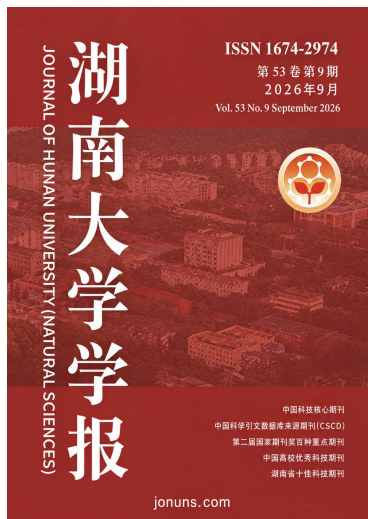




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Barnacle Colonization and *Avicennia marina* Performance During Mangrove Restoration in the Arabian Gulf

Saleh Alzamanan¹, Ahmed Al-Mansi¹, Abdullah Alwetaid¹, Osama Al-Kashef¹,
Naif Alqahtani¹, Amal Aldaej¹, Mohammed Awad^{1*}

¹National Center for Vegetation Cover Development and Combating Desertification (NCVC),
Riyadh, Kingdom of Saudi Arabia

* Corresponding author: mohammed_aay@yahoo.com

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Abstract: Barnacle colonization is widespread in mangrove habitats, but its spatial variability and relationship with restoration performance remain poorly understood in arid coastal environments. This study quantified barnacle colonization across the upper, middle, and lower intertidal zones of a restored *Avicennia marina* plantation on Abu Ali Island, Arabian Gulf, Saudi Arabia, and examined its spatial association with plant growth performance and natural regeneration. Colonization prevalence was consistently high (94–100%), whereas abundance increased from 27 ± 9 to 124 ± 29 individuals plant⁻¹, and surface-area-standardized density increased approximately 6.5-fold from the upper to the lower zone (0.075–0.485 individuals cm⁻²). Estimated biomass burden showed a similar increase, from 0.037 to 0.243 g cm⁻². Despite the pronounced seaward increase in barnacle burden, three-year-old plants maintained 100% survival, with no significant differences in vegetative growth among zones. Propagules and natural regeneration were observed in the upper and middle zones but were absent from the lower zone, where barnacle burden was highest. Extensive colonization of one-year-old plants at an additional afforestation site further indicated site-level variation in barnacle pressure on Abu Ali Island. Because intertidal position and associated environmental conditions were not experimentally controlled, these patterns should be interpreted as spatial associations rather than direct effects of barnacle colonization. By integrating surface-area-standardized barnacle density and estimated biomass burden with vegetative, reproductive, and recruitment indicators across an intertidal gradient, this study extends biofouling assessment beyond occurrence-based observations and seedling survival. The approach provides



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a quantitative basis for characterizing spatial variation in barnacle colonization intensity and assessing its ecological relevance to *A. marina* restoration under Arabian Gulf conditions.

Keywords: *Avicennia marina*; barnacle biofouling; intertidal gradient; mangrove restoration; natural regeneration; Arabian Gulf.

阿拉伯湾红树林恢复过程中藤壶定殖与海榄雌 (*Avicennia marina*) 生长表现

摘要: 藤壶定殖在红树林生境中十分普遍, 但其空间变异特征以及与恢复成效之间的关系, 在干旱海岸环境中仍缺乏充分认识。本研究对沙特阿拉伯阿拉伯湾阿布阿里岛一处恢复中的海榄雌 (*Avicennia marina*) 人工林进行了调查, 量化上部、中部和下部潮间带不同区域的藤壶定殖情况, 并分析其与植物生长表现和自然更新之间的空间关联。结果表明, 藤壶定殖率始终较高 (94–100%), 而单株藤壶数量则由上部区域的 27 ± 9 个增加至下部区域的 124 ± 29 个; 按表面积标准化后的藤壶密度由上部向下部区域增加约 6.5 倍 ($0.075\text{--}0.485$ 个 $\cdot\text{cm}^{-2}$)。估算的生物量负荷呈现类似趋势, 由 0.037 g $\cdot\text{cm}^{-2}$ 增加至 0.243 g $\cdot\text{cm}^{-2}$ 。尽管藤壶负荷沿向海方向显著增加, 三年生植株的存活率仍保持在 100%, 且不同区域之间的营养生长指标无显著差异。在上部和中部区域观察到繁殖体和自然更新, 而在藤壶负荷最高的下部区域未发现此类现象。另一处造林地的一年生植株也表现出较为严重的藤壶定殖, 这进一步表明阿布阿里岛不同地点之间的藤壶压力存在差异。由于潮间带位置及其相关环境条件并未进行实验控制, 因此这些结果应解释为空间关联, 而非藤壶定殖的直接效应。通过将按表面积标准化的藤壶密度和估算生物量负荷, 与潮间带梯度上的营养生长、繁殖及更新指标相结合, 本研究将生物污损评估从单纯的发生情况和幼苗存活进一步拓展。该方法为刻画藤壶定殖强度的空间差异, 并评估其在阿拉伯湾条件下对海榄雌恢复的生态意义, 提供了定量依据。

关键词: 海榄雌 (*Avicennia marina*); 藤壶生物污损; 潮间带梯度; 红树林恢复; 自然更新; 阿拉伯湾。

1. Introduction

Mangrove restoration is increasingly used to recover degraded coastal ecosystems, yet successful planting and short-term survival do not necessarily indicate the development of self-sustaining stands. Restoration outcomes are influenced by tidal position, hydroperiod, salinity, sediment characteristics, and hydrodynamic conditions, while reproductive development and natural recruitment provide complementary indicators of longer-term establishment. Recent restoration frameworks therefore emphasize monitoring multiple ecological attributes rather than relying primarily on survival of planted seedlings [1, 2]. Within this context, biological interactions during establishment merit consideration alongside the environmental conditions that regulate mangrove performance.

Barnacle colonization is a conspicuous form of biofouling in mangrove habitats, occurring on stems, branches, leaves, and pneumatophores. Settlement and abundance can vary with intertidal position, inundation,

salinity, hydrodynamics, larval supply, and characteristics of the attachment surface [3, 4]. Dense colonization can result in substantial coverage of young mangrove tissues and has been considered a potential biological constraint in mangrove rehabilitation [4, 5]. However, conspicuous biofouling does not necessarily indicate impaired plant performance. Experimental removal of barnacles from *Avicennia marina* seedlings did not significantly improve overall growth or survival [6], indicating that barnacle presence alone is insufficient to infer adverse effects. Quantitative measures of colonization intensity are therefore more informative than presence-absence observations when examining potential relationships with mangrove performance.

This distinction is particularly relevant in the Arabian Gulf, where *A. marina* occurs under arid conditions characterized by high salinity, pronounced seasonal thermal variability, and spatially heterogeneous hydrographic conditions [7, 1]. Recent regional evidence demonstrates substantial spatial variation in the abundance and biomass of macro-epibionts

associated with *A. marina*, including differences among locations and vertical positions on mangrove surfaces [8]. Despite these observations, quantitative information on barnacle biofouling across intertidal gradients within restored *A. marina* plantations remains limited, particularly regarding whether variation in barnacle burden coincides with vegetative performance, reproductive development, and natural recruitment. Because intertidal position can simultaneously influence barnacle settlement and mangrove performance, observed relationships may reflect shared environmental controls rather than direct effects of biofouling.

Accordingly, this study quantified barnacle prevalence, abundance, surface-area-standardized density, and estimated biomass burden across upper, middle, and lower zones of a restored *A. marina* plantation on Abu Ali Island, Saudi Arabia, and examined their spatial correspondence with plant survival, height, stem diameter, propagule occurrence, and natural regeneration. Observations from an additional one-year-old afforestation site were included to document site-level variation in biofouling intensity beyond the principal study transect. By integrating standardized measures of barnacle burden with vegetative, reproductive, and recruitment indicators, the study examines whether pronounced biofouling gradients coincide with broader differences in restoration performance. Given the observational design, these relationships are interpreted as spatial associations rather than causal effects. This integrated approach extends assessment beyond barnacle occurrence and seedling survival by quantitatively linking biofouling intensity with multiple indicators of restoration performance across an intertidal gradient, providing a basis for evaluating the ecological relevance of barnacle colonization in Arabian Gulf mangrove restoration.

2. Materials and Methods

2.1. Study area

The study was conducted on Abu Ali Island, Eastern Province, Saudi Arabia, along the western Arabian Gulf (Figure 1). The area has an arid coastal climate characterized by high evaporation, limited freshwater input, elevated salinity, and pronounced seasonal temperature variability [7, 1]. Natural mangrove vegetation is dominated by *Avicennia marina*, which occurs in fragmented intertidal stands adapted to the high salinity and thermal stress characteristic of the Arabian Gulf [9, 1]. At the study site, natural mangrove stands occur adjacent to restored *A. marina* plantations. Abu Ali Island has also experienced historical petroleum contamination, with persistent oil residues documented along portions of its intertidal shoreline [10, 11]. These environmental conditions provide a relevant setting for evaluating seedling performance and barnacle colonization across the intertidal gradient.

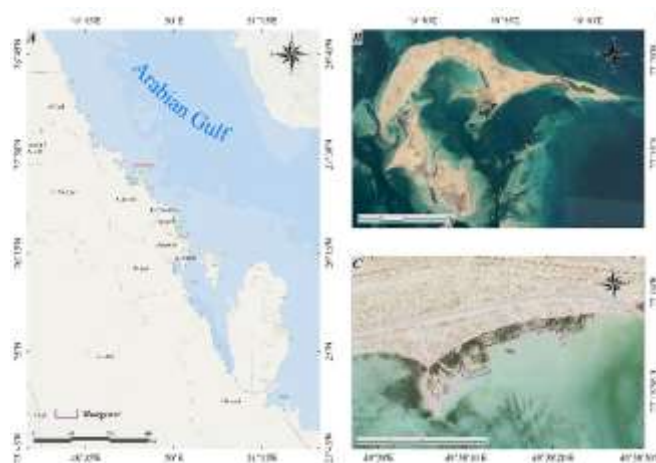


Figure 1. Location of the study area and *A. marina* mangrove habitat at Abu Ali Island, Arabian Gulf, Saudi Arabia. (A) Regional location of Abu Ali Island along the eastern Saudi Arabian coast; (B) Abu Ali Island showing the study-site location; and (C) detailed view of the study site and mangrove extent

2.2. Topographic and Ecological Zonation

A landward–seaward transect was established across the study site to characterize microtopographic variation and ecological zonation. Sequential horizontal distances and vertical elevation changes were measured from the landward beach to the seaward limit of the *Avicennia marina* plantation, covering a total transect length of approximately 130 m. Relative elevation was calculated cumulatively from successive vertical changes, using the landward transect origin as the reference datum (0.0 m). The transect was classified into three major ecological zones: beach, natural mangrove forest, and restored *A. marina* plantation; the plantation was further divided into upper, middle, and lower zones along the landward–seaward gradient. The position at which barnacle colonization was first observed was recorded along the transect and incorporated into the topographic profile to evaluate its spatial relationship with elevation and ecological zonation.

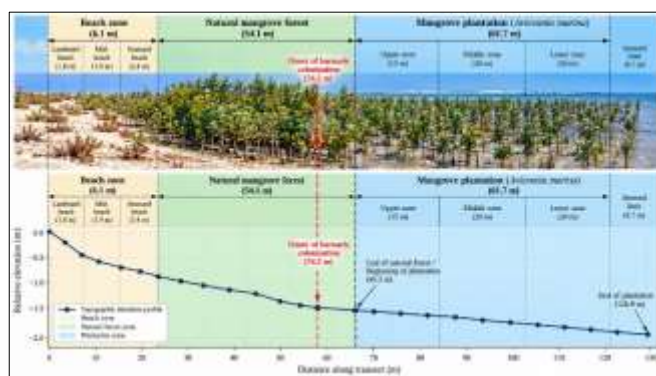


Figure 2. Topographic elevation profile and ecological zonation along the mangrove restoration transect

2.3. Barnacle Colonization Assessment

Barnacle colonization of *A. marina* was quantified separately in the upper, middle, and lower

intertidal plantation zones. Colonization prevalence was expressed as the percentage of examined plants bearing barnacles, and abundance as the mean number of barnacles per plant. To standardize colonization intensity for differences in plant size, the surface area of the assessed stem section was approximated as a cylinder ($SA = \pi DL$), where D is stem diameter (cm) and L is the vertical stem length assessed for barnacle colonization; barnacle density was then expressed as individuals cm^{-2} . Mean individual barnacle mass was determined from the pooled barnacle samples (0.50 ± 0.03 g, mean $\pm$ SD). Because barnacle mass was not measured independently within each zone, zone-level biomass was estimated as barnacle abundance $\times$ pooled mean individual mass, and surface-area-standardized biomass burden was calculated as $(N \times W)/(\pi DL)$, where N is barnacle abundance and W is pooled mean individual mass. This approach provides standardized measures of colonization intensity and physical biomass loading while avoiding unsupported assumptions of zone-specific differences in barnacle size.

3. Results and Discussion

3.1. Barnacle Colonization Gradient

Barnacle colonization exhibited a pronounced intertidal gradient across the *A. marina* plantation (Figure 3A–C). Prevalence increased only marginally from 94% in the upper zone to 100% in the lower zone, whereas abundance increased from 27 ± 9 to 124 ± 29 individuals plant^{-1} and surface-area-standardized density from 0.075 to 0.485 individuals cm^{-2} , representing an approximately 6.5-fold seaward increase (Table 1). Estimated biomass similarly increased from 13.5 to 62.0 g plant^{-1} , while surface-area-standardized biomass burden increased from 0.037 to 0.243 g cm^{-2} . Representative barnacle specimens collected from the study area are shown in Figure 3D, illustrating the calcareous fouling organisms contributing to the quantified barnacle burden. Thus, intertidal position was more strongly associated with colonization intensity and physical loading than with occurrence alone. The spatial pattern corresponded with the observed field zonation, with comparatively limited barnacle loading in the upper landward zone and progressively greater colonization toward the lower seaward zone (Figure 3C).

Similar spatial heterogeneity has been documented for macro-epibionts associated with *A. marina* in the Arabian Gulf and Gulf of Oman, where abundance and biomass varied among locations and vertical positions, with local hydrographic conditions identified as important determinants of epibiont assemblages [8]. The occurrence of *Amphibalanus amphitrite*, a widespread fouling barnacle in the region, further demonstrates its capacity to persist under environmentally variable marine conditions [12]. The substantially greater barnacle burden toward the lower

zone is consistent with greater marine exposure and potentially longer or more frequent access of planktonic larvae to submerged plant surfaces. However, this mechanism cannot be established from the present spatial observations because inundation duration, hydrodynamics, and larval supply were not measured directly. Arabian Gulf mangrove environments are influenced by interacting hydrographic, salinity, sediment, and water-quality conditions that may further contribute to fine-scale spatial variation in fouling pressure [13]. Collectively, these results indicate that barnacle abundance, surface-area-standardized density, and biomass burden provide greater discriminatory power for detecting spatial variation in fouling intensity than prevalence alone and may serve as useful quantitative metrics for monitoring barnacle colonization in *A. marina* restoration plantations.

Table 1. Barnacle colonization intensity and estimated biomass burden on *A. marina* across intertidal zones

Parameter	Up per zone	Mid dle zone	Low er zone
Colonization prevalence (%)	94	98	100
Mean abundance (No. plant^{-1})	27 ± 9	63 ± 1	124 ± 29
Barnacle density (No. cm^{-2})	0.07	0.228	0.485
Estimated biomass (g plant^{-1})	5 ± 0.023	± 0.052	± 0.108
Biomass burden (g cm^{-2})	13.5	31.5	62
	0.03	0.114	0.243

Note: Values for barnacle abundance and density are presented as mean $\pm$ SD ($n = 20$ randomly selected plants per zone). Colonization prevalence is expressed as a percentage. ^a Estimated biomass and biomass burden were calculated using the pooled mean individual barnacle mass of 0.50 ± 0.03 g (mean $\pm$ SD).

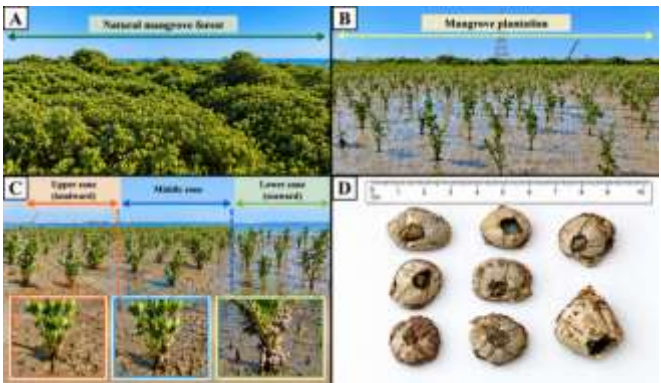


Figure 3. Spatial zonation and barnacle colonization of *A. marina* along the intertidal gradient at Abu Ali Island, Arabian Gulf, Saudi Arabia. (A) Natural mangrove forest; (B) mangrove plantation; (C) upper (landward), middle, and lower (seaward) plantation zones showing the spatial gradient in barnacle colonization; and (D) representative barnacle specimens collected from the study area, shown with a metric scale for size reference.

3.2. Seedling Performance

Despite the pronounced seaward increase in barnacle colonization, *A. marina* maintained 100% survival across all intertidal zones, with no significant differences in vegetative growth. Mean plant height and stem diameter nevertheless showed numerical declines from the upper (66.7 cm; 20.5 mm) through the middle (55.5 cm; 18.3 mm) to the lower zone (54.5 cm; 17.3 mm). Representative morphological characteristics of the established three-year-old seedlings, including plant height and stem diameter, are shown in Figure 4A–B. These findings indicate successful establishment and suggest that the observed barnacle burden was not associated with detectable mortality or statistically significant growth suppression during the study period, consistent with experimental evidence that barnacle colonization does not necessarily reduce the growth or survival of *A. marina* seedlings [6].

In contrast, propagules and natural regeneration were observed only in the upper and middle zones and were absent from the lower zone. Propagule development on established seedlings is illustrated in Figure 4C. This spatial pattern suggests a potential divergence between vegetative persistence and reproductive and recruitment performance. The absence of propagules and natural regeneration in the lower zone cannot be attributed directly to barnacle colonization because intertidal position integrates several interacting environmental factors, including inundation frequency and duration, sediment aeration, hydrodynamic disturbance, salinity variability, propagule transport, and opportunities for propagule retention and establishment [14–16]. Nevertheless, the co-occurrence of the highest barnacle density and biomass burden with the absence of propagules and natural regeneration in the lower zone is ecologically noteworthy. Heavy fouling may represent an additional physical or physiological constraint under comparatively stressful lower-intertidal conditions, although the present observational design cannot isolate such an effect from tidal position and associated environmental factors. These findings indicate that reproductive development and natural regeneration may provide complementary indicators of restoration performance beyond survival and vegetative growth. Repeated phenological observations combined with measurements of hydroperiod, sediment conditions, and barnacle burden would help distinguish potential fouling effects from those associated with tidal position and other environmental drivers.

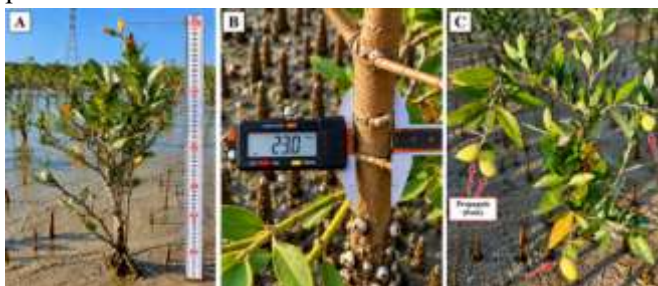


Figure 4. Morphological and reproductive characteristics of three-year-old *A. marina* seedlings (A) Representative measurement of seedling height; (B) stem diameter measured using a digital caliper; and (C) developing propagules observed on established seedlings.

3.3. Site-Specific Barnacle Biofouling

At an additional *Avicennia marina* afforestation site on Abu Ali Island, one-year-old plants exhibited extensive barnacle colonization, with dense aggregations covering substantial portions of the stems and branches (Figure 5A–C). The occurrence of such pronounced biofouling within the first year of establishment indicates that barnacle settlement can develop rapidly on young mangroves where local conditions favor larval settlement and persistence. Previous studies have shown that barnacle abundance on mangroves can vary markedly with intertidal position and environmental conditions, including inundation, hydrodynamic exposure, salinity, and availability of suitable attachment surfaces [3, 4]. However, extensive colonization alone does not demonstrate adverse effects on plant performance, as experimental evidence for *A. marina* found no significant reduction in seedling growth or survival associated with barnacle presence [6]. The observation at this separate one-year-old plantation therefore provides independent field evidence of strong spatial variability in barnacle pressure within Abu Ali Island and suggests that biofouling intensity may be highly site-dependent, supporting its inclusion alongside growth, survival, hydroperiod, and environmental variables in the monitoring of young mangrove afforestation sites.



Figure 5. Heavy barnacle colonization of *Avicennia marina* at an additional site on Abu Ali Island. (A–B) Extensive barnacle coverage of stems and branches; and (C) close-up view showing dense barnacle aggregation and associated epibionts on the stem surface.

3.4. Restoration Implications

The combined findings indicate that survival alone may provide an incomplete measure of early *A. marina* restoration performance. Although three-year-old plants maintained 100% survival across the intertidal gradient, barnacle density and biomass burden increased markedly toward the lower seaward zone, where

propagule development and natural regeneration were not observed. The occurrence of extensive barnacle colonization at an additional one-year-old afforestation site further demonstrates that substantial biofouling can develop early after planting and vary considerably among restoration sites. Such spatial heterogeneity is consistent with regional evidence showing significant variation in the abundance and biomass of macroepibionts associated with *A. marina*, with local hydrographic conditions contributing to differences among locations and vertical positions on mangrove surfaces [8]. Importantly, the present observations do not establish barnacle colonization as the cause of reduced reproductive and recruitment indicators in the lower zone because barnacle burden covaried with intertidal position and associated environmental conditions.

Instead, the results identify barnacle biofouling as a potentially informative component of restoration monitoring, particularly when evaluated together with tidal position, hydroperiod, plant growth, reproductive development, and natural recruitment. This multidimensional assessment is consistent with recent mangrove restoration monitoring frameworks that incorporate survival and natural regeneration alongside site conditions and other ecological outcomes rather than relying on a single establishment metric [2]. Long-term monitoring integrating these variables would help determine whether intensive biofouling represents a transient feature of early establishment or is associated with subsequent differences in plantation development and functional recovery.

4. Conclusion

This study extends current understanding of barnacle biofouling in restored *A. marina* by quantifying colonization intensity across the intertidal gradient and relating standardized biofouling metrics to indicators of plant performance and regeneration. Integrating surface-area-standardized barnacle density and estimated biomass burden with vegetative growth, reproductive development, and natural recruitment provides a quantitative approach for evaluating biofouling within restoration assessment. Barnacle burden and mangrove performance, however, need to be interpreted in the context of tidal position and associated environmental conditions, as their spatial correspondence does not demonstrate a direct biological effect. Incorporating biofouling metrics into restoration monitoring can help distinguish initial plant establishment from broader ecological development and identify conditions requiring further investigation. Long-term and experimentally controlled studies are needed to determine whether persistent barnacle loading influences reproductive performance, natural recruitment, and the development of self-sustaining *A. marina* stands in arid mangrove environments.

Declarations

Author Contributions

Conceptualization, M.A., S.A. and A.A.-M.; methodology, M.A.; validation, M.A., S.A., A.A.-M. and A.A.; formal analysis, M.A.; investigation, M.A., A.A.-M., A.A., O.A.-K., N.A. and A.Ald.; resources, S.A., A.A.-M. and A.A.; data curation, M.A.; writing—original draft preparation, M.A.; writing—review and editing, M.A., S.A., A.A.-M., A.A., O.A.-K., N.A. and A.Ald.; visualization, M.A.; supervision, S.A. and A.A.-M.; project administration, S.A., A.A.-M. and A.A.; funding acquisition, S.A. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest

The author declares that there is no conflict of interests regarding the publication of this manuscript.

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