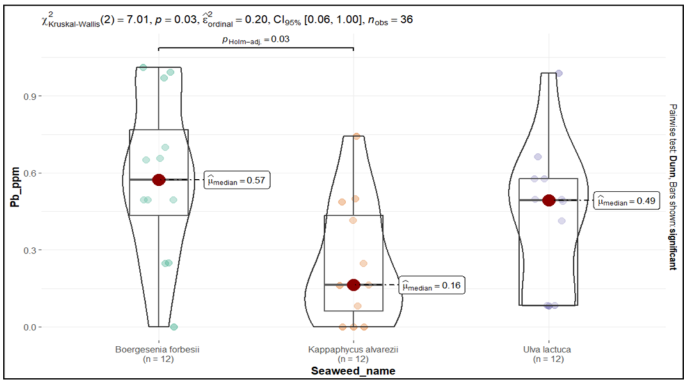


Figure 2. *Kruskal-Wallis test for effect of seaweed type on the lead concentrations at Mkwiro Seaweeds farm in Kwale County, Kenya.*

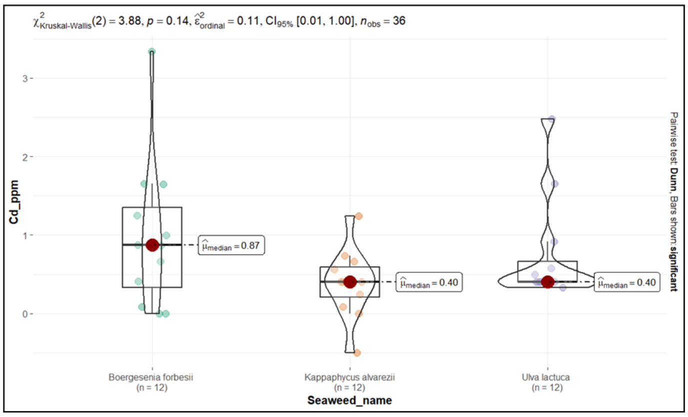


Figure 3. *Kruskal-Wallis test for effect of seaweed type on the cadmium concentrations at Mkwiro Seaweeds farm in Kwale County, Kenya.*

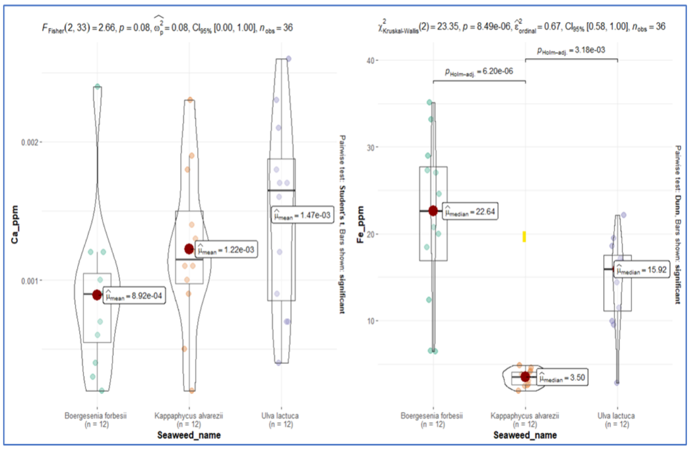


Figure 4. *Kruskal-Wallis test for effect of seaweed type on the calcium (Ca_ppm) and iron (Fe_ppm) concentrations at Mkwiro Seaweeds in Kwale County, Kenya.*

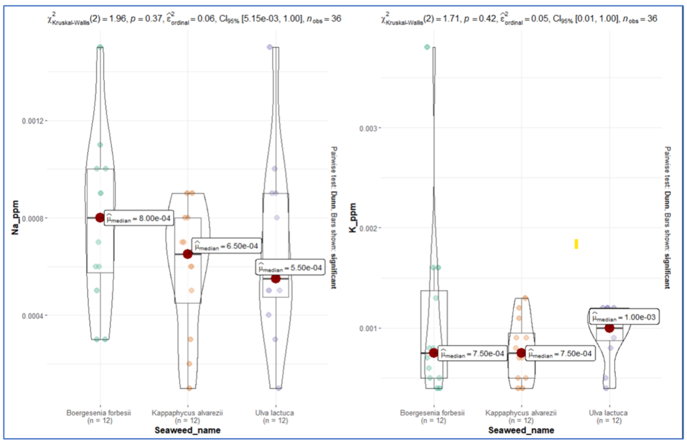


Figure 5. *Kruskal-Wallis test for effect of seaweed type on the sodium (Na_ppm) and potassium (K_ppm) concentrations at Mkwiro Seaweeds in Kwale County, Kenya.*

contained in land plants (Sadhukhan *et al.*, 2019). The bioaccumulation capacity is dependent on the species type, life cycle stage as well as environmental conditions (Ji and Gao, 2021). In this study, a one-way analysis of variance (ANOVA) was conducted to examine the concentrations of calcium in three types of seaweeds collected from Mkwiro Seaweeds in Kwale County, Kenya. Fisher's exact test did not reveal a significant effect of seaweed type on calcium concentration (F (2,21.86) = 2.52, p = 0.08). A post-hoc Tukey HSD test was not conducted due to the non-significant ANOVA result. However, calcium was slightly higher in *B. forbesii* (Mean =0.0008.92 ppm) as compared to *K. alvarezii* and *U. lactuca* respectively (Figure 4). The calcium range observed in this study were lower compared to those reported by Rasyid (2017) in sea weeds from Indonesia and Xavier and Jose (2020) from Gulf of Manner in India.

Kruskal-Wallis test was conducted to compare the iron concentrations among the three seaweed types. The test statistic was significant (χ^2 (2) = 23.35, p = 0.00001, adjusted using Holm's method), indicating that there are significant differences in iron concentration among the groups (Figure 4). *Boergesenia forbesii* had significantly higher median of iron concentration (22.64 ppm) while *K. alvarezii* had significantly lower median [(3.5 ppm) Figure 4]. Our results differed with those from a similar study (Huerta-Diaz *et al.*, 2007; Adharini *et al.*, 2020) where metal concentrations including that of iron did not differ among the different seaweed species on the west coast of the Gulf of California and in Indonesia respectively. However, our results are in agreement with reports from other studies Filippini *et al.*, 2021; Pasumpon *et al.*, 2023). Variations on the results reported by different authors may have been due to difference in study time. For instance Villares *et al.* (2013) observed that seasons significantly influenced the concentrations of metals in seaweeds at a coastal embayment in northwest Spain. Further as explained by Huerta-Diaz *et al.* (2007), high vertical water mixing at the sea zones may cause nutrient surge or a decrease in elemental concentration. Kruskal-Wallis test did not reveal a significant effect (χ^2 (2) =1.71, p=0.42). This suggests that there are no significant differences in potassium concentrations among the three seaweed types. However, the concentration of potassium (K) was slightly lower in *Ulva lactuca* (*Median* = 0.001) as compared to concentrations in *Boergesenia forbesii* and in *Kappaphycus alvarezii* (Figure 5). The finding of this study differs with those of Thodhal *et al.* (2019) which reported significance difference of metals including potatium among the sea weeds. It's important to highlight that the K levels observed in our study were lower compared to findings in other studies (Farzanah *et al.*, 2022). Kruskal-Wallis test yielded a non-significant result (χ^2 (2) = 1.96, p = 0.37), indicating that there are no significant differences in sodium concentrations among the three seaweed types. However, the concentration of sodium was slightly lower in *Ulva lactuca* (Median = 0.00055 ppm) as compared to concentrations in *Boergesenia forbesii* and in *Kappaphycus alvarezii* respectively (Figure 5).

Conclusion and recommendation

The study's findings indicate significant concentrations of cadmium, with levels surpassing recommended limits in a majority of the seaweed samples. This highlights a potential risk associated with heavy metal contamination in seaweed farms. Additionally, essential elements such as sodium, iron, calcium, and potassium were observed to be lower than reported in existing literature. This suggests the need for further investigation into the factors influencing essential element uptake and distribution in seaweeds. Notably, the study also revealed that both Iron and Lead have a direct influence on seaweed height, providing valuable insights into the complex interactions between metals and seaweed growth patterns. To safeguard the safety and quality of seaweed products, it is imperative to establish routine monitoring programs for heavy metal concentrations in seaweed farms, coupled with effective pollution control measures. This proactive approach will mitigate potential risks associated with heavy metal contamination. In addition, diversifying seaweed cultivation by exploring a range of species with lower heavy metal uptake and higher nutritional value is crucial. This strategy not only contributes to more resilient and sustainable practices but also enhances overall product quality and safety for consumers. By harmonizing these efforts, the seaweed industry can ensure a safer and more diverse range of nutritional options.

ACKNOWLEDGEMENT

We wish to express our sincere appreciation to the Kwale County government for granting permission to conduct this study at the Mkwiro seaweed farm. We are grateful to Chuka University for their financial support, which was instrumental in making this study possible.

Authors contribution

Conceptualization, writing—original draft preparation P.L.L., J.G. and E.C.N.; Resources, methodology, data collection, writing—review and editing, all authors; Data curation, analysis and visualization, F.O.O.; Supervision, J.G. and E.C.N. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

Ethical approval: Not applicable.

Data availability: The data that support the findings of this study are available on request from the corresponding author.

Conflict of interest: The authors of this manuscript declare no conflicts of interest.

REFERENCES

Adharini, R. I., Setyawan, A. R., & Jayanti, A. D. (2020). Comparison of nutritional composition in red and green strains of Kappaphycus Alvarezii cultivated in Gorontalo Province, Indonesia. In *E3S Web of Conferences*, 147, 03029.

Ahmad, S., Pandey, A., Pathak, V., Tyagi, V., & Kothari, R. (2020). Phycoremediation: Algae as eco-friendly tools for the removal of heavy metals from wastewaters. In Bioremediation of Industrial Waste for Environmental Safety. *Springer*, 53-76.

Ankit, Bauddh, K., & Korstad, J. (2022). Phycoremediation: Use of algae to sequester heavy metals. *Hydrobiology*, *1*(3), 288-303.

ANSES. (2020). *Opinion of the French Agency for Food, Environmental and Occupational Health & Safety on "maximum cadmium levels for seaweed intended for human consumption"*. Maisons-Alfort; France: ANSES. Retrieved from anses.fr/en/system/files/ER

Baghazadeh Daryaii, L., Samsampour, D., Bgheri, A., & Sohrabipour, J. (2020). The high content of heavy metals in seaweed species: A case study in the Persian Gulf and the Gulf of Oman in the southern coast of Iran. *Journal of Phycological Research*, *4*(2), 576-589.

Bixler, H. J., & Porse, H. (2011). A decade of change in the seaweed hydrocolloids industry. *Journal of applied Phycology*, *23*(3), 321-335.

Busetti, A., Maggs, C. A., & Gilmore, B. F. (2017). Marine macroalgae and their associated microbiomes as a source of antimicrobial chemical diversity. *European Journal of Phycology*, *52*(4), 452–465.

Campbell, I., Macleod, A., Sahlmann, C., Neves, L., Funderud, J., Øverland, M., & Stanley, M. (2019). The environmental risks associated with the development of seaweed farming in Europe-prioritizing key knowledge gaps. *Frontiers in Marine Science*, *6*, 107.

Chen, Q., Pan, X. D., Huang, B. F., & Han, J. L. (2018). Distribution of metals and metalloids in dried seaweeds and health risk to population in southeastern China. *Scientific Reports*, *8*(1), 3578.

Chen, Y., Liu, Y. T., Wang, F. H., Wen, D., Yang, H., & Zhao, X. L. (2021). An investigation of toxic metal levels (Pb, Cd, Cr, As, Hg) in dried Porphyra and Laminaria collected from coastal cities, China. *Biological Trace Element Research*, 1-11.

Chennubhotla, V. S., Rao, M. U., & Rao, K. S. (2013). Commercial importance of marine macro algae. *Seaweed Research and Utilization*, *35* (1 & 2), 118-128.

Church, J. E., & Obura, D. O. (2004). Management recommendations for the Kiunga Marine National Reserve, based on coral reef and fisheries catch surveys, 1998-2003. *CORDIO/WWF KMNR*, 1-57.

Circuncisão, A. R., Catarino, M. D., Cardoso, S. M., & Silva, A. M. (2018). Minerals from macroalgae origin: health benefits and risks for consumers. *Marine Drugs*, *16*(11).

El-Sorogy, A., Al-Kahtany, K., Youssef, M., Al-Kahtany, F., & Al-Malky, M. (2018). Distribution and metal contamination in the coastal sediments of Dammam Al-Jubail area, Arabian Gulf, Saudi Arabia. *Marine Pollution Bulletin*, *128*, 8-16.

Farzanah, R., Clausen, M. P., Arnspang, E. C., Schmidt, J. E., & Bastidas-Oyanedel, J. R. (2022). Feasibility of United Arab Emirates Native Seaweed Ulva intestinalis as a Food Source: Study of Nutritional and Mineral Compositions. *Phycology*, *2*(1).

Fatima, G., Raza, A., Hadi, N., Nigam, N., & Mahdi, A. (2019). Cadmium in human diseases: It's more than just a mere metal. *Indian Journal of Clinical. Biochemistry*, *34*, 371–378.

Fernandes, S. (2020). Benthic Seaweeds of the Cibratel Beach, Itanhaém, SP. *International Journal of Current Science Research and Review*, *8*(3). https://doi.org/10.47191/ijcsrr/v3-i 08-03

Filippini, M., Baldisserotto, A., Menotta, S., Fedrizzi, G., Rubini, S., Gigliotti, D., & Vertuani, S. (2021). Heavy metals and potential risks in edible seaweed on the market in Italy. *Chemosphere*, *263*, 127983.

Ghasemi, A., Jamali, M. R., & Es' haghi, Z. (2021). Ultrasound assisted ferrofluid dispersive liquid phase microextraction coupled with flame atomic absorption spectroscopy for the determination of cobalt in environmental samples. *Analytical Letters*, *54*(3), 378-393.

Grainger, M. N., Hewitt, N., & French, A. D. (2020). Optimised approach for small mass sample preparation and elemental analysis of bees and bee products by inductively coupled plasma mass spectrometry. *Talanta*, *214*, 120858.

Häder, D. P. (2021). Phycocolloids from macroalgae. *Natural Bioactive Compounds*, 187–201.

Hashim, M. A., & Chu, K. H. (2004). Biosorption of cadmium by brown, green, and red seaweeds. *Chemical Engineering Journal*, *97*(2-3), 249-255.

Huerta-Diaz, M. A., de León-Chavira, F., Lares, M. L., Chee-Barragán, A., & Siqueiros-Valencia, A. (2007). Iron, manganese and trace metal concentrations in seaweeds from the central west coast of the Gulf of California. *22*(7), 1380-1392.

Janadeleh, H., & Jahangiri, S. (2016). Risk assessment and heavy metal contamination in fish (Otolithes ruber) and sediments in Persian Gulf. *Journal of Community Health Research*, *5*(3), 169-181.

Ji, Y., & Gao, K. (2021). Effects of climate change factors on marine macroalgae: A review. *Advances in marine biology*, *88*, 91-136.

Kim, S. K. (2012). *Handbook of marine macroalgae: biotechnology and applied phycology*. John Wiley & Sons Inc.

Kimathi, A. G., Wakibia, J. G., & Gichua, M. K. (2018). Growth rates of *Eucheuma denticulatum* and *Kappaphycus alvarezii* (Rhodophyta; Gigartinales) cultured using modified off-bottom and floating raft techniques on the Kenyan coast. *Western Indian Ocean Journal of Marine Science*, *17*(2), 11-24.

Lezcano, V., Fernández, C., Parodi, E. R., & Morelli, S. (2018). Antitumor and antioxidant activity of the freshwater macroalga *Cladophora surera*. *Journal of Applied Phycology*, *30*(5), 2913–2921, https://doi.org/10.1007/s10811-018-1422-5

Mantri, V. A., Kavale, M. G., & Kazi, M. A. (2019). Seaweed biodiversity of India: Reviewing current knowledge to identify gaps, challenges, and opportunities. *Diversity*, *12*(1), 13.

McClanahan, T., & Obura, D. (1984). Status of Kenyan coral reefs. *Coastal Management*, *23*, 57–76.

Melsasail, K., Awan, A., & Papilaya, P. M. (2018). Analysis of environmental physical -chemical factors and macroalga species. In: The Coastal Water of Nusalaut, Central Maluku - Indonesia. *Sriwijaya Journal of Environment*, *3*(1), 31–36.

Msuya, F. E., Bolton, J., Pascal, F., Narrain, K., Nyonje, B., & Cottier-Cook, E. J. (2022). Seaweed farming in Africa: current status and future potential. *Journal of Applied Phycology*, *34*(2), 985-1005.

van Hoof, L., & Steins, N. A. (2017). *Mission report Kenya: Scoping mission marine fisheries Kenya* (No. C038/17). Wageningen Marine Research.

Nyamora, J., Magondu, E., Mwihaki, G. M., & Nyakeya, K. (2018). Long Line Seaweed Farming as an alternative to other Commonly used Methods in Kenyan Coast. *Kenya Aquatica Journal*, *4*(1), 23–28.

Obasi, P. N., & Akudinobi, B. B. (2020). Potential health risk and levels of heavy metals in water resources of lead–zinc mining communities of Abakaliki, southeast Nigeria. *Applied Water Science*, *10*(7), 1-23.

Pasumpon, N., Varma, R., & Vasudevan, S. (2023). Bioaccumulation level of metals and health risk assessment of selected red and green seaweeds validated by ICP-MS. *Environmental Science and Pollution Research*, *30*(25), 66781-66799.

Rajaram, R., Rameshkumar, S., & Anandkumar, A. (2020). Health risk assessment and potentiality of green seaweeds on bioaccumulation of trace elements along the Palk Bay coast, Southeastern India. *Marine Pollution Bulletin*, *154*, 111069.

Rasyid, A. (2017). Evaluation of nutritional composition of the dried seaweed Ulva lactuca from Pameungpeuk waters, Indonesia. *Tropical Life Sciences Research*, *28*(2), 119.

Riaz, M. U., Ayub, M. A., Khalid, H., ul Haq, M. A., Rasul, A., ur Rehman, M. Z., & Ali, S. (2020). Fate of micronutrients in alkaline soils. *Resources use efficiency in agriculture*, 577-613.

Rogel-Castillo, C., Latorre-Castañeda, M., Muñoz-Muñoz, C., & Agurto-Muñoz, C. (2023). Seaweeds in Food: Current Trends. *Plants*, 12(12), 2287.

Sadhukhan, J., Gadkari, S., Martinez-Hernandez, E., Ng, K. S., Shemfe, M., Torres-Garcia, E., & Lynch, J. (2019). Novel macroalgae (seaweed) biorefinery systems for integrated chemical, protein, salt, nutrient and mineral extractions and environmental protection by green synthesis and life cycle sustainability assessments. *Green Chemistry*, *21*(10), 2635-2655.

Shah, Y., Yadav, A., Kumar, M. A., Kavale, M. G., Prasad, K., & Mantri, V. A. (2021). 'Proof of concept'of how tube-net diameter affects growth and agar content in industrially important farmed red seaweed *Gracilaria dura*. *Journal of Applied Phycology*, *33*, 2349-2358.

Spector, P. E. (2019). Do not cross me: Optimizing the use of cross-sectional designs. *Journal of Business and Psychology*, *34*(2), 125-137.

Thodhal Yoganandham, S., Raguraman, V., Muniswamy, G., Sathyamoorthy, G., Rajan Renuka, R., Chidambaram, J., & Santha Ravindranath, R. R. (2019). Mineral and trace metal concentrations in seaweeds by microwave-assisted digestion method followed by quadrupole inductively coupled plasma mass spectrometry. *Biological Trace Element Research*, *187*, 579-585.

Trochim, W. M., & Donnelly, J. P. (2001). *Research methods knowledge base* (Vol. 2). New York: Atomic Dog Publications: Macmillan Publishing Company.

Villares, R., Fernández-Lema, E., & López-Mosquera, E. (2013). Seasonal variations in concentrations of macro-and micronutrients in three species of brown seaweed. *Botanica Marina*, *56*(1), 49-61.

Wong, K. H., & Cheung, P. C. (2000). Nutritional evaluation of some subtropical red and green seaweeds: Part I—proximate composition, amino acid profiles and some physico-chemical properties . *Food Chemistry*, *71*(4), 475-482.

Xavier, J., & Jose, J. (2020). Study of mineral and nutritional composition of some seaweeds found along the coast of Gulf of Mannar, India. *Plant Science Today*, *7*(4), 631-637.

Zhang, L., Liao, W., Huang, Y., Wen, Y., Chu, Y., & Zhao, C. (2022). Global seaweed farming and processing in the past 20 years. *Food Production, Processing and Nutrition*, *4*(1), 23.