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Production of nama seaweed (*Caulerpa spp.*) in an experimental lagoon cultivation setting and land-based system – Influence of cultivation depth and nutrient load on growth and morphology

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Declaração de Autoria

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Declaro ser autora deste trabalho, que é original e inédito. Autores e trabalhos consultados estão devidamente citados no texto e constam da listagem de referências incluída.

Aaron Johannes Cordes

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Abstract

With the increasing impacts of climate change and declining fishery yields, interest in aquaculture is growing in Pacific Island Countries (PICs). One promising solution to produce nutritious and sustainable food without further exploiting the environment is the cultivation of seaweeds, which provide valuable biomass while simultaneously removing carbon dioxide and excess nutrients from the water. To offer fishers an economic alternative to high-value fishery products, seaweeds of the genus Caulerpa are particularly promising due to their comparatively high market price. In Fiji, these edible seaweeds, locally known as nama, are traditionally hand-harvested from shallow lagoon waters and reefs. However, rising demand has placed increasing pressure on natural stocks, making sustainable cultivation an important alternative.

This study evaluated two cultivation approaches for nama. First a lagoon-based system using submerged trays at different depths, and secondly a land-based tank system with and without fertilizer supplementation. Because nama is highly sensitive to environmental parameters such as light intensity, nutrient availability, salinity, temperature, and hydrodynamics, the central aim was to determine which approach provides the most favorable conditions for optimal growth and desirable morphology.

Replicated floating trays were deployed at four depths in lagoon waters, while land-based tanks were used to assess the effects of nutrient enrichment. Over a four-week period, relative growth rate (RGR), frond weight, ramuli density, and frond coloration were measured. To provide a benchmark for cultivated biomass, commercial nama sold in Fijian markets was also analyzed for the same parameters.

The results suggest that nutrient limitation may be the primary bottleneck preventing successful cultivation in lagoon waters, as nama did not have access to sediment nutrient deposits. In contrast, fertilizer addition in the land-based system promoted growth but also caused pronounced morphological changes, resulting overall in a poor quality of the cultivated biomass.

This study underscores the critical influence of nutrient availability on the successful cultivation of nama and can serve as a valuable proxy for future research. Particular attention should be directed toward the identification of the cultivated nama species and the composition of the applied fertilizer.

Keywords

Seaweed Mariculture; Sea Grapes, Sustainable aquaculture, Fiji

Resumo

Com os impactos crescentes das alterações climáticas e a redução progressiva dos rendimentos das pescas a aquacultura tem vindo a assumir uma importância cada vez maior nos Países das Ilhas do Pacífico. As comunidades costeiras dependem fortemente da pesca como principal fonte de proteína animal e de rendimento económico. Contudo, a sobre-exploração dos recursos marinhos, a degradação ambiental e as alterações no clima global têm reduzido a disponibilidade de peixe. Esta situação tem criado uma necessidade urgente de encontrar alternativas sustentáveis de produção de alimentos aquáticos que assegurem tanto a segurança alimentar como a subsistência das populações locais.

Uma das soluções mais promissoras para responder a este desafio é a cultura de algas marinhas. As algas representam um recurso biológico de grande valor, não apenas pelo seu potencial como alimento nutritivo, mas também pelo contributo que oferecem aos ecossistemas marinhos. Ao serem cultivadas em larga escala, as algas conseguem sequestrar dióxido de carbono da água do mar, ajudando a mitigar os efeitos da acidificação oceânica. Além disso, absorvem nutrientes em excesso que, de outro modo, poderiam levar à eutrofização e à perda de biodiversidade em áreas costeiras. Estas funções ecológicas fazem da aquacultura de algas uma atividade ambientalmente benéfica, em contraste com outras formas de aquacultura animal que podem estar associadas a impactos negativos.

Para além das vantagens ecológicas, a produção de algas pode ter efeitos sociais e económicos relevantes. A aquacultura de algas marinhas diversifica as fontes de rendimento das comunidades costeiras, gera oportunidades de emprego e promove a inclusão social, uma vez que muitas vezes envolve a participação ativa de mulheres em todas as fases do processo, desde a colheita até à comercialização. Em regiões que enfrentam o declínio contínuo das capturas de peixe, a introdução de algas cultivadas no mercado representa uma alternativa viável para sustentar as economias locais e reduzir a pressão sobre os recursos naturais.

Entre as várias espécies de algas que podem ser cultivadas, as algas verdes comestíveis do género Caulerpa apresentam características particularmente atrativas. Estas algas são consumidas há gerações em várias culturas do Pacífico e da Ásia, não apenas pelo seu sabor delicado e textura crocante, mas também pelo seu elevado valor nutricional. A sua procura crescente nos mercados internacionais deve-se à presença de vitaminas, minerais, antioxidantes e ácidos gordos insaturados, que as tornam um alimento funcional com benefícios para a saúde. O seu valor de mercado é relativamente elevado quando comparado com outras espécies de algas, o que aumenta a sua atratividade como produto de exportação e como alternativa económica para os pescadores locais.

Nas Fiji, as espécies de Caulerpa são conhecidas localmente como nama. Tradicionalmente, estas algas são colhidas manualmente em recifes pouco profundos e lagoas costeiras. O nama é considerado uma iguaria culinária, consumida principalmente em saladas frescas, em pratos típicos ou como guarnição. É vendido nos mercados locais e possui potencial para exportação devido à sua procura crescente. Contudo, a popularidade crescente e o aumento da procura exercem uma pressão significativa sobre os stocks naturais. Em algumas regiões do Pacífico, como nas Ilhas Salomão, já foram registados episódios de sobre-exploração que levaram à redução ou mesmo ao desaparecimento local de populações de Caulerpa. Esta situação

evidencia a vulnerabilidade das reservas naturais e a necessidade de desenvolver sistemas de cultivo sustentáveis que possam complementar ou substituir a colheita direta.

Apesar da sua importância económica e cultural, a aquacultura de Caulerpa comestível nos países do Pacífico encontra-se numa fase inicial de desenvolvimento. Diferentemente do Sudeste Asiático, onde a espécie C. lentillifera é cultivada em viveiros de maré há várias décadas, nas ilhas do Pacífico as tentativas de cultivo permanecem sobretudo experimentais. As práticas de cultivo testadas incluem tabuleiros plásticos flutuantes em lagoas, colocados a diferentes profundidades, bem como sistemas em tanques terrestres. No entanto, os resultados reportados são muitas vezes contraditórios e subsistem lacunas importantes sobre as condições ideais de cultivo, nomeadamente no que se refere à intensidade luminosa, à disponibilidade de nutrientes, à salinidade, à temperatura e à hidrodinâmica.

O presente estudo teve como objetivo avaliar de forma comparativa duas abordagens distintas para o cultivo de nama. A primeira abordagem consistiu na instalação de tabuleiros flutuantes em lagoas a diferentes profundidades, enquanto a segunda utilizou tanques terrestres com tratamentos com e sem suplementação de nutrientes. O objetivo central foi determinar em qual destas condições o nama apresenta melhor crescimento e características morfológicas mais adequadas para o consumo e comercialização. Durante quatro semanas, foram registados parâmetros de crescimento e qualidade, incluindo a taxa de crescimento relativo, a espessura e o peso dos frondes, a densidade de râmulos e a coloração. Para contextualizar os resultados, foram também analisadas amostras comerciais de nama vendidas nos mercados locais das Fiji.

Os resultados da experiência em lagoa mostraram que a limitação de nutrientes constitui provavelmente o principal entrave ao cultivo bem-sucedido. Como as algas não estavam em contacto com o sedimento, ficaram privadas das reservas de nutrientes ali presentes e, por isso, o crescimento foi reduzido. Nos tabuleiros colocados em águas mais superficiais observou-se um aumento inicial da taxa de crescimento relativo nas primeiras duas semanas, mas a biomassa declinou rapidamente em todos os tratamentos. As alterações na coloração, com valores mais elevados no canal vermelho, indicaram branqueamento e redução do teor de clorofila, reforçando a hipótese de défice nutricional. A densidade de râmulos também diminuiu de forma significativa em relação à biomassa inicial, reduzindo o valor comercial, enquanto a espessura dos frondes não apresentou melhorias notáveis. A biomassa colhível manteve-se estável, mas com morfologia alterada.

Na experiência em tanques terrestres, a suplementação de nutrientes promoveu inicialmente um crescimento mais robusto. O tratamento de controlo, sem fertilização, sofreu um rápido declínio após a primeira semana, enquanto o tratamento enriquecido manteve taxas positivas de crescimento durante duas semanas e atingiu valores superiores em comparação com o controlo. Contudo, a partir da terceira semana o crescimento estagnou e a biomassa entrou em declínio. Este resultado sugere que os níveis de nutrientes se tornaram insuficientes ou que foram rapidamente absorvidos por organismos competidores, como o fitoplâncton. A morfologia refletiu estas condições: tanto a espessura dos frondes como a densidade de râmulos diminuíram nas primeiras duas semanas, mas registaram uma recuperação parcial no final da experiência, demonstrando alguma plasticidade morfológica. A biomassa colhível reduziu-se significativamente nas duas primeiras semanas, mas estabilizou posteriormente nos tanques com suplementação. Relativamente à pigmentação, observou-se uma diminuição inicial dos valores no canal vermelho, indicando maior concentração de clorofila e coloração verde mais

intensa. Contudo, na quarta semana os valores aumentaram de forma acentuada, evidenciando novamente branqueamento e perda de pigmentos.

A comparação entre o nama cultivado e as amostras comerciais de mercado mostrou que, embora a suplementação em tanques terrestres tenha melhorado o crescimento, a qualidade morfológica do produto final não atingiu os padrões desejados. O nama cultivado apresentou frondes mais finos e menor densidade de râmulos, características fundamentais para a aceitação no mercado. Apenas nas fases iniciais os valores de pigmentação foram semelhantes aos das amostras comerciais. Em fases posteriores, os sinais de branqueamento comprometeram a qualidade visual e, consequentemente, o valor de mercado.

De forma geral, os resultados obtidos indicam que a limitação de nutrientes é o maior desafio para o cultivo sustentável de nama. Nas condições testadas, o cultivo em lagoa sem contacto com o sedimento não é viável. Já o cultivo em tanques terrestres com suplementação revelou maior potencial, embora ainda apresente limitações devido a alterações morfológicas e ao declínio final da biomassa. Importa destacar que este estudo analisou apenas uma espécie de Caulerpa, pelo que não é possível generalizar as conclusões para todas as espécies semelhantes que ocorrem nas Fiji. Investigações futuras deverão incluir a identificação molecular das diferentes espécies e a avaliação das suas preferências nutricionais específicas.

Outro aspeto que merece atenção é o papel das associações microbianas. Estudos recentes em Caulerpa e em Ulva demonstraram que alterações no microbioma podem ter impacto significativo no crescimento, na pigmentação e na resistência a doenças. Assim, a integração do conhecimento sobre microbiomas poderá representar uma nova abordagem para otimizar o cultivo.

De um ponto de vista prático, os sistemas terrestres com níveis controlados e estáveis de nutrientes parecem ser a estratégia mais promissora. Estes sistemas permitem afinar as condições ambientais e podem integrar o nama em sistemas multitróficos juntamente com camarões, peixes ou pepinos-do-mar já cultivados nas Fiji. Nestes sistemas, a reciclagem de nutrientes provenientes das excreções e da ração não consumida pode sustentar o crescimento das algas, reduzindo simultaneamente o desperdício e proporcionando benefícios ecológicos e económicos.

Palavras-chave

Maricultura de algas, Uvas do mar, Aquacultura sustentável, Fiji

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Abbreviations:

ANOVA	Analysis of Variance
α - level	Level of significance
Chl a	Chlorophyll a
°C	Degrees Celsius
Df	Degrees of Freedom
FAO	Food and Agriculture Organization of the United Nations
HBM	Harvestable Biomass
IMTA	Integrated Multitrophic Aquaculture
NH_4	Ammonia
NO_3	Nitrate
NPK	Nitrogen Phosphorous Potassium
PAR	Photosynthetic Active Radiation
PICs	Pacific Island Countries
RGB	Red Green Blue
RGR	Relative Growth Rate
S_A	Absolute Salinity
SEA	Southeast Asia
SD	Standard Deviation

1. Introduction

The fast-growing human population and declining fish stocks have made marine aquaculture an increasingly important source of aquatic food and income (Tidwell & Allan, 2001). In 2022, global marine aquaculture production included 17.7 million tons of mollusks (mainly bivalves), 11.2 million tons of crustaceans, and 8.3 million tons of fish, with expectations for further growth (FAO, 2024). Additionally, more than 36 million tons of seaweeds were produced, which corresponds to more than 50% of the marine and coastal aquaculture production biomass (FAO, 2024)

In contrast to animal farming, which can harm marine ecosystems through high stocking densities, nutrient pollution, and the use of pharmaceuticals, seaweed aquaculture produces sustainable and health-promoting biomass and is carried out on large scale, especially in Southeast Asia (Chopin & Tacon, 2021; Naylor et al., 2000; Rico & Van den Brink, 2014; Tacon & Metian, 2015; Wu et al., 2021). Furthermore, seaweed aquaculture in coastal areas promotes bioremediation by removing excess nutrients from the environment, thereby mitigating eutrophication, sequestering carbon, producing oxygen, and providing nursery grounds for juvenile fish (Cotas et al., 2023; Gao et al., 2021; He et al., 2008) and also benefits coastal communities by creating jobs in cultivation, transport, and processing (Cai et al., 2021). Out of more than 10,500 described seaweed species, only a few are cultivated for commercial purposes, with eight genera accounting for over 96% of total seaweed production in 2018 (Chopin & Tacon, 2021). The cultivation of brown and red seaweeds (Phaeophyceae and Rhodophyta) dominates, with the most commonly farmed species including Japanese kelp (*Laminaria japonica*), *Eucheuma* seaweeds (*Eucheuma spp.*), *Gracilaria* seaweeds (*Gracilaria spp.*), wakame (*Undaria pinnatifida*), nori (*Porphyra spp.*), elkhorn sea moss (*Kappaphycus alvarezii*), and *fusiform sargassum* (*Sargassum fusiforme*), (FAO, 2024). Green seaweeds (Chlorophyta) represent only a small fraction of total production, even though some species from this genus yield high market prices. For seaweed farming to be viable on a small scale, cost-effective cultivation methods and a high market value for the seaweed biomass are crucial factors in selecting species for farming, bringing Chlorophyta species to the table for future species selection (Bolton et al., 2016; de Gaillande et al., 2017).

1.1. The role of seaweed production in the South Pacific region

In the Pacific Island Countries (PICs), aquaculture plays a relatively minor role, with the majority of marine protein sourced from fisheries (FAO, 2024). However, declining fish stocks due to overfishing and the effects of climate change have sparked increased interest in cultivating marine organisms as an alternative (Johnson et al., 2017). Despite the region's rich diversity of potential seaweed species, their farming remains underdeveloped in the PICs (Mori et al., 2023). Since the year 2000, seaweed production in PICs has declined, stabilizing at around 1,500 tons per year, primarily consisting of *Kappaphycus* species (Paul et al., 2020). This figure is a stark contrast to other tropical countries like Indonesia and the Philippines, where annual seaweed production exceeds 1 million tons (Rimmer et al., 2021; Trono & Largo, 2019). According to McHugh (2006) key barriers to seaweed aquaculture growth in the PICs industry include limited marketing efforts, a lack of local processing infrastructure, and high transportation costs to processing hubs. Furthermore, for seaweed production to become profitable in this region, a consistent supply of high-quality biomass must be readily available.

Edible green seaweed species from the *Caulerpa* genus provide exciting seaweeds for future farming in PICs, specifically *C. lentillifera* and *C. racemosa*. These seaweeds are already harvested locally in many PICs, contributing significantly to stable incomes from fishery products (Morris et al., 2014). Fiji has emerged as the main producer of edible *Caulerpa* seaweeds in the region, locally known as nama, with *C. racemosa* being the dominant harvested species (Morris et al., 2014). Similar to other regions, nama harvesting in Fiji is significantly influenced by women, who often engage in nama harvesting as a supplementary livelihood (Kitolelei et al., 2022). According to Morris et al., (2014) the demand of nama exceeds the available harvested biomass and countries in the area like the Solomon Islands already experienced vanishing of nama from their local waters due to over-harvesting, underlining the need of nama farming as a promising way of sustainable income and protecting local stocks (WWF Pacific, 2024).

In Fiji, the National Fisheries Policy for 2024–2028, issued by the Ministry of Fisheries, aims to ensure that the fisheries and aquaculture sectors will not only be economically productive, but also environmentally sustainable and socially inclusive (Fiji Ministry of Economy, 2021). Therefore, the cultivation of nama aligns very well with the government's goal of not only diversifying the aquaculture sector ecologically but also promoting inclusivity by supporting small coastal communities and female harvesters. As nama can be also used as an integrated species into animal aquaculture systems to take up and reuse excreted nutrients and unused feed, it could also transform existing animal aquaculture systems in an ecological and economical manner (Bambaranda et al., 2019).

1.2. An introduction into edible *Caulerpa* seaweeds

Edible green seaweeds from the *Caulerpa* genus like *C. racemosa* and *C. lentillifera* (Chlorophyta, Bryopsidales, *Caulerpaceae*), commonly known as sea grapes or nama in Fiji have a longstanding tradition of being harvested from shallow waters in many PICs and Southeast Asian (SEA) countries such as Japan, Vietnam and the Philippines (de Gaillande et al., 2017; Morris et al., 2014; Stuthmann et al., 2024). Morphologically, nama are siphonous seaweeds, consisting of a single, multinucleate cell that can be divided into three main parts as indicated in Figure 1.1, top which are stolon (S), fronds (B), and rhizoid (R), (Paul et al., 2014). The stolons grow horizontally and serve as the base from which fronds, covered with small, spherical beads, known as ramuli, extend. The rhizoids anchor the seaweeds to the substrate, while the fronds provide the harvested and consumed part of the seaweed (Figure 1.1 middle). The stolons and fronds are typically bright green, while the rhizoids are colorless (Arimoto et al., 2019; Estrada et al., 2020). When consumed, the small ramuli burst in the mouth, releasing a mildly salty flavor that is highly valued in culinary applications. Globally, nama are appreciated for their distinctive taste, texture, and high nutritional value, and are sold as a delicacy in regions like Japan, Southeast Asia,

Figure 1.1: top: Nama frond (B) with stolon (S) and rhizoid (R) (Guo et al., (2015a); middle: fresh nama fronds in a traditional Fijian dish; bottom: female nama harvesters in the field

PICs and Europe, where they command premium prices. They are commonly used in fresh salads, sushi, and even high-quality cosmetics (Brix da Costa et al., 2023; Nama Fiji, 2025; Paul et al., 2014). Nama seaweeds are rich in vitamins, polyunsaturated fatty acids, and minerals such as calcium, potassium, magnesium, sodium, and iodine, along with antioxidants (Aroyehun et al., 2020; Syakilla et al., 2022). This nutrient profile, combined with exceptional sensory properties, has driven a significant rise in demand for nama seaweeds in recent years and led to increased cultivation and harvesting activities in PICs and Southeast Asian countries (Morris et al., 2014; Zhou et al., 2025).

In Southeast Asia, *C. lentillifera* is the dominant farmed species (Estrada et al., 2021). In many of these countries shallow, shaded tidal ponds are used for cultivation, where the seaweed is planted directly into the substrate, allowing the stolons to spread horizontally and enabling fronds to be harvested about four weeks after planting (Stuthmann et al., 2021; Zuldin, 2023). In Fiji, *C. racemosa* is the predominant nama species, but various other species and phenotypes are present, making the exact species identification without molecular-biological tools almost impossible (Morris et al., 2014; Zubia et al., 2020). Nama grows natively in lagoon waters and is traditionally harvested from shallow reefs, where the whole seaweed is detached from the soil (commonly known as uprooting, Figure 1.1 bottom), edible fronds are collected, and the stolons are discarded (de Gaillande et al., 2017; Morris et al., 2014).

Farming attempts in the PICs region differ from the tidal pond method used in Southeast Asia and focused on the cultivation of nama on plastic trays floating in the water column of the lagoon or in land-based tanks without soil contact (de Gaillande et al., 2017). This farming method seems to be in its early development, as contradictory results were obtained so far. De Gaillande et al., (2017) suggest that farming methods must be strictly adapted to the physiological requirements of each nama species, and that farming in lagoon waters may be limited by natural events such as salinity drops or strong hydrodynamics caused by weather conditions. Furthermore, de Gaillande et al., (2017) suggest that a land-based farming attempt of nama in an integrated multitrophic aquaculture system might be the superior solution in PICs, as ecological parameters can be controlled and adjusted to meet the species' requirements, and nutrients from farmed animal species can be reused, making cultivation more sustainable.

As a high-value organism with international market demand, nama aligns well with Fiji's push for more sustainable and profitable aquaculture, offering coastal communities an opportunity for a stable and sustainable income through seaweed cultivation. To meet Fiji’s growing demand for fresh nama while protecting natural ecosystems from overharvesting, controlled and sustainable cultivation methods are essential. Cultivating nama directly in Fiji’s lagoon waters could offer a minimally invasive cultivation approach without the need to construct tidal ponds that could negatively impact the fragile coastal ecosystem. On the other hand, the sensitivity of nama to environmental factors, which may not always be favorable due to sudden weather events, could limit this approach. Therefore, cultivating nama in land-based tanks or integrating nama cultivation into existing land-based animal farming systems, such as shrimp or sea cucumber hatcheries, may be the more effective cultivation method.

Nama seaweeds are generally known to have strong morphological variation and are particularly sensitive to high light levels, low salinity, and temperature changes (Estrada et al., 2020). Therefore, any cultivation system must consider not only growth optimization, but also morphological consistency to ensure a high-quality end product that can compete with wild-harvested nama in local markets.

1.3. Previous research on nama seaweeds

To successfully introduce cultivated nama to the Fijian and international markets, not only must high biomass productivity be achieved, but quality standards defined by traders, processors, and consumers must also be maintained. Since the growth and morphology of nama are significantly influenced by physical factors such as salinity, illumination, water movement and nutrient availability, the effects of these parameters on the cultivation system must be considered (Estrada et al., 2020; Windarto et al., 2021).

Salinity

As a stenohaline species, seaweeds of the *Caulerpa* genus are less tolerant of strong fluctuations in salinity and are typically cultivated at around 35 absolute salinity (S_A), (Paul et al., 2014). At salinities below 20 S_A, *C. racemosa* has been shown to degrade (Carruthers et al., 1993), and (Guo et al., 2015b) demonstrated that *C. lentillifera* could not sustain growth under such low salinity conditions. As heavy rainfall can rapidly decrease lagoon salinity levels, de Gaillande et al., (2017) suggest that cultivating nama species in lagoon waters may only be feasible during the dry season. However, salinity drops often lead to the formation of haloclines and water stratification (Carrasco et al., 2023), which could be mitigated by cultivating nama at sufficient depths. Research by Carruthers et al., (1993) indicates that *C. racemosa* can tolerate short-term salinity drops down to 20 S_A, and findings by Rougerie et al., (2004) show that surface salinities in the South Pacific lagoon of Tikehau typically remain around 25 S_A during the rainy season. This may serve as a reference for other lagoons in the PICs region. As tidal action regularly introduces higher-salinity seawater into lagoons, it is conceivable that nama cultivation may also be viable during the rainy season if implemented at greater depths. According to Estrada et al., (2020) not only growth but also morphology of *C. racemosa* is affected by salinity, as frond length appears to be negatively correlated with salinity. This further underlines the importance of choosing appropriate cultivation depths to buffer against environmental fluctuations during wet seasons.

Illumination

When cultivating nama at greater depths, particular attention must be paid to illumination levels, as light availability decreases with depth and may impact growth (Guo et al., 2015a). Although *C. lentillifera* and *C. racemosa* are considered sensitive to high irradiance, which supports the feasibility of deeper cultivation, insufficient illumination could lead to reduced growth rates. Research by Guo et al., (2015a) demonstrated that *C. lentillifera* achieved optimal growth under 40 μmol photons m^{-2} s^{-1} photosynthetically active radiation (PAR). However, illumination levels lower than this significantly impaired growth. Despite this light sensitivity, Paul et al. (2014) also successfully exposed both species to 170 PAR. Moreover, Morris et al. (2014) and Söhnen et al., (2025) reported that wild stocks of *C. racemosa* in the South Pacific occasionally fall dry during low tide, and de Gaillande et al. (2017) documented cultivation of *C. racemosa* in shallow waters on floating plastic trays in Samoan lagoons. These observations suggest that regional nama species can possibly tolerate or adapt to higher light intensities, although exact values for optimal irradiance remain uncertain (Raniello et al., 2004). According to Estrada et al. (2020), fronds of *C. racemosa* tend to elongate at shallower depths, where light intensity is higher. Excessive irradiance must be avoided, as when light intensity surpasses the level required for carbon assimilation, the excess energy is not converted and instead leads to the formation of singlet oxygen molecules, which can damage the organism (Sharma et al., 2012; Triantaphylidès et al., 2008). Hence, identifying an optimal cultivation depth that provides suitable light intensity while avoiding the shallower, more variable salinity zone might be essential.

Water movement

In addition to changes in salinity fluctuations and light, deeper cultivation affects wave action and water currents. Research by de Gaillande et al. (2017) identified strong water movement as a potential limiting factor for nama cultivation in PIC lagoons. Stewart & Carpenter, (2003) found that macroalgae exposed to strong currents tend to develop more compact morphologies as a mechanical adaptation to reduce breakage. Given that nama fronds are highly extended and delicate, exposure to strong currents may lead to smaller or more compact growth forms or changes in ramuli density per unit frond length when cultivated in exposed lagoon waters.

Nutrient availability

Unlike terrestrial plants, seaweeds do not possess true roots and are able to absorb nutrients across their entire body surface, the thallus (Roleda & Hurd, 2019). Although nama species have been successfully cultivated on plastic trays or suspended freely in the water column in some previous studies, other investigations have shown that these seaweeds can also absorb nutrients through their rhizoids directly from the sediment (Alexander, 1965; Brix da Costa et al., 2023; Williams, 1984). This suggests that cultivation within the substrate may be superior to off-bottom systems using plastic trays. Experimental evidence suggests that nutrient enrichment, particularly with inorganic fertilizers, can significantly enhance growth rates, which supports the integration of nama into co-cultivation systems or integrated multitrophic aquaculture systems (IMTA), (Fakhrulddin et al., 2021). However, in tray-based cultivation methods, where seaweeds are suspended without direct sediment contact, it remains uncertain whether sufficient nutrients are available in the surrounding water column. Especially as tropical reef environments are often characterized by low concentrations of dissolved nutrients (Wood, 1993).

Despite these challenges, de Gaillande et al. (2017) successfully cultivated nama in lagoon environments in French Polynesia and reported that this cultivation method also performs well in Samoa. On the other hand, research by Robles & Tahiluddin, (2022) has demonstrated that *C. racemosa* shows significantly improved growth under nutrient-enriched conditions, particularly at total nitrogen concentrations of around 4.8 mg l^{-1}. It is therefore essential to investigate whether Fijian nama species can be effectively cultivated in off-bottom systems without sediment access or whether external nutrient supplementation is necessary to maintain adequate growth performance and product quality.

As described, the morphology of nama is a crucial determinant of quality and market value. In Southeast Asia, frond length, ramuli density, and the bright green coloration of rachis and ramuli are key quality indicators (Brix da Costa et al., 2023; Stuthmann et al., 2023). In contrast, vendors in Fijian markets emphasize frond thickness (higher weight per length unit), ramuli density, and overall frond coloration as primary quality characteristics (own interviews with market vendors). While frond length, thickness, and ramuli density can be measured and quantified relatively easily, determining frond color requires a more specialized approach. One practical method for field application involves the use of standardized photography to assess frond coloration using RGB (red, green, blue) values.

According to Stuthmann et al., (2024) the green color of the frond is closely linked to its chlorophyll-a (chl-a) content and thus responsible for the green coloration of the frond. While spectrophotometric chl-a analysis is possible in laboratory settings, it is not feasible for smallholder farmers or remote communities without laboratory access. A simpler and cost-effective alternative, proposed by Winters et al., (2009) and later applied by Stuthmann et al., (2021), uses photographing fronds in a standardized light box under artificial lighting and a gray card as a reference to investigate frond coloration and chl-a content.

Based on previous research, and with the intention to fill scientific gaps, the present study aims to provide a foundation for the sustainable cultivation of nama in Fiji in order to protect wild populations, meet the growing demand for nama, and create a sustainable source of income for coastal communities. The following research questions will therefore be addressed in this study.

1. Can nama be grown in lagoon waters or is a land-based cultivation the superior approach?

2. How is nama growth and morphology affected by changing cultivation depths and the presents of nutrients?

2. Material & Methods

The following paragraph describes the lagoon-based and land-based cultivation experiments, as well as the analysis of nama morphology observed in Fijian market specimens.

2.1. Lagoon cultivation experiment

The lagoon cultivation experiment was conducted in the lagoon of Kavewa Island, Vanua Levu (coordinates: -16.19059, 179.57558). Surveys of wild nama populations showed that nama naturally occurs at depths between depths of approximately 0 and 4 meters. This depth range was confirmed through interviews with local women who traditionally harvest nama.


Figure 2.1: Double layer tray for experimental nama cultivation with weight stone and data logger

For the experiment, four depths were selected for comparison: D1 at 0.1 meters, D2 at 1 meter, D3 at 2.5 meters, and D4 at 4 meters. All depth measurements were taken during spring low tide. The four respective depths were chosen in a way that they were in one line at the reef to assure as equal conditions as possible.

At each depth, three double-layer cultivation trays measuring 25 by 25 cm with a mesh size of 0.9 by 0.9 mm were deployed. Each tray was secured with a 6-kg concrete block, and the initial tray weight was recorded. To obtain continuous data about illumination and temperature levels at each depth, HOBO data loggers (HOBO MX2002, Onset USA) were deployed at each depth (Figure 2.1).

To gain insights into total water movement, 100 g clod cards made with plaster of Paris were prepared following Jokiel & Morrissey, (1993) and three clod cards were deployed at each respective depth. The clod cards weight was then compared to a control block in a no-flow tank. After a defined period, weight loss from each block reflected the relative water movement at each depth, enabling quantitative comparisons of hydrodynamic conditions within the cultivation environment.

Fresh nama biomass was collected from nearby harvesting areas with the help of local villagers. Each cultivation tray was stocked with about 200 g of initial biomass (D1: 202.6 ± 2.1 g; D2: 202.4 ± 0.4 g; D3: 202.73 ± 1.4 g; D4: 202.1 ± 1.0 g) using a digital scale (Scale: T-Scale T28 NTEP, d = 0.01). To gain insights into frond coloration, the RGB color model was used. Pure green is represented by RGB (0, 255, 0), neutral gray by RGB (128, 128, 128), white by RGB (255, 255, 255), and black by RGB (0, 0, 0). Stuthmann et al. (2024), demonstrated that in a linear regression analysis of RGB channel values against the measured concentrations of chl-a, that as pigment content increased, the intensity values of all three color channels decreased. The strongest correlation with pigment content was found in the RGB red channel (R-value). Consequently, analyzing the red channel in a standardized field photobox was used for comparing the green color quality of nama fronds across the different cultivation depths.
To determine the morphology characteristics for this study (frond thickness, ramuli density, RGB- R-value and the ratio of fronds to total biomass- further called harvestable biomass HBM), 15 percent of the initial biomass was subsampled. Fronds were separated from stolon and rhizoid to calculate the HBM. Fronds then were measured in length and weighed to calculate the frond thickness (given as g cm^{-1}). Afterwards, fifteen fronds were placed in a standardized photo box equipped with LED bars (Chihiros A Series A302, 8500K) and a gray card (B.I.G. Stufengraukeil). Pictures were taken using an Olympus TG -6, ISO set to 160 and a white balance of 4300K. To calculate the ramuli density, the number of ramuli were counted on the right side of each frond and then divided by the respective frond length, following Stuthmann et al. (2024). RGB values were obtained using the software GNU Octave (version 6.2.0). Images were first calibrated to the grey bar. Calibrated images were analyzed for the nama RGB values by testing 6 points per frond (frond tip, each frond side top, frond side bottom, rachis bottom, Figure A 7.1)

The trays were transported by boat to their designated cultivation sites in the lagoon. Over a four-week period, each tray was removed weekly, and its total biomass weight was recorded. Water samples were taken from each depth twice a week with 15 mL falcon tubes and salinity was analyzed with a refractometer (Model: Red Sea, R12018). Clod cards were weighed on day 1, 15 and 22 and their weight was compared to the weight of clod cards sitting in a shaded seawater bucket on land. Hobo loggers were cleaned twice a week to minimize fluctuations due to biofilms growing on the sensors. As nama growth didn't improve too much across treatments, biomass subsampling was only done at the end of the experiment. Therefore, after four weeks, the trays were opened, and all biomass was harvested and weighed. Fifteen percent of the biomass was again sampled to analyze their morphological properties (frond thickness, ramuli density, RGB R-value and HBM). The relative growth rate (RGR) was calculated following the method described by Marques et al., (2021):

$$RGR = \frac{(\ln(w2)-\ln(w1)}{\Delta t} * 100,$$

Equation 2.1: Relative growth rate RGR is calculated following Marques et al., (2021) where w1 and w2 are the weights at timepoint one and two and Δt *represents the time duration between timepoints one and two*

2.2. Land-based cultivation experiment

The land-based cultivation experiment was conducted at the Galoa Fisheries Station in Galoa Village, Viti Levu. The trials took place in concrete tanks, each measuring 12 m in length, 2 m in width, and 1 m in depth (24,000 L volume). The tanks were filled with fresh seawater and aerated using bubble stones (Figure 2.2). Both tanks were shaded using gauze. Initial nama biomass was collected from the village of Namuaimada (coordinates: -17.40553,178.25574). One of the tanks was enriched with one kg of Nitrogen Phosphorous Potassium (NPK) fertilizer (15%; 3%, 5%), further named TN (tray nutrient) while the other served as a control, further named TC (tray control). The amount of total - N was adapted to the study of Robles & Tahiluddin, (2022) and a slightly higher total -N concentration of 6.8 mg l^{-1} was chosen. Water movement was not measured as no clod cards were available anymore but both trays received the same amount of aeration, therefore making water movement comparable between tanks.

Figure 2.2: Land-based cultivation ponds with double layer nama tray fixed to weight stones, HOBO logger and aeration

Three double-layer cultivation trays, each measuring 25 by 25 cm with a mesh size of 0.9 by 0.9 mm, were secured with 6-kg concrete blocks. The trays were weighed and placed in each of the two tanks, resulting in a sample size of three per treatment and tank. Each cultivation tray was stocked with 200 g of initial biomass (TC: 202.7 ± 1.5 g; TN: 203.4 ± 2.3 g), (Scale: T-Scale T28 NTEP, d=0.01).

Measurements of RGR and the morphological characteristics of nama was done following the procedure as described in the lagoon cultivation experiment. Subsampling of nama fronds took place every 14 days. A 20% water exchange was conducted every two days. In the nutrient-enriched tank, fertilizer was replenished accordingly after each water exchange. After 14 days, a noticeable morphological shift was observed in the nama growing in the nutrient-enriched tank. The amount of fertilizer was therefore reduced on purpose by 50 percent to 3.4 mg l^{-1} total - N. Weekly water samples were collected from both tanks for S_A analyzation.

2.3. Collection of morphological data from commercial nama

To assess the morphological characteristics of commercially traded nama, samples were purchased from local markets in Suva, Labasa, Rakiraki and Savusavu. Nama samples were sorted by their origin, which were Yasawa Islands, Rakiraki, Bua, and Savusavu.

From each sample batch with the same origin, 40 fronds were randomly selected (n = 40) and analyzed to determine the previously described morphological traits frond thickness, ramuli density and the RGB R-value.

2.4. Statistical analysis

All statistical analyses and graphical outputs were conducted using R and RStudio (Version 2023.09.1+494). For the comparison of the environmental parameters, light intensity, temperature, salinity, clod card weight, and nutrient concentrations, a non-parametric approach was chosen due to the small sample size (n = 3). This approach was also used to detect significant differences within the relative growth rate (RGR) and the morphological properties from the lagoon and land-based experiment due to minimal sample sizes (n = 3). In this case, testing for normality was not necessary. Treatments were analyzed for significant differences using the Kruskal–Wallis test, with a significance level (α) set at 0.05. Kruskal–Wallis results are reported with the corresponding p-value and degrees of freedom (df), (Ostertagová et al., 2014).

In cases where significant differences were detected, Dunn's post-hoc test with a Bonferroni correction was applied to determine which treatments differed significantly from one another. The Bonferroni correction adjusts the nominal alpha value (here 0.05) by dividing it by the number of comparisons conducted (p-adjusted, further named p-value) to minimize the likelihood of obtaining false-positive results. These results of the Dunn's test are reported as adjusted p-values (further named p-value) and the Z statistic. The Z value represents the standardized test statistic from Dunn's post-hoc test, indicating both the magnitude and the direction of the difference between group ranks (Dinno, 2015).

To compare the morphological characteristics of the nama samples obtained from the markets, the data were first tested for normality using the Shapiro–Wilk test and for homogeneity of variances to ensure that the assumptions for an analysis of variance (ANOVA) were met (Emerson, 2022). If these assumptions were satisfied, the samples were compared using ANOVA, and in cases where significant differences were detected, a post-hoc Tukey test was performed. If the assumptions were not met, a Kruskal–Wallis test was applied following the procedure described above, along with the corresponding post-hoc test and correction.

3. Results:

Results of the lagoon - based and land - based cultivation experiment are displayed in the following section.

3.1. Environmental data of the lagoon cultivation experiment:

Over the course of the lagoon experiment, photosynthetically active radiation (PAR, μmol photons m^{-2} s^{-1}), temperature (°C), water movement, and absolute salinity (SA) were measured at the depths of the corresponding treatments D1, D2, D3 and D4. Measurements taken throughout the duration of the experiment revealed no significant differences in PAR between depths ($p = 0.812$, df = 3). Similarly, temperature did not fluctuate significantly over the course of the experiment ($p = 0.791$, df = 3).

PAR - and temperature values for the different treatments are presented as a 24-hour profile for the day with the highest recorded light intensity and temperature in Figure 3.1. At the shallowest depth, D1, the maximum PAR value of 1714.1 was reached at 11:56 am, followed by D2 with 1350.4 PAR, D3 with 1059.6 PAR, and D4 with 712.2 PAR, all recorded at the same time, respectively (Figure 3.1., left). At the shallowest depth, temperature reached a maximum of 33.6 °C at 11:56 am, followed by D2 with 33.2 °C at 13:56 pm, D3 with 32.0 °C at 12:56 pm, and D4 with 31.8 °C also at 12:56 pm. None of the treatments cooled below 29 °C during the hottest day of the observation period (Figure 3.1. right).

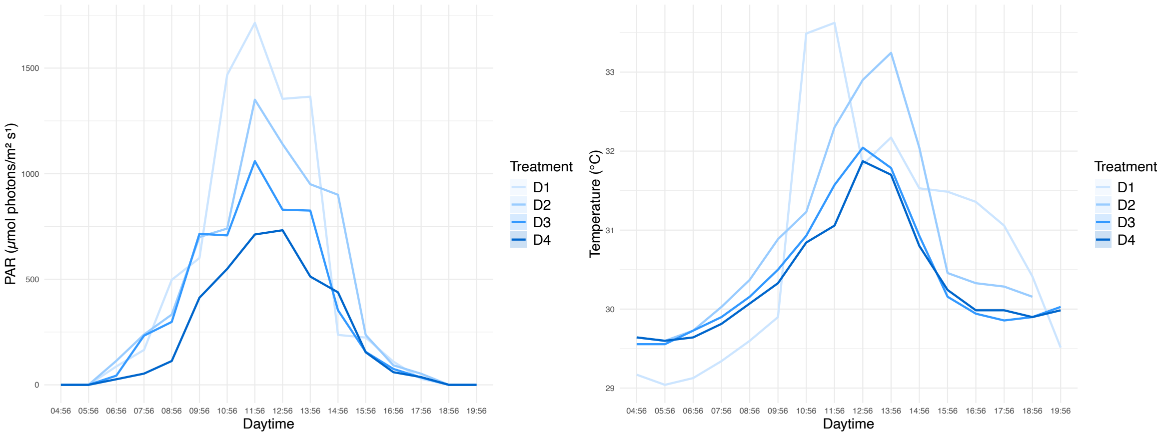

Figure 3.1: left: Photosynthetic active radiation PAR in μmol photons m^{-2} s^{-1}over a one-day period for each respective treatment D1-D4 and depth; right: Temperature in °C, over one day period for each respective treatment D1-D4 and depth

The weight loss of the clod cards differed significantly between treatments (Figure 3.2, left) and compared to the control at the end of the experiment ($p = 0.012$, df = 3). D1 reached a final weight of 35.8 ± 1.4 g, D2 of 42.5 ± 1.05 g, D3 of 41.9 ± 0.35 g, and D4 of 32.8 ± 1.1 g. The control C reached a final weight of 44.2 ± 0.9 g, with all values given as mean ± SD, respectively.

Weight loss of clod cards differed significantly between D1 and D2 ($p = 0.021$, Z-value: 2.83), between D2 and D4 ($p < 0.01$, Z-value: 2.99), and between D3 and D4 ($p < 0.01$, Z-value: 3.01). Treatments D1, D3, and D4 were all significantly lighter than the control at the end of the experiment, whereas D2 and the control did not differ significantly ($p = 0.102$, Z-value: 1.93).

Salinity differed between depths only on days with rainfall (days 1, 9, 14, and 22), showing significant differences from the other depths ($p < 0.01$, Z-value: 3.12). The lowest salinity was recorded on day 14 in the shallow depths D1 and D2, with both measuring 30.0 ± 0.1 S_A. The highest salinity was recorded on day 28 in depth D4, with a value of 33.2 ± 0.4 SA (Figure 3.2, right). All values given as mean ± SD, respectively.

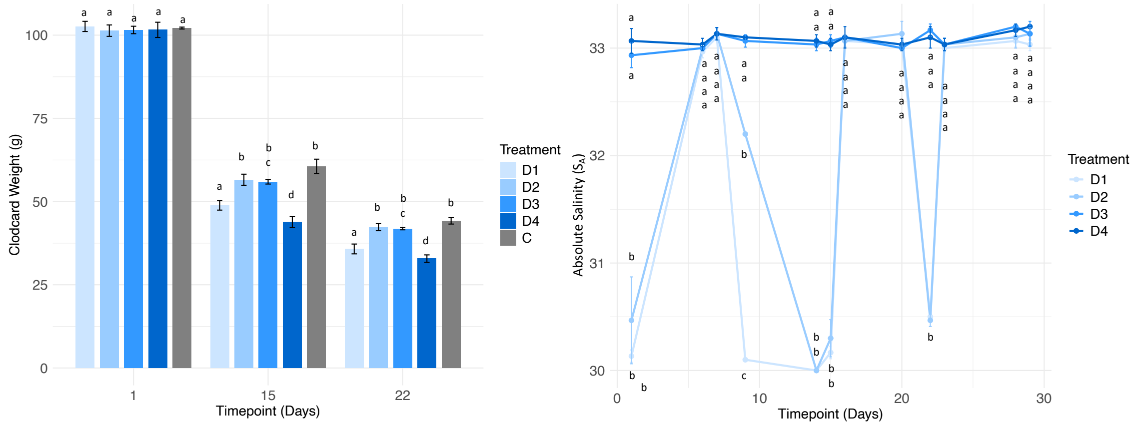

Figure 3.2: left: weight loss of clod cards from each treatment D1-D4 and respective depth, as well as control treatment (C),given as mean ± standard deviation. Right: Salinity changes over the duration of the experiment for each respective treatment and depth D1-D4, given as mean ± standard deviation. Small letters in both figures indicate the Dunns test post-hoc results where significant differences between treatments are displayed by non-matching letters and matching letters correspond to no significant differences.

3.2. Lagoon cultivation experiment

The relative growth rate (RGR) of the lagoon culture experiment is displayed in Figure 3.3. In week one, the treatment at depth D2 achieved the highest relative growth rate (RGR) at 2.16 ± 0.58 % day^{-1}, higher than D3 (Z-value = 3.32, p-value < 0.01) with values given as mean ± SD. No significant differences were detected between D2 and D1, D2 and D4.

In week two, this trend persisted, although the RGR in D4 dropped into negative values, falling behind D1 and D2. After the second week, fish were observed feeding on the nama trays in depth D3, effectively destroying the biomass. Occasional grazing was also observed in D4. In D1 and D2, no fish or other organisms feeding on nama were observed.

From week three onwards, no biomass remained in D3 for further measurements. In week three, the RGR of D1 and D2 decreased to 0.22 ± 0.31 % day^{-1} and 0.45 ± 0.50 % day^{-1}, respectively, while the RGR of D4 declined further to –8.65 ± 2.83 % day^{-1}.

In week four, all RGR values were clearly in the negative range, with –5.51 ± 1.30 % day^{-1} for D1, –5.74 ± 0.70 % day^{-1} for D2, and –9.71 ± 8.34 % day^{-1} for D4. Again, no significant differences between treatments were found. All dunns test results are displayed in table A 7.2 in the appendix.

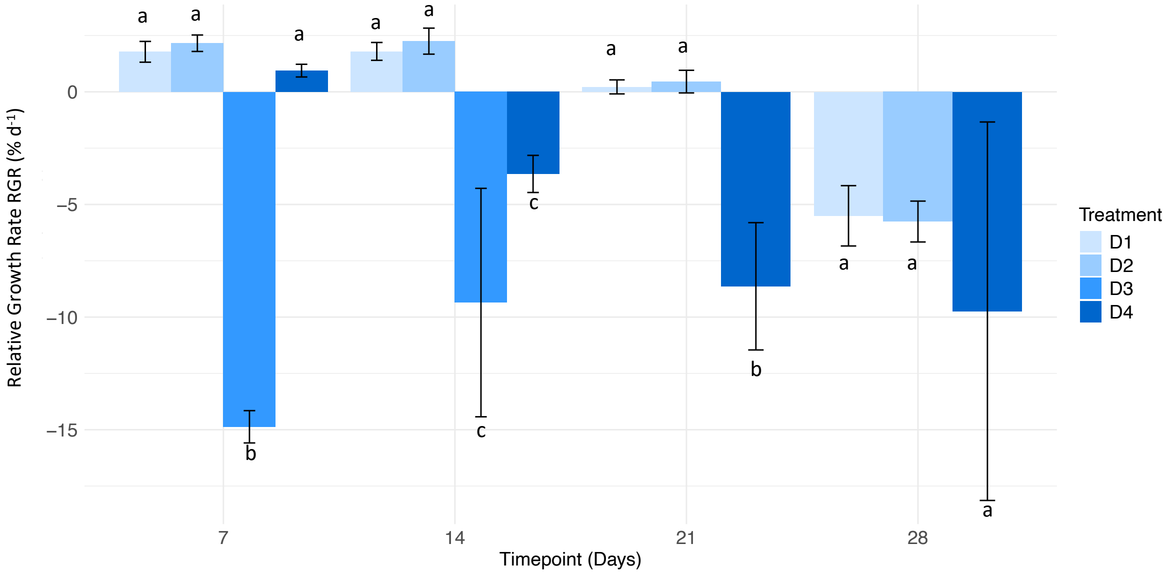

Figure 3.3: Daily relative growth rate RGR (% day^{-1}) for each treatment D1-D4 measured in weekly intervals, given as mean ± standard deviation. Small letters in both figures indicate the Dunns test post-hoc results where significant differences between treatments are displayed by non-matching letters and matching letters correspond to no significant differences.

Frond thickness (Figure 3.4 left) decreased over the course of the experiment from the initial biomass mean value of all treatments of 0.24 ± 0.05 g cm^{-1}. However, no significant differences between treatments were detected at the end of the experiment (p-value = 0.67, df = 2).

Ramuli density (Figure 3.4 right) decreased in all treatments compared to the initial biomass mean value of 3.61 ± 0.17 units cm^{-1}. D1 decreased to 3.30 ± 0.14 units cm^{-1} and was significantly lower compared to the initial biomass ($p < 0.01$, Z = 3.08). D2 decreased to 3.27 ± 0.17 units cm^{-1}, also significantly lower than the initial biomass ($p < 0.01$, Z = 3.06), and D4 decreased significantly to 3.10 ± 0.08 units cm^{-1} ($p < 0.01$, Z = 3.71). Treatment D4 was also significantly lower than D1 and D2 (p < 0.01, Z = 3.39; p = 0.04, Z = 2.71 respectively). All dunns test results are displayed in table A 7.3 in the appendix.

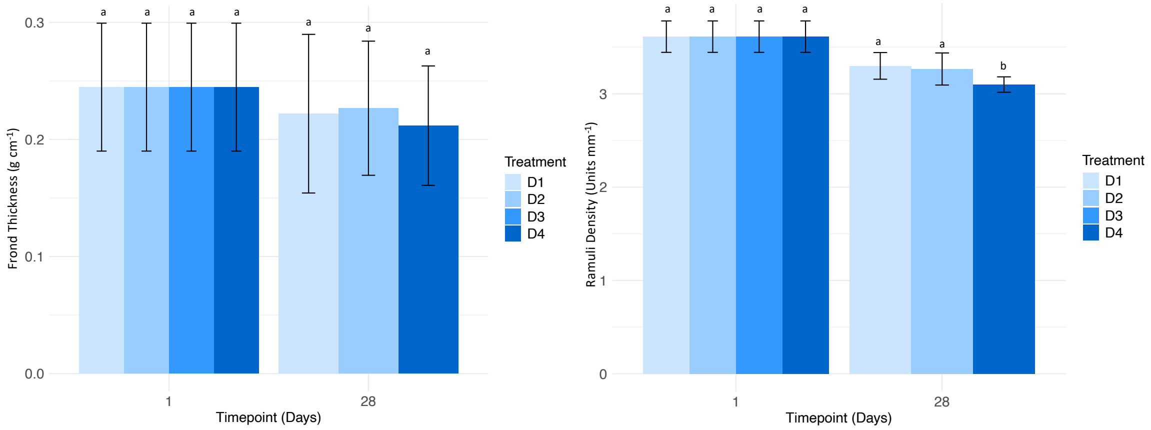

Figure 3.4: left: Frond thickness (g cm^{-1}) for each treatment D1-D4 on day 1 (initial values) and day 28 (end of the experiment), given as mean ± standard deviation. ; right: Ramuli density (units cm^{-1}) for each treatment D1-D4on day 1 (initial values) and day 28 (end of the experiment) , given as mean ± standard deviation. Small letters in both figures indicate the Dunns test post-hoc results where significant differences between treatments are displayed by non-matching letters and matching letters correspond to no significant differences.

The RGB red-channel value (R-value; (Figure 3.5 left)) increased from the initial biomass mean value of 65.46 ± 3.78 in treatment D1 to 151.0 ± 12.21, which was significantly higher than the initial value (p = 0.01, Z = –3.04). Treatment D2 increased to 152.3 ± 6.76, also significantly higher than the initial value (p < 0.01, Z = –3.30), and D4 increased to 144.0 ± 11.17, likewise significantly higher than the initial value (p = 0.04, Z = –2.72). Final values didn't differ significantly between treatments (p = 0.81, df = 2). All dunns test results are displayed in table A 7.4 in the appendix.

The harvestable biomass (HBM; (Figure 3.5 right) showed an increase in all treatments compared to the initial biomass mean value of 51.33 ± 1.52 %. D1 increased to 52.33 ± 0.57 %, D2 to 53.67 ± 2.31 %, and D4 to 53.33 ± 1.52 %. None of the treatments differed significantly from the initial biomass (D1: p = 0.36, df = 1; D2: p = 0.18, df = 1; D4: p = 0.18, df = 1), and no significant differences were observed between treatments (p = 0.67, df = 2).

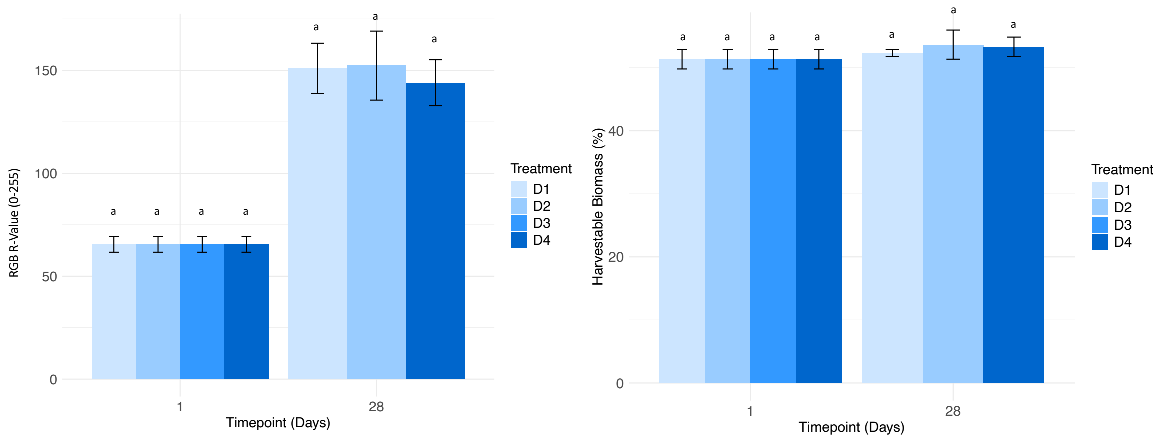

Figure 3.5: left: Frond RGB R-value for each treatment D1-D4 on day 1 (initial values) and day 28 (end of the experiment), given as mean ± standard deviation; right: Harvestable biomass (%) for each treatment D1-D4 on day 1 (initial values) and day 28 (end of the experiment), given as mean ± standard deviation. Small letters in both figures indicate the Dunns test post-hoc results where significant differences between treatments are displayed by non-matching letters and matching letters correspond to no significant differences.

3.3. Environmental data of the land-based experiment

Over the course of the land-based experiment, photosynthetically active radiation (PAR, µmol m^{-2} s^{-1}), temperature (°C) and absolute salinity (SA) were measured in both tanks of the TC (tray control) and TN (tray nutrient) treatment. Measurements taken throughout the duration of the experiment revealed no significant differences in PAR between treatments ($p = 0.981$, df = 2). Similarly, temperature did not fluctuate significantly over the course of the experiment ($p = 0.992$, df = 2).

PAR - and temperature values for both treatments are presented as a 24-hour profile for the day with the highest recorded light intensity and temperature in Figure 3.6 left and right. In TC, the highest recorded light intensity was 1172.3 PAR an temperature 30.64 °C. In TN the maximum light intensity and temperature was 1154.5 PAR and 30.7 °C.

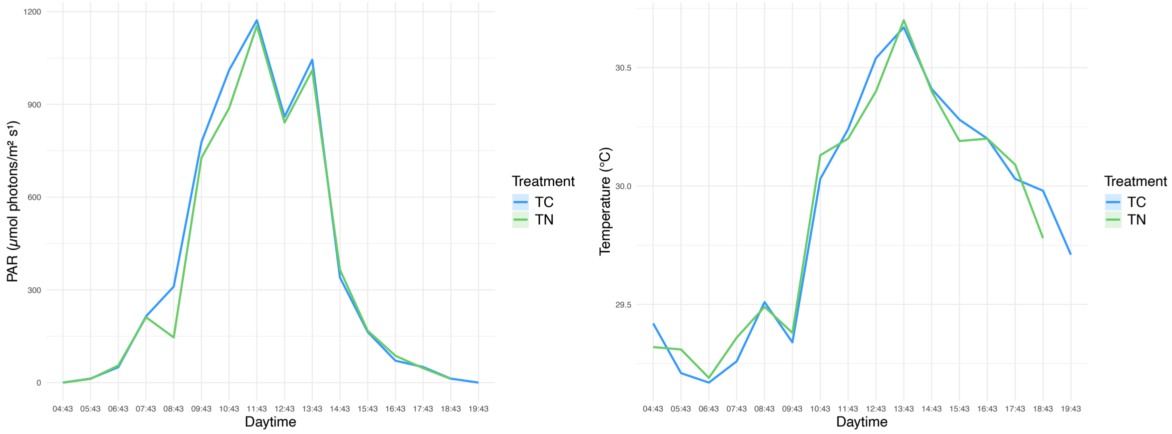

Figure 3.6: left: Photosynthetic active radiation PAR (µmol photons m^{-2} s^{-1}) over a one-day period for each respective treatment (TC: Tray Control; TN: Tray Nutrient); right: Temperature (°C) over one day period for each respective treatment (TC: Tray Control; TN: Tray Nutrient)

Salinity was measured over the entire time of the experiment and with a mean salinity of 33.2 ± 0.1 S_A in TC and 33.2 ± 0.1 S_A in TN, with no significant differences between treatments ($p = 1$, $df = 3$).

Laboratory nutrient analysis of the water failed, wherefore only the added nutrient amounts can be used as proxy. The TN tank received 1 kg of NPK fertilizer with a total-N amount of 6.8 mg l^{-1}. After two weeks, the fertilizer dosage was cut down to 0.5 kg, 3.4 mg l^{-1} total-N receptively

3.4. Land-based cultivation experiment

The daily RGR in the first week was 1.89 ± 0.43 % day^{-1} in the TC (tray control) treatment and 1.68 ± 0.21 % day^{-1} in the TN (tray nutrient) treatment (Figure 3.7). No significant differences were detected between treatments ($p = 0.51$, $df = 1$). In the second week, the daily RGR in the TC treatment decreased to –14.3 ± 1.3 % day^{-1}, with the biomass bleaching and partially disintegrating. In the TN treatment, the RGR remained positive at 2.03 ± 0.01 % day^{-1}, significantly higher than TC ($p < 0.01$, $Z = -2.88$), but not significantly higher than the TN RGR in week one. In the third week, no biomass remained in the TC treatment, as it had completely disintegrated. The TN RGR decreased to 0.48 ± 0.25 % day^{-1}, significantly lower than the RGR value in week two ($p = 0.02$, $Z = -2.84$). In the fourth week, the RGR of the TN treatment further decreased to –7.31 ± 1.12 % day^{-1}, significantly lower than the RGR in week three ($p = 0.03$, $Z = 2.88$).

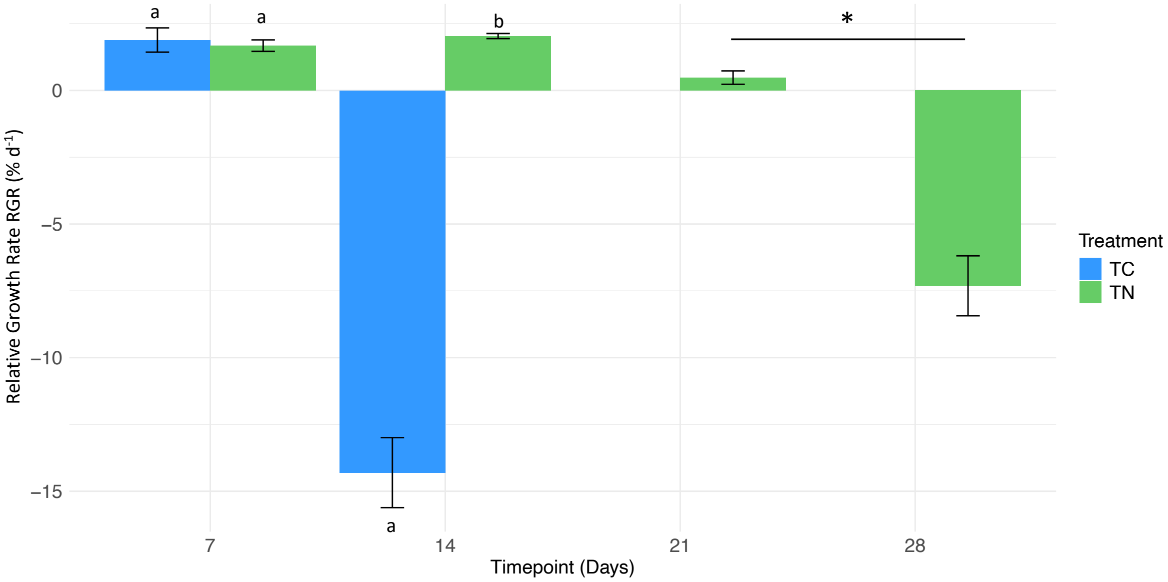

Figure 3.7: Daily relative growth rate RGR (% day^{-1}) for both treatments TC = Tray Control and TN =Tray Nutrients measured in weekly intervals, given as mean ± standard deviation. No biomass was available for treatment TC, resulting in missing values. Small letters indicate the Dunns test post-hoc results where significant differences between treatments are displayed by non-matching letters and matching letters correspond to no significant differences.

From week two onwards, the biomass in the TC treatment trays began to decompose, and insufficient intact biomass remained to allow for the analysis of morphological characteristics. Therefore, this investigation was carried out only with the TN treatment from the nutrient-enriched raceway.

Frond thickness (Figure 3.8 left) decreased significantly after 14 days compared to the initial biomass value, from 0.23 ± 0.06 g cm^{-1} to 0.08 ± 0.04 g cm^{-1} ($p < 0.01$, $Z = 5.5$). A significant increase in thickness to 0.11 ± 0.05 g cm^{-1} was observed from day 14 to day 28 ($p = 0.02$, $Z = 2.63$).

Ramuli density (Figure 3.8 right) followed a similar trend, decreasing significantly from the initial biomass value of 3.43 ± 0.09 units cm^{-1} to 1.57 ± 0.21 units cm^{-1} after 14 days ($p < 0.01$, $Z = 6.7$). By day 28, ramuli density had partially recovered to 2.33 ± 0.08 units cm^{-1}, which was significantly higher than the day 14 value, but still significantly lower than the initial biomass value (day 14–28: $p < 0.01$, $Z = –5.8$; day 1–28: $p = 0.02$, $Z = 2.7$). This was also higher than the initial biomass value ($p = 0.03$, $Z = –3.2$) and significantly higher than the week two value ($p < 0.01$, $Z = 5.8$).

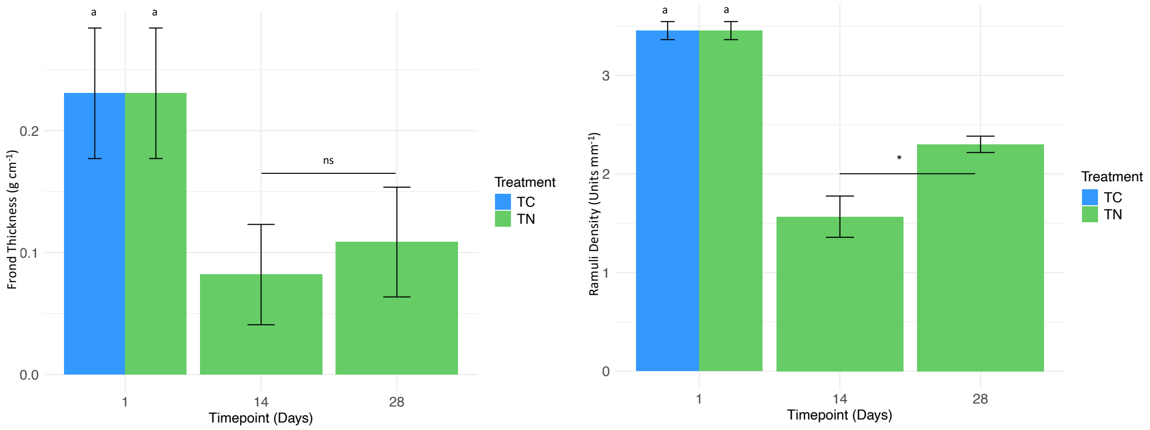

Figure 3.8: left: Frond thickness (g cm^{-1}*) for both treatments TC = Tray Control and TN =Tray Nutrients on day 1 (initial values) and day 28 (end of the experiment) for treatment TN as no biomass was available for TC , given as mean ± standard deviation; right: ramuli density (units* cm^{-1}*) for each treatment TC = Tray Control and TN =Tray Nutrients on day 1 (initial values) and day 28 (end of the experiment) for TN treatment as no biomass was available for TC , given as mean ± standard deviation. Small letters in both figures indicate the Dunns test post-hoc results where significant differences between treatments are displayed by non-matching letters and matching letters correspond to no significant differences. Significant results of pairwise comparison within treatments are indicated by **

The RGB red-channel (R-value) of the fronds (Figure 3.9 left) decreased significantly during the first two weeks compared to the initial biomass value of 66.3 ± 1.3, reaching 53.3 ± 1.7 ($p = 0.03$, $Z = 3.3$). From week two to week four, the value increased to 76.0 ± 3.6, which was significantly higher than the values from week 2 and the initial biomass ($p < 0.01$, $Z=2.8$; $p = 0.02$, $Z = 2.7$).

Harvestable biomass (HBM; Figure 3.9 right) decreased significantly during the first two weeks compared to the initial biomass, from 52.7 ± 0.8 % to 29.13 ± 1.51 % ($p < 0.01$, $Z = 3.8$). From week two to week four, HBM increased slightly to 32.8 ± 1.8 %, which was not significantly higher than the week two value but remained significantly lower than the initial biomass value ($p < 0.01$, $Z = 2.2$).

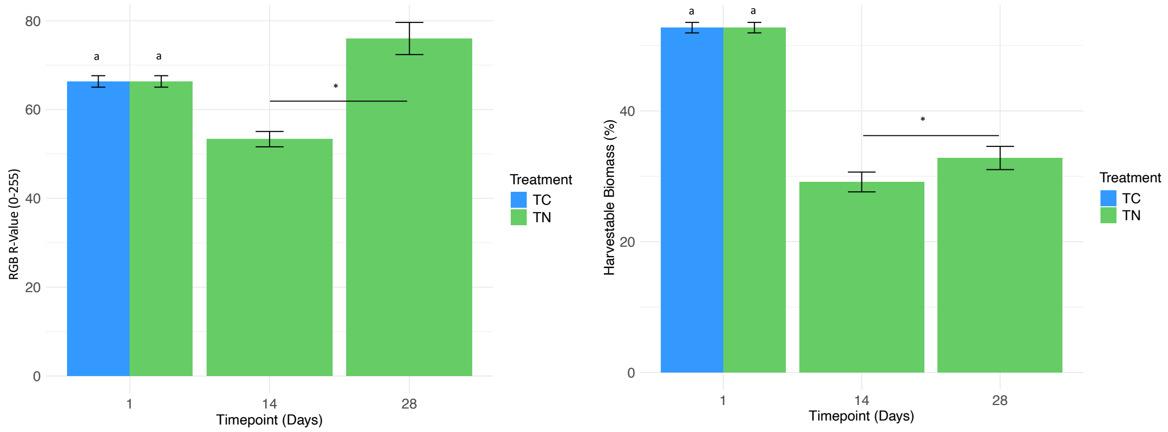

*Figure 3.9: left: Frond RGB R-value for both treatments TC = Tray Control and TN =Tray Nutrients on day 1 (initial values) and day 28 (end of the experiment) for treatment TN as no biomass was available for TC , given as mean ± standard deviation; right: harvestable biomass HBM (%) for each treatment TC = Tray Control and TN =Tray Nutrients on day 1 (initial values) and day 28 (end of the experiment) for TN treatment as no biomass was available for TC, given as mean ± standard deviation Small letters in both figures indicate the Dunns test post-hoc results where significant differences between treatments are displayed by non-matching letters and matching letters correspond to no significant differences. Significant results of pairwise comparison within treatments are indicated by **

3.5. Market nama

The variables frond thickness, ramuli density and RGB red-channel (R-value) were tested for normality using the Shapiro–Wilk test and for homogeneity of variances using Levene’s test to determine whether the assumptions for an ANOVA were met. None of the datasets were normally distributed (thickness: $p < 0.01$; ramuli density: $p < 0.01$; R-value: $p = 0.01$). Variances were also not homogeneously distributed (thickness: $p < 0.01$; ramuli density: $p < 0.01$; R-value: $p < 0.01$). Statistical differences between the nama samples were therefore assessed using the non-parametric Kruskal–Wallis test followed by Dunn’s post-hoc test with Bonferroni correction.

Frond thickness (Figure 3.10 left) differed significantly between origins ($p < 0.01$, $df = 3$), with nama from Savusavu being the thickest at 0.46 ± 0.10 g cm^{-1}, followed by Yasawa at 0.33 ± 0.07 g cm^{-1}, Bua at 0.24 ± 0.06 g cm^{-1}, and Rakiraki at 0.21 ± 0.04 g cm^{-1}. Fronds from Savusavu were significantly thicker than fronds from Bua ($p < 0.01$, $Z=-3.23$) and Rakiraki ($p < 0.01$, $Z= -3.30$). All dunns test results are displayed in table A 7.5 in the appendix.

Ramuli density (Figure 3.10 right) also fluctuated significantly between origins ($p < 0.01$, $df = 3$), with Savusavu showing the highest value at 3.86 ± 0.13 units cm^{-1}, followed by Yasawa at 3.60 ± 0.04 units cm^{-1}, Bua at 3.53 ± 0.13 units cm^{-1}, and Rakiraki at 3.43 ± 0.05 units cm^{-1}. Ramuli density from Savusavu nama was significantly higher than nama from Yasawa (p =

0.04, Z= 2.74), Bua (p = 0.04, Z= -2.75) and Rakiraki (p = 0.02, Z = -2.95). All dunns test results are displayed in table A 7.6 in the appendix.

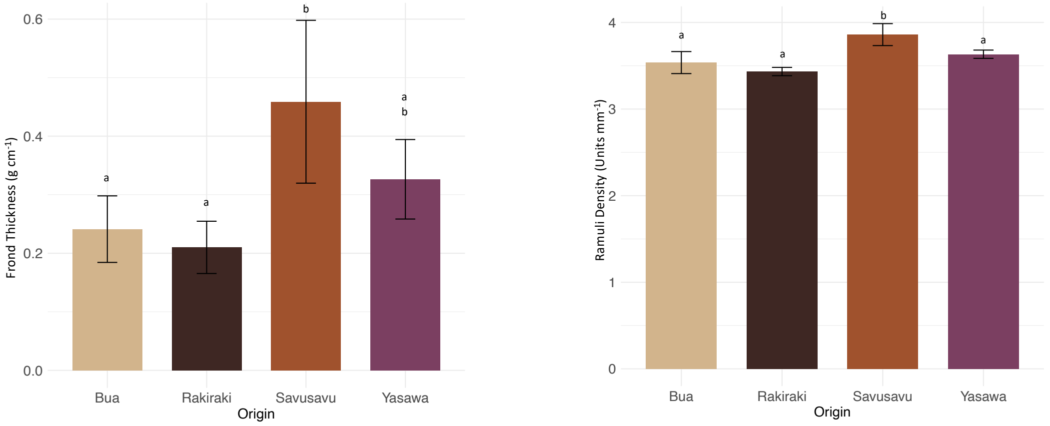

Figure 3.10: left: Frond thickness (g cm^{-1}) of nama from different origins (Bua, Rakiraki, Savusavu, Yasawa), bought on local markets, given as mean ±standard deviation; right: frond ramuli density (units cm^{-1}) of nama from different origins, bought on local markets, given as mean ±standard deviation. Small letters in both figures indicate the Dunns test post-hoc results where significant differences between treatments are displayed by non-matching letters and matching letters correspond to no significant differences.

The RGB red-channel value of the treatments (Figure 3.11) also varied significantly between origins ($p < 0.01$, df = 3), with Savusavu showing the lowest value at 51.27 ± 2.03, followed by Yasawa at 61.00 ± 2.21, Bua at 65.92 ± 3.12, and Rakiraki at 67.33 ± 2.67. Nama from Savusavu had significant lower red channel values than Yasawa samples (p = 0.01, Z = -3.11), Bua (p =0.01, Z = 3.05) and Rakiraki ($p < 0.01$, Z = 3.60). All dunns test results are displayed in table A 7.7 in the appendix.

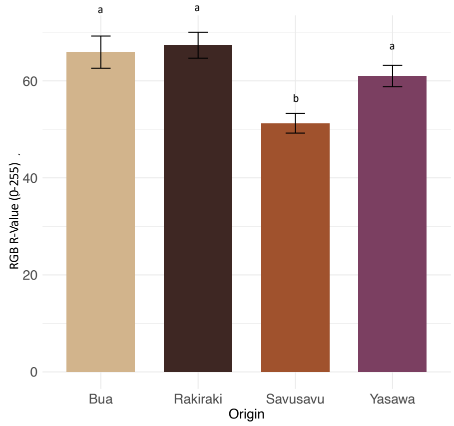

Figure 3.11: left: Frond R-value of nama from different origins (Bua, Rakiraki, Savusavu, Yasawa), bought on local markets, given as mean ±standard deviation; right: nama price per kg from different origins, bought on local market. Small letters in both figures indicate the Dunns test post-hoc results where significant differences between treatments are displayed by non-matching letters and matching letters correspond to no significant differences.

4. Discussion

This study investigated cultivating nama in protected lagoon waters using floating trays as well as in a land-based setting. Particular attention was given to the influence of environmental conditions, cultivation depth, and nutrient availability on growth performance and morphological traits of nama. Furthermore, the findings were evaluated in relation to local market requirements and their implications for the future development of sustainable aquaculture practices in Fiji.

4.1. Did the cultivation depth affect nama growth and morphology in the lagoon based set up?

In the lagoon-based cultivation experiment, treatment D2 achieved the highest relative growth rate (RGR) during weeks one and two. In contrast, D3 and D4 exhibited substantially reduced RGR values. Morphological analyses revealed a general trend toward reduced frond thickness across treatments compared to the initial biomass, although these differences were not statistically significant, neither relative to the starting biomass nor between treatments at the end of the experiment. Ramuli density, however, declined significantly in all treatments relative to the initial biomass, suggesting that ramuli development may be particularly sensitive when nama seaweeds lack essential elements for growth. This assumption is supported by Malta et al., (2005), who demonstrated that the closely related but non-edible species *C. prolifera* exhibited drastic morphological changes under nutrient limitation, producing extended stolons and spreading horizontally. Interestingly, the harvestable biomass (HBM) remained unchanged throughout the experiment, which may indicate that nama continued to produce fronds under suboptimal growth conditions, although frond morphology was strongly affected.

The RGB red-values (R-value) of the fronds increased strongly and significantly in all treatments, indicating a shift toward a brighter, bleached coloration. Since frond coloration is closely linked to chl-a concentration, this result suggests a decrease in chlorophyll content in parallel with declines in structural morphology and biomass (Stuthmann et al., 2021). Nutrient availability is a key factor influencing chl-a production in seaweeds (Zainuddin et al., 2024). Without sediment contact, nama may have been unable to access sufficient nutrients from possibly oligotrophic lagoon waters, leading to nutrient starvation.

Another possible explanation for reduced pigmentation could be excessive irradiance levels, which may damage chloroplasts and reduce chlorophyll content (Guo et al., 2015a). Stuthmann et al., (2021) reported that *C. lentillifera* grew best under shaded conditions below photosynthetic active radiation (PAR) values of 100 µmol photons m^{-2} s^{-1}, which is far below the irradiance levels recorded in this study, where peaks up to 1714.1 PAR were achieved. Nevertheless, excessive irradiance is unlikely to have been the main limiting factor, since shallower treatments D1 and D2 showed better growth than deeper treatments, D3 and D4 in the first two weeks. Furthermore, Paul et al., (2014) demonstrated that *C. lentillifera* and *C. racemosa* could be cultivated under mean light intensities of 170 PAR, with peaks exceeding 1200 PAR. As nama in the present study also naturally occurred at the investigated depths, it seems unlikely that irradiance levels exceeded the physiological tolerance range for cultivation. Temperatures across all treatments remained between 29 and 32 °C, which is above the reported optimum of 27.5 °C for *C. lentillifera* (Guo et al., 2015a). However, Horstmann, (1983), reported that ponds used for cultivating *C. racemosa* reached up to 38 °C, and since nama was naturally present at all experimental depths, it also appears unlikely that temperature levels were unsuitable for cultivation in this study.

Salinity fluctuated in the shallowest treatments, occasionally dropping during rainfall events, but never below 30 S_A. Given that the best growth occurred in shallow treatments where salinity fluctuations were most pronounced, while deeper treatments with more stable salinity performed poorly, salinity variability can most probably be excluded as a major limiting factor. This aligns with findings by Fakhrulddin et al., (2021) and Guo et al., (2015b), who reported that salinities as low as 25 S_A are suitable for nama growth.

Hydrodynamic conditions, on the other hand, may have played a more important role. Clod card measurements showed significantly higher water movement in D1, D3, and D4 compared to the control. Excessive hydrodynamics have previously been shown to limit the growth of delicate macroalgae by mechanically stressing fronds, altering morphology, and increasing susceptibility to breakage. De Gaillande et al., (2017) identified strong water movement as one of the limiting factors for nama aquaculture in lagoon waters. The fact that clod card weight loss in D2 did not differ significantly from the control indicates that water movement was lowest in this treatment, which also achieved the highest RGR in weeks one and two. This suggests that moderate or low water movement might be favorable for nama growth. Nevertheless, as all treatments eventually experienced severe biomass loss despite differences in hydrodynamics, water movement alone cannot explain the observed mortality, but may have acted as an additional stressor.

Finally, grazing was observed in both D3 and D4, and was particularly pronounced in D3. This suggests that herbivory by local fish populations may have been a major driver of biomass loss at these depths. However, this grazing pressure appears to be a site-specific factor linked to local fish community structure, rather than an inherent limitation of cultivation depth, since it was not observed in D1 or D2.

Comparison of cultivated nama samples with nama sampled from Fijian markets provides a useful proxy for local quality requirements. Market samples showed frond thickness values ranging from 0.21 ± 0.04 g cm^{-1} in Rakiraki to 0.46 ± 0.10 g cm^{-1} in Savusavu, ramuli density from 3.43 ± 0.05 units cm^{-1} in Rakiraki to 3.86 ± 0.13 units cm^{-1} in Savusavu, and RGB R-values between 51.27 ± 2.03 and 67.33 ± 2.67. For cultivated nama to be competitive in the market, the harvested biomass should at least match these local quality standards. In the lagoon experiment, frond thickness did not differ significantly from market samples, ramuli density was only significantly lower in D4. Nevertheless, RGB R-values were significantly higher in all treatments, indicating paler coloration and reduced pigment content compared to market biomass.

Taking these factors into account, cultivation depth appeared to influence the growth of nama during the first two weeks, with shallower depths providing more favorable conditions, possibly due to lower water movement and the absence of grazing fish. Morphological traits were generally unaffected by cultivation depth, with the exception of ramuli density, which showed a trend toward reduced coverage in the deepest treatment (D4), again indicating that shallower cultivation may be more suitable. Although the final cultivated biomass mostly matched the quality characteristics of market nama, its coloration deviated significantly, indicating inferior quality of the cultivated product. Since biomass in all treatments began to decline after week two, it is likely that an essential factor required for sustained growth was missing, thereby limiting the overall feasibility of lagoon-based cultivation.

4.2. How did the nutrient load affect nama growth and morphology when cultivated land-based?

The land-based raceway experiment demonstrated clear differences in the growth and morphology of nama between TN (tray-nutrient) and TC (tray-control) treatment. Growth performance diverged sharply between treatments after the first two weeks. While both TC and TN maintained similar positive RGR values in week one, TC biomass declined rapidly in week two, accompanied by bleaching and disintegration. By week three, no biomass remained in TC, indicating that a key element necessary to sustain physiological function was missing, similar to the observations in the lagoon culture experiment. In contrast, TN maintained a positive and significantly higher RGR in weeks two and three.

Environmental variables illumination, temperature, salinity, and water movement, did not differ significantly between treatments. Moreover, the measured illumination and temperature values were comparable to those recorded in the lagoon cultivation experiment and were within the ranges previously reported as suitable for nama growth (Fakhrulddin et al., 2021; Guo et al., 2015a, 2015b; Horstmann, 1983; Paul et al., 2014). This strongly suggests that the observed differences in growth performance were not caused by environmental factors but rather by surplus nutrient availability in the TN treatment. These findings align with previous studies demonstrating that *C. racemosa* grows better under high nutrient conditions (Fakhrulddin et al., 2021; Robles & Tahiluddin, 2022).

Robles & Tahiluddin, (2022) reported an RGR (mean ± SD) of 4.06 ± 2.43 % day^{-1} under ammonium (NH4^{+}) enrichment at 4.8 mg l^{-1} total-N, which is substantially higher than the maximum RGR achieved in the present study (2.03 ± 0.01% day^{-1} in TN) with higher total-N concentrations of 6.8 mg l^{-1} total-N. This discrepancy may be attributed to differences in fertilizer composition and nitrogen source. Some nama species preferentially utilize ammonium (NH_4^+), while others rely on nitrate (NO_3) as their nitrogen source (Alexandre & Santos, 2020; Liu et al., 2016). As in this recent study, the applied fertilizer was labelled only as "total-N," leaving the proportions of the nitrogen forms unknown. Furthermore, the exact nama species used in this study could not be determined, and growth dynamics are known to vary strongly between species (Paul et al., 2014).

The decline in RGR after the second week, along with the gradual die-off of biomass after week three in TN, suggests that nutrient availability became insufficient over time, particularly as the nutrient load was halved after week two from 6.8 mg l^{-1} total-N to 3.4 mg l^{-1} total-N. Although a concentration of 3.4 mg l^{-1} total-N should theoretically have been adequate, Robles and Tahiluddin (2022) showed that *C. racemosa* could still achieve an RGR (mean ± SD) of 1.41 ± 1.09 % day^{-1} at 1.6 mg l^{-1} total-N. In the present experiment, however, nutrient concentrations were not measured directly but were only calculated from the amount of fertilizer applied relative to water volume. It is therefore possible that phytoplankton or other competing organisms rapidly absorbed nutrients, leading to much lower effective concentrations or no nutrients available to nama, therefore negatively affecting growth. Supporting this assumption, Robles & Tahiluddin, (2022) also observed that the RGR in *C. racemosa* became negative after 21 days without nutrient supplementation which aligns well with the observed results from this study.

Morphological traits reflected these nutrient-driven differences. Frond thickness in TN declined significantly during the first two weeks, from 0.23 ± 0.06 g cm^{-1} to 0.08 ± 0.04 g cm^{-1}, resulting in very thin fronds. A partial recovery to 0.11± 0.05 g cm^{-1} was observed by day 28, suggesting morphological plasticity under prolonged nutrient exposure. A similar trend was observed in ramuli density, which dropped sharply from 3.43 ± 0.1 units cm^{-1} to 1.57 ± 0.2 units cm^{-1} after 14 days, but increased to 2.33 ± 0.1 units cm^{-1} by day 28. Although this pattern differs from the findings of Malta et al., (2005), who reported that *C. prolifera* produced more stolons under nutrient enrichment, the study underlines the strong effect of nutrient conditions on overall *Caulerpa* morphology.

Harvestable biomass (HBM) in the TN treatment declined steeply during the first two weeks, from 52.7 ± 0.8 % to 29.1 ±1.51 %, but subsequently stabilized at 32.8 ± 1.8 %. Although this remained significantly lower than the initial biomass, the stabilization suggests that nutrient enrichment buffered further declines. This finding correlates strongly with the observed stolon production of *C. prolifera* from the study of Malta et al., (2005) and again highlights the strong impact of nutrient conditions on morphological allocation. In the present nama species used for this study, higher nutrient availability appeared to favor stolon formation at the expense of HBM.

Frond green coloration, given indirect as R-value, also reflected possible nutrient-driven changes. The R-value decreased during the first two weeks to 53.3 ± 1.7, indicating increased pigmentation and therefore higher chl-a content (given as mean ± SD). However, it then increased strongly, reaching 76.0 ± 3.6 by week four, significantly exceeding both the initial and week-two values. Since higher R-values correspond to paler coloration (Stuthmann et al., 2021), this result suggests a decrease in chl-a content during the later stages of the experiment, most likely due to nutrient depletion. This assumption is consistent with previous findings that pigment content in seaweeds is directly influenced by nutrient availability (Ismail & Osman, 2016).

Comparisons with market nama provide additional insights into quality aspects. Considering that cultivated nama performed significantly better during the first 14 days under nutrient enrichment, quality characteristics are evaluated at this earlier stage. At that time, frond thickness and ramuli density of cultivated nama were significantly lower than those of market samples, highlighting the inferior quality of cultivated nama compared to market biomass. Only the R-values fell within the range of market samples, suggesting acceptable pigmentation.

Taken together, these findings indicate that nutrient availability seems to be a key driver for nama aquaculture, significantly influencing both growth and morphology. Although good growth was achieved under nutrient enrichment, morphological traits shifted in an unfavorable direction, deviating from expectations of improved quality under higher nutrient loads. Since nutrients in this study were supplied only as total-N, without specification of nitrogen source, and nutrient concentrations could not be measured directly, while the exact cultivated nama species also remained unknown, these results cannot be generalized to all nama species. Nonetheless, they highlight the crucial role of nutrient management in determining growth performance, morphology, and overall cultivation success.

4.3. Can nama be cultivated in lagoon waters or is a land-based approach superior?

Although the environmental parameters illumination, temperature salinity and water movement are unlikely to have limited the cultivation of nama in lagoon waters, the results of the present lagoon-based experiments indicate that cultivation is not feasible under the tested conditions, as nama biomass died off, most likely due to nutrient limitation. The extent to which these findings can be generalized to all nama species, however, remains uncertain. The PICs region harbors several morphologically similar nama species that are difficult to distinguish visually (de Gaillande et al., 2017; Söhnen et al., 2025; Zubia et al., 2020). It is plausible that only certain species are capable of sustaining growth on trays. For example, species naturally occurring on rocky reef substrates may be better adapted to extract nutrients directly from the water column, whereas sediment-associated species may rely more heavily on nutrient pools within the sediment (Stuthmann et al., 2023). Beyond nutrient limitation, grazing pressure from herbivorous fishes presents another major challenge to lagoon cultivation. This constraint, however, could potentially be mitigated through protective measures such as cages or netting.

In the land-based system, positive growth was only achieved when water was supplemented with additional nutrients, supporting the assumption that nutrient availability is a critical factor. The early die-off of nama in the TC treatment further strengthens this interpretation, while also demonstrating that nutrient enrichment promotes growth. Nevertheless, biomass from the nutrient-enriched TN treatment stagnated after three weeks and subsequently began to decline, suggesting that this approach also has limitations. As discussed above, uptake of nutrients by competing organisms may have substantially reduced the concentrations available to nama, ultimately contributing to biomass decline.

When comparing lagoon cultivation with the land-based approach, the RGR achieved in the lagoon treatment D2 during week two was significantly higher than that of the TN treatment.

This difference may be explained by the closer proximity to land, which may have resulted in higher nutrient loads in the lagoon water. Alternatively, another factor inherent to the natural lagoon environment might be microbial associations that may have supported nama growth and physiology in ways that the artificial land-based system could not replicate. Kopprio et al., (2021) demonstrated that shifts in the microbiome of farmed *C. lentillifera* can lead to bleaching and decomposition, while research by van der Loos et al., (2024) demonstrated that the microbiome of the green seaweed *Ulva* is strongly influenced by environmental conditions and fluctuates markedly between controlled land-based cultivation stages and offshore sea farms. This view is consistent with the holobiont concept, which posits that seaweeds and their epiphytic microbes form an integrated functional unit (Egan et al., 2013). In favorable conditions, associated bacterial communities can influence morphogenesis, nutrient acquisition and defense (Malik et al., 2020). Under stress, the microbiome may modulate adaptation and pigment dynamics (Ghaderiardakani et al., 2020). It seems reasonable that the microbiome of nama between a land based concrete tank with filtered seawater and a natural environment with numerous other organisms differs, thus that could potentially explain the difference in RGR and morphology between lagoon farmed and on shore farmed nama.

5. Conclusion & Outlook

This study demonstrated that nama could not be successfully cultivated in either lagoon waters or land-based tanks under the tested conditions, as either growth or morphological traits shifted in an unfavorable way. Cultivated nama can therefore not yet be considered a viable alternative to harvested market biomass. Nevertheless, valuable insights were gained that may help guide future efforts toward successful nama aquaculture. Nutrient limitation appears to be the most likely constraint when nama is cultivated on trays without sediment contact. However, since this study focused on only a single nama species, the findings cannot be generalized to all species. For future cultivation of nama in Fiji, an important first step will be to identify the different species present and to investigate their specific nutrient preferences. It will also be necessary to determine whether morphology changes under cultivation conditions and whether cultivated biomass can meet the quality standards of nama sold on local markets.

Land-based systems with secured and stable nutrient availability currently appear to be the most promising approach, as environmental conditions and nutrient levels can be optimally controlled. In addition to fine-tuning cultivation parameters, attention should also be directed toward the microbiome of nama, as it may significantly influence cultivation success.

A potential strategy for land-based nama production might be a co-cultivation approach with aquatic animals such as shrimp, fish, or sea cucumbers, which are already farmed in Fiji. The metabolism of these animals would provide a continuous and diverse nutrient supply that nama could convert into valuable biomass, offering a more natural and cost-effective cultivation method.

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7. Appendix

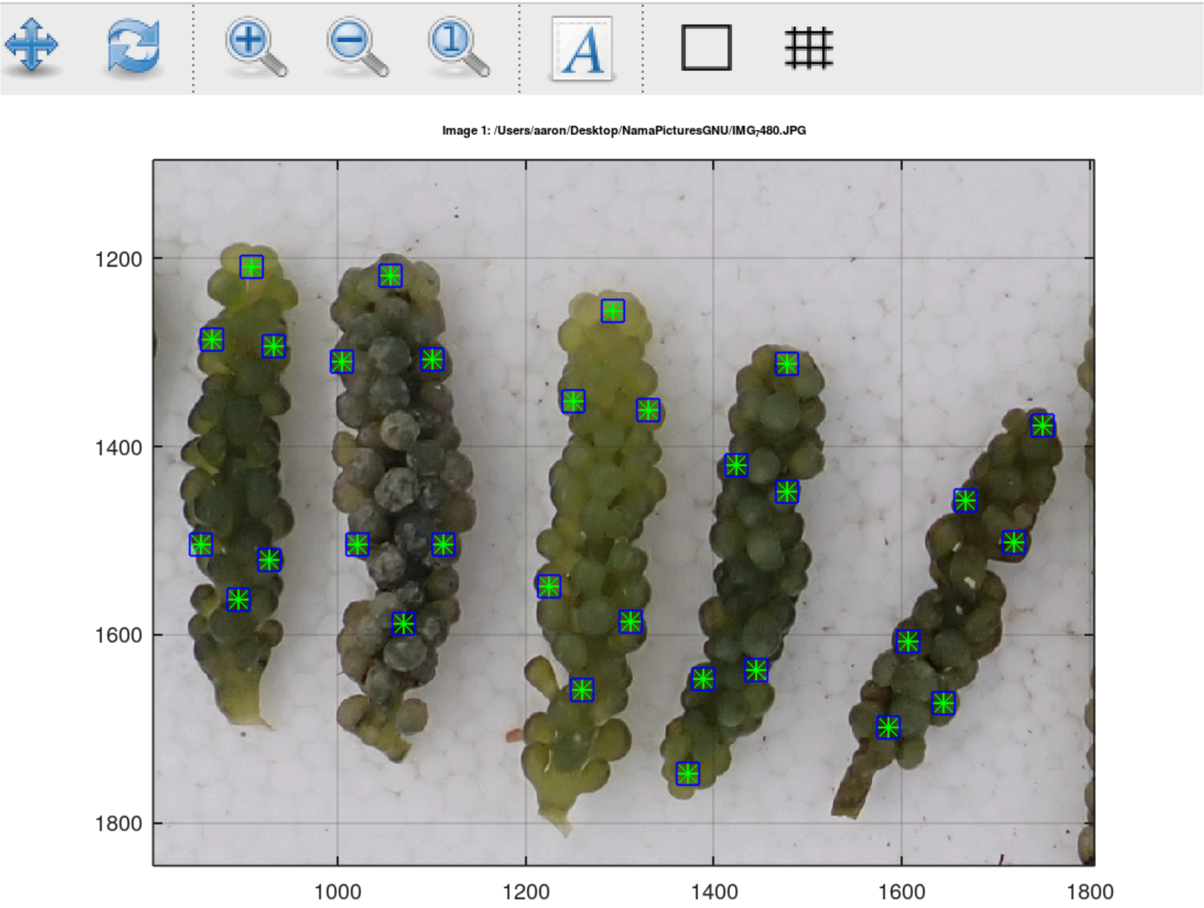

Figure A 7.1: Example of the analyzation of the RGB R-value of nama fronds with the GNU Octave software. Green dots indicate the respective measurement point on each nama frond

*Table A 7.2: Dunns test post-hoc results for pairwise comparison between treatments D1-D4 at respective timepoints from Relative Growth Rate RGR calculation of the lagoon culture experiment. The Z-value shows the standardized rank difference between two groups and the adjusted p value gives the level of significance after Bonferroni correction and * indicates significance*

Timepoint (Days)	Comparison	Z-Value	p – value (unadjusted)	p – value (adjusted)
7	D1 – D2	-0.281	0.78	1.0
7	D1 – D3	2.833	0.0045	0.027*
7	D2 – D3	3.322	0.00089	0.0053*
7	D1 – D4	0.563	0.567	1.0
7	D2 – D4	2.211	0.027	0.162
7	D3 – D4	-2.841	0.0045	0.021*
14	D1 – D2	-0.941	0.352	1.0
14	D1 – D3	3.188	0.0015	0.009*
14	D2 – D3	3.791	0.00015	0.0009*
14	D1 – D4	2.86	0.0043	0.0258*
14	D2 – D4	2.966	0.0031	0.0186*
14	D3 – D4	-0.513	0.612	1.0
21	D1 – D2	-0.512	0.612	1
21	D1 – D4	3.083	0.002	0.0126*
21	D2 – D4	3.15	0.0012	0.0072*
28	D1 – D2	0.66	0.510	1
28	D1 – D4	0.45	0.652	1
28	D2 – D4	0.98	0.325	1

*Table A 7.3: Dunns test post-hoc results for pairwise comparison between treatments D1-D4 at respective timepoints from ramuli density calculation of the lagoon culture experiment. The Z-value shows the standardized rank difference between two groups and the adjusted p value gives the level of significance after Bonferroni correction and * indicates significance*

Treatment	Comparison	Z-Value	p – value (unadjusted)	p – value (adjusted)
D1	1-28	3.081	0.0021	0.0063*
D2	1-28	3.062	0.0022	0.0066*
D4	1-28	3.711	0.00021	0.00063*
Timepoint (Days)				
28	D1-D2	0.324	0.751	1
28	D1-D4	3.392	0.00069	0.0041*
28	D2-D4	2.712	0.0067	0.0402*

*Table A 7.4: Dunns test post-hoc results for pairwise comparison between treatments D1-D4 at respective timepoints from RGB R-Value calculation of the lagoon culture experiment. The Z-value shows the standardized rank difference between two groups and the adjusted p value gives the level of significance after Bonferroni correction and * indicates significance*

Treatment	Comparison	Z-Value	p – value (unadjusted)	p – value (adjusted)
D1	1-28	-3.041	0.0024	0.01444*
D2	1-28	-3.301	0.00098	0.0059*
D4	1-28	-2.715	0.0067	0.0402*
Timepoint (Days)				
28	D1-D2	-0.433	0.671	1
28	D1-D4	0.562	0.573	1
28	D2-D4	0.711	0.478	1

*Table A 7.5: Dunns test post-hoc results for pairwise comparison between thickness of market nama. The Z-value shows the standardized rank difference between two groups and the adjusted p value gives the level of significance after Bonferroni correction and * indicates significance*

Comparison	Z-Value	p – value (unadjusted)	p – value (adjusted)
Bua-Rakiraki	1.213	0.232	1
Bua-Savusavu	-3.232	0.00122	0.0073*
Bua – Yasawa	-0.991	0.3222	1
Rakiraki – Savusavu	-3.299	0.0011	0.0061*
Rakiraki – Yasawa	-1.541	0.1232	0.7388
Savusavu – Yasawa	1.702	0.0891	0.534

*A 7.6: Dunns test post-hoc results for pairwise comparison between the ramuli density of market nama. The Z-value shows the standardized rank difference between two groups and the adjusted p value gives the level of significance after Bonferroni correction and * indicates significance*

Comparison	Z-Value	p – value (unadjusted)	p – value (adjusted)
Bua-Rakiraki	0.588	0.562	1
Bua-Savusavu	-2.751	0.0059	0.0354*
Bua – Yasawa	-0.275	0.789	1
Rakiraki – Savusavu	-2.951	0.0032	0.0192*
Rakiraki – Yasawa	-0.566	0.577	1
Savusavu – Yasawa	2.744	0.0061	0.0366*

*Table A 7.7: Dunns test post-hoc results for pairwise comparison between the RGB R-value of market nama. The Z-value shows the standardized rank difference between two groups and the adjusted p value gives the level of significance after Bonferroni correction and * indicates significance*

Comparison	Z-Value	p – value (unadjusted)	p – value (adjusted)
Bua-Rakiraki	-0.79	0.431	1
Bua-Savusavu	3.05	0.00231	0.0139*
Bua – Yasawa	0.561	0.573	1
Rakiraki – Savusavu	3.601	0.00032	0.0019*
Rakiraki – Yasawa	0.571	0.572	1
Savusavu – Yasawa	-3.112	0.0019	0.0114*