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RESEARCH ARTICLE

Cutting and juvenile cutting as complementary strategies for the propagation and conservation of *Conocarpus erectus*

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Abstract

Introduction: Limited seed availability constrains mangrove restoration, but vegetative propagation through cutting and juvenile cutting (mini-cutting), supported by indole-3-butyric acid (IBA), a synthetic auxin that stimulates adventitious rooting, offers a scalable solution for *Conocarpus erectus*.

Objectives: To evaluate cutting and juvenile cutting (mini-cutting) techniques, with and without IBA, for the vegetative propagation of *C. erectus*, supporting genotype rescue and effective ex situ conservation for mangrove restoration.

Methods: Cuttings of *C. erectus* were collected from mature stock plants. The effect of IBA was tested at 0, 2000, 4000, 6000, and 8000 mg/L in a completely randomized design with three replicates. A semi-hydroponic system was used to evaluate mother plants (mini-stump) survival and sprouting capacity. Juvenile cuttings were rooted under greenhouse conditions with IBA concentrations of 0, 4000, and 8000 mg/L, following a randomized block design with four replicates. Data were analyzed using one-way analysis of variance followed by Tukey's test for mean comparison, and polynomial regression to assess dose–response trends.

Results: *Conocarpus erectus* reached 56–57% rooting cuttings at 4000–6000 mg/L of IBA and up to 75% in juvenile cuttings. Mini-gardens proved highly effective for *C. erectus*, achieving 100% mini-stump survival and producing 388 sprouts/m^2 (5.8 sprouts per stump at 15 × 10 cm spacing).

Conclusions: Cutting is a reliable propagation method for *C. erectus*, whereas juvenile cuttings are highly efficient, particularly when combined with IBA at 4000 and 6000 mg/L.

Implications for Practice: Cutting is an efficient strategy for the rapid propagation of *Conocarpus erectus*, enabling the rescue and multiplication of genotypes from natural populations while contributing to their conservation and the maintenance of genetic variability. Juvenile cutting (mini-cutting), particularly when combined with optimal IBA concentrations, markedly enhances rooting success and overall propagation efficiency in *C. erectus*, representing a plastic strategy suitable for changing or heterogeneous environments due to its physiological vigor. Mini-gardens operate as compact and productive living germplasm banks, facilitating continuous ex situ conservation and large-scale plant production. Vegetative propagation techniques therefore provide reliable alternatives in situations where seed availability is low or natural regeneration is limited, strengthening the resilience and scalability of mangrove restoration programs.

Key words: genetic rescue, indole-3-butyric acid (IBA), mangrove conservation, mangrove restoration, mini-gardens, vegetative propagation

Introduction

Mangrove forests are vital coastal ecosystems situated at the interface between land and sea, providing essential ecological functions and ecosystem services. These forests act as nurseries and habitats for numerous marine and terrestrial species, thereby supporting biodiversity and coastal productivity (Su et al. 2021). In addition to their ecological roles, mangroves contribute to carbon sequestration, shoreline protection, raw material supply, and socio-cultural services such as education and tourism (Das 2017; Sidik et al. 2018). Their root systems stabilize sediments and buffer coastlines against erosion and climate-related disturbances (Sidik et al. 2018).

Despite their significance, mangroves face increasing degradation due to urbanization, aquaculture, agriculture, deforestation,

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and climate-induced stressors such as sea-level rise and salinity shifts (Goldberg et al. 2020; Saintilan et al. 2020; Su et al. 2021). Brazil contains one of the world's largest mangrove areas, hosting high species richness, including Red mangrove (*Rhizophora mangle* L.), Button mangrove (*Conocarpus erectus* L.), and other key taxa (Diniz et al. 2019; Matta et al. 2025). However, habitat loss and fragmentation threaten the genetic diversity and long-term persistence of these species (Santos et al. 2019; Goldberg et al. 2020).

Conocarpus erectus is a salt-tolerant species of ecological and economic importance, widely distributed in tropical regions and valued for its medicinal properties and phytoremediation potential (Rad et al. 2019; Ochoa-Gomez et al. 2021; El-Mahrouk et al. 2024). However, its natural regeneration is constrained by seed predation, salinity stress, and low propagule availability (Elster & Perdomo 1999). Seed propagation is particularly constrained due to low viability (often below 12%) and high seedling mortality, with germination rates as low as 5% during the dry season and only 1.6% of seedlings surviving to the reproductive phase (Tomlinson 1986; Hernandez & Espino 1999; Kass et al. 2007). These limitations create a natural propagation bottleneck for restoration initiatives.

To overcome this, vegetative propagation has been applied successfully in mangrove and coastal species. Stem cuttings of *C. erectus* have shown rooting percentages of 57–71%, particularly when apical cuttings are treated with IBA concentrations around 3000 mg/L (Safaa et al. 2014; Abdel-Rahman et al. 2020). Other methods, such as micropropagation (Dewir et al. 2018) and aerial layering (Abdul-Hafeez 2020), have also been explored but remain costly and labor-intensive.

In this context, two vegetative propagation strategies can be applied to restoration and conservation programs, each suited to distinct ecological scenarios. Standard cuttings, derived from mature stems, serve as a rapid-propagation strategy appropriate for stable environments, where uniform clonal establishment accelerates site recovery. In contrast, juvenile cuttings (commonly termed *mini-cuttings* in the literature) are obtained from managed propagation systems under controlled conditions and represent a long-term conservation strategy for heterogeneous or changing environments. Juvenile propagules exhibit greater physiological vigor, which can enhance acclimation and continuous production under variable environmental conditions (Dias et al. 2012; Wendling et al. 2014; Felice et al. 2024).

Both techniques are affected by factors such as the physiological status of the donor plants, cutting maturity, and environmental conditions. The application of growth regulators such as indole-3-butyric acid (IBA) can promote adventitious root formation and improve propagation efficiency (Stuepp et al. 2017b; Díaz-Sala 2020, 2021). Despite the ecological and economic importance of *C. erectus*, no studies have yet investigated its propagation using juvenile cuttings or compared these techniques within an integrated restoration framework.

Therefore, this study evaluates the effectiveness of standard and juvenile cuttings, with and without IBA treatment, for the vegetative propagation and conservation of *C. erectus*. We propose a dual framework in which cutting is a rapid-response method for genotype rescue and in situ restoration in stable environments, while juvenile cutting serves as a continuous, long-term ex situ conservation strategy in variable environments. We hypothesize that: (1) *C. erectus* exhibits high adaptability to juvenile cutting systems due to its physiological vigor; (2) IBA enhances rooting efficiency in both techniques; and (3) the managed propagation system can function as a germplasm bank supporting sustained conservation and restoration efforts.

Methods

Cutting Propagation: Collection of Propagules and Effect of IBA on Rooting

Vigorous shoots used as propagules for cutting propagation were collected from the basal portion of the canopy formed during the current growing season (Fig. 1). These propagules were obtained from 20 mature parent trees located in a mangrove area in Icapuí, Ceará, Brazil. Propagule collection was carried out at 5:00 hours to minimize water loss due to evapotranspiration. After collection, the propagules were placed in insulated styrofoam boxes and transported to the Forest Research Nursery of the Federal Rural University of the Semi-Arid (UFERSA), Brazil.

To evaluate the capacity of cuttings to rescue genotypes of *Conocarpus erectus*, we tested different concentrations of IBA on rooting performance. Propagules were prepared as 10 cm cuttings, retaining two pairs of leaves reduced to 50% of their original area. The basal 2 cm of each cutting was immersed in IBA solutions at 0 (control), 2000, 4000, 6000, and 8000 mg/L. Cuttings were planted in 55 cm^3 polypropylene tubes filled with a commercial substrate (70% sphagnum peat and 30% vermiculite) with the following properties: pH (H_2O) = 5.70; available water = 8%; remaining water = 25%; total porosity = 60%; bulk density = 878.84 kg/m^3; air space = 30%; electrical conductivity = 0.5 mS/cm. Cuttings were maintained in a greenhouse for 30 days, with relative humidity kept above 80% using an automatic irrigation system with micro-sprinklers activated every hour for 60 seconds. During this period, air temperatures ranged between 25 and 34°C.

The experiment was conducted in a completely randomized design (CRD) with three replicates and 12 cuttings per plot. After 30 days, survival and rooting rates were calculated, and cutting efficiency was defined as the proportion of propagules that successfully rooted relative to the total number of propagules produced. Rooted cuttings were later used to establish a mini-garden for continued propagation and conservation.

Juvenile Cutting Propagation: Mother Plants Management and Effect of IBA on Rooting

After rooting (30 days), *C. erectus* were acclimatized for 15 days under 50% shade. Forty-five days after cutting propagation, seedlings were transplanted to a sand bed (7.5 m × 0.9 m × 0.3 m) filled with medium-textured sand, with 15 × 10 cm spacing. Both irrigation and fertigation were applied through a drip system: irrigation was automated hourly for 60 seconds, and fertigation was performed once daily. Fertigation

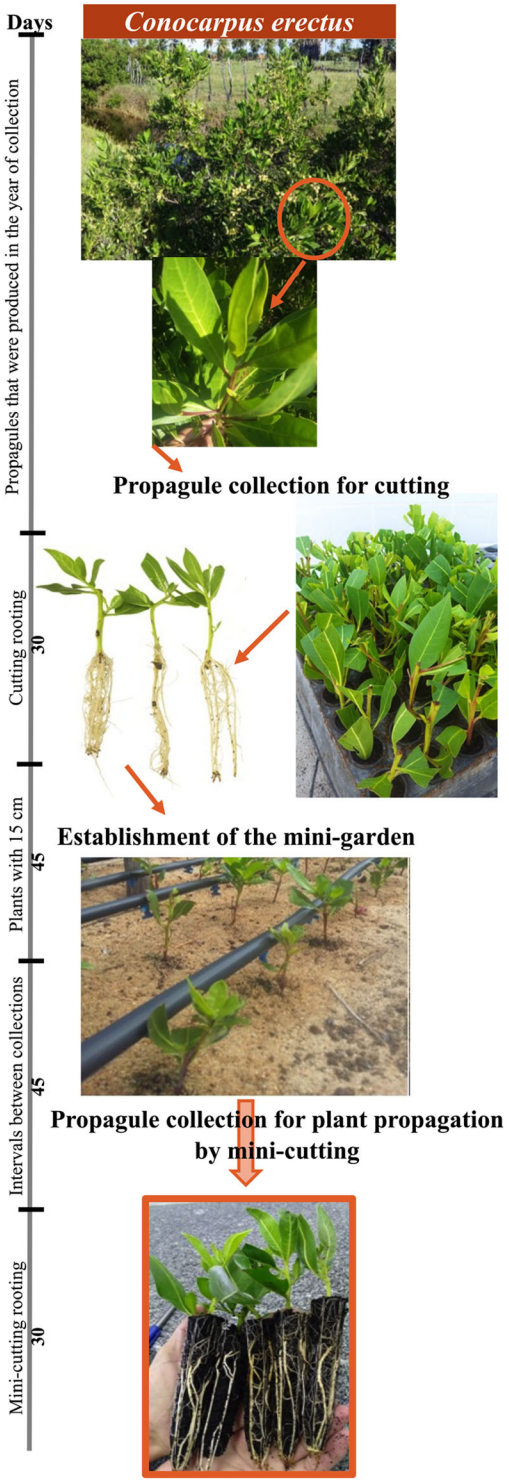


Figure 1. Chronological workflow of cutting and juvenile cutting (mini-cutting) propagation of *Conocarpus erectus*, highlighting donor plant selection, mother plants (mini-garden) establishment, propagule harvesting, and rooting.

was provided using a nutrient solution containing: 117.0 mg/L nitrate-N, 15.75 mg/L ammonium-N, 14.63 mg/L P, 131.62 mg/L K, 84.0 mg/L Ca, 25.21 mg/L Mg, 73.28 mg/L S, 0.01 mg/L B, 0.02 mg/L Cu, 69.73 mg/L Fe, 0.03 mg/L Mn, 0.008 mg/L Zn, and 0.0016 mg/L Mo. Solution conductivity was maintained between 1.5 and 2.0 mS/cm at 27°C.

After 30 days, seedlings were apically pruned to 10 cm height to induce epicormic sprouting (Fig. 1). A CRD was used with four replicates of 25 *mini-stumps* (mother plants maintained under controlled conditions for continuous propagule production) each. To assess the effect of successive pruning in mini-gardens on propagule production and genotype conservation, the following characters were evaluated every 45 days over four successive collections (prunings): survival rate (%), sprout production per mini-stump (number of sprouts/mini-stump), and productivity (number of sprouts m^{-2} $month^{-1}$). Formulas used: survival (%) = (surviving mini-stumps/initial mini-stumps) × 100; sprout production = total sprouts/surviving mini-stumps; and productivity = total sprouts/(area × time).

To evaluate the rooting response of juvenile cuttings (mini-cuttings) and the effect of IBA, 5-cm-long cuttings with one pair of fully expanded leaves (no leaf area reduction) were collected from mini-stumps. The basal 2 cm of each cutting was immersed in IBA solutions at 0, 4000, and 8000 mg/L for 10 seconds. The cuttings were then inserted into 55 cm^3 tubes filled with the same substrate previously described for standard cuttings.

Propagules were maintained in a climate-controlled greenhouse with greater than 80% humidity and 25–34°C, and irrigated with micro-sprinklers every hour for 60 seconds. The experiment followed a randomized block design, with four replicates and 10 cuttings per plot. Rooting was assessed 30 days after the cuttings were set in the substrate, when more than 50% of the mini-cuttings had developed roots ≥0.5 cm.

The rooting evaluation of cuttings included: survival rate, rooting rate, number of roots per mini-cutting, length of the longest root, and fresh and dry biomass of both shoot and root systems. Mini-cuttings were considered rooted and viable when they exhibited roots longer than 0.5 cm and green-colored leaves. For root system analysis, excess substrate was removed using water; the number of roots emerging from the base of the mini-cutting was counted, and the length of the longest root was measured with a millimeter ruler. The shoot and root systems were separated by cutting at the root collar. Fresh mass was measured using an analytical balance, and dry mass was determined after drying in a forced-air oven at 65°C until constant weight, followed by weighing.

The rooting and survival rates of the mini-cuttings were calculated as: (number of rooted propagules/total number of propagules) × 100. The means for the number of roots, length of the longest root, fresh and dry mass of shoots and roots were calculated based on the rooted mini-cuttings only.

Finally, the mini-cutting efficiency index (*Emini-cutting*) was calculated as the product of normalized variables: *Emini-cutting* = (*S*/100) × (Sp/Spmax) × (Rr/100), where *S* is the survival rate of mini-stumps, ranging from 0 to 100% (normalized to 0–1); Sp is the number of sprouts produced per mini-stump, normalized in relation to an expected maximum value (the value obtained from the first harvest for both *C. erectus* and *Rhizophora mangle*); and Rr is the rooting rate, ranging from 0 to 100%, using the highest observed rooting value as

the reference for normalization. The resulting index ranges from 0 to 1, with values closer to 1 indicating higher mini-cutting efficiency. No specific efficiency indices for mini-cutting were found in the literature for mangrove species; therefore, the present criteria were developed by the authors for this study.

The efficiency of mini-stumps (*Emini-stump*) was calculated based on the number of rooted propagules produced per mini-stump (Stuepp et al. 2021). It was estimated using the mean number of propagules produced per mini-stump (MSp) and the rooting percentage of the produced propagules (RP): *Emini-stump* = (MSp × RP)/100.

Statistical Analysis

All data were initially tested for normality of residuals and homogeneity of variances using the Shapiro–Wilk and Bartlett tests, respectively. To evaluate the effect of five concentrations of IBA on the rooting response of cuttings, a second-order polynomial regression model was fitted in R. The model was specified as $y = \beta_2 x^2 + \beta_1 x + \beta_0$, where y represents the rooting rate, and the coefficients β_2, β_1, and β_0 were estimated via least squares regression using the lm() function. Model performance was assessed using the coefficient of determination (r^2) and diagnostic plots to verify model assumptions and goodness-of-fit. In addition, the p values for individual regression coefficients (linear and quadratic terms) were calculated using t tests and reported in the figure. This allows for the interpretation of the significance of each component's contribution to the overall model response.

For the mother plants (mini-stump) and juvenile cutting (mini-cutting) experiments, a one-way analysis of variance (ANOVA) was conducted to assess the effects of IBA dose (for mini-cutting) or collection time (for mini-stump), followed by Tukey's Honestly Significant Difference test when significant differences were detected ($p < 0.05$). Lastly, comparisons of cutting and mini-cutting, efficiency were performed using independent samples t-tests.

Results

Cutting Propagation: Effect of IBA on Rooting

Rooting rates in *Conocarpus erectus* exhibited a quadratic response to increasing IBA concentrations (Fig. 2). Rooting peaked at 4000 mg/L (57%) and 6000 mg/L (56%), followed by a sharp decline at 8000 mg/L (13.75%). The control treatment (0 mg/L) and IBA concentrations of 2000 and 8000 mg/L resulted in similarly low rooting percentages (13.75, 19.5, and 13.75%, respectively). These findings suggest that cutting, when guided by optimized auxin concentrations, is a practical approach for rescuing and propagating valuable genotypes.

Juvenile Cutting Propagation: Mother Plants Management and Effect of IBA on Rooting

As shown in Figure 3, *C. erectus* maintained 100% mother plants (mini-stump) survival throughout all collection cycles

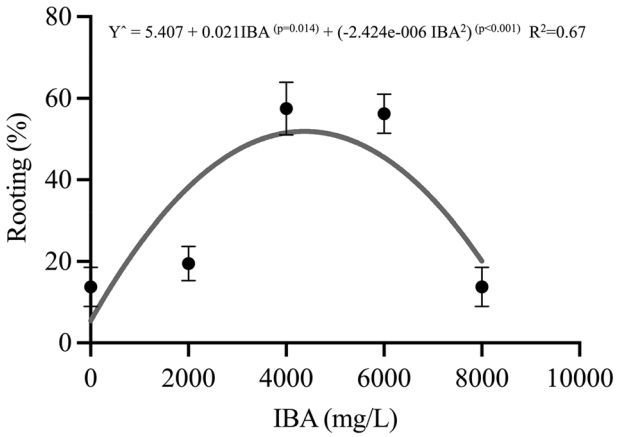


Figure 2. Rooting rate (%) of *Conocarpus erectus* cuttings subjected to different IBA (indole-3-butyric acid) concentrations (0—control; 2000; 4000; 6000; and 8000 mg/L). The fitted quadratic regression equations for *Conocarpus erectus* are presented in the graph, along with the coefficient of determination (r^2) values and p values for the regression coefficients. Error bars represent ± SE.

(Fig. 3A). The species produced a maximum of six sprouts per mini-stump during the first collection, followed by a decline to an average of 4.5 sprouts in subsequent cycles (Fig. 3B). Sprout productivity ranged from 388.7 sprouts m^{-2} $month^{-1}$ in the first collection to 276.6 sprouts m^{-2} $month^{-1}$ in the latest evaluation (Fig. 3C).

The overall propagation efficiency of the system, expressed as the ratio between the number of rooted mini-cuttings per mini-stump, averaged approximately 4.5 during the first collection (Fig. 3D). This indicates that, on average, each mini-stump produced six propagules, of which 4.5 successfully rooted, corresponding to an adventitious rooting efficiency of approximately 75%. These results highlight the high physiological vigor and rooting potential of *C. erectus* under controlled mini-garden conditions. These results demonstrate the technical feasibility and consistency of the mini-garden system for the continuous production of juvenile propagules of *C. erectus* under controlled environmental conditions.

No significant effects of IBA concentration were observed for mini-cutting survival ($p = 0.983$; Fig. 4A), root length ($p = 0.405$; Fig. 4C), number of roots ($p = 0.222$; Fig. 4D), or shoot fresh mass ($p = 0.784$; Fig. 4E). *Conocarpus erectus* showed 100% survival, a mean root length of 9 cm, 5.4 roots per mini-cutting, and 83.4 mg of shoot fresh mass (Fig. 4A–D).

In contrast, IBA concentration significantly affected rooting percentage ($p = 0.012$; Fig. 4B), shoot dry mass ($p = 0.018$; Fig. 4F), root fresh mass ($p = 0.0002$; Fig. 4G), and root dry mass ($p = 0.003$; Fig. 4H). Rooting rate in *C. erectus* increased with IBA concentration, showing a similar response at 4000 and 6000 mg/L, and peaking at 75% rooting with 6000 mg/L of IBA, representing a 22.6% increase compared with the control (Fig. 4B). Shoot dry mass was also significantly higher under IBA treatments, ranging from 23.6 to 25.0 mg per mini-cutting

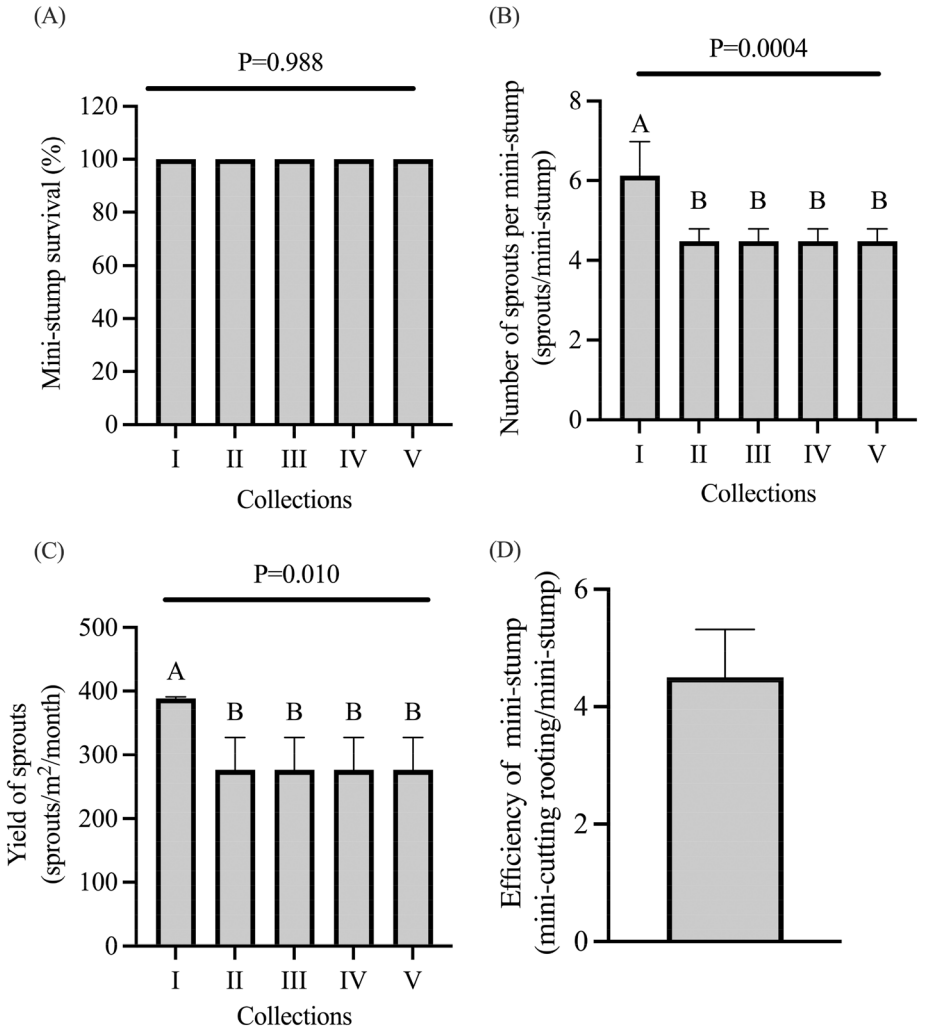


Figure 3. Survival, sprouting dynamics, and propagation efficiency of *Conocarpus erectus* mother plants (mini-stumps) during successive collection cycles. (A) Mini-stump survival rate ($p = 0.988$); (B) mean number of sprouts per mini-stump ($p = 0.0004$); (C) sprout yield per square meter per month ($p = 0.010$); and (D) propagation efficiency of mini-stumps, expressed as the ratio between the number of rooted mini-cuttings and the total number of mini-stumps. Different uppercase letters indicate significant differences among collections according to Tukey's test ($p < 0.05$). Bars represent mean + SE ($n = 3$).

at 4000 and 6000 mg/L, respectively (Fig. 4F). Root fresh (Fig. 4G) and dry masses (Fig. 4H) reached their highest values at 6000 mg/L, averaging 55 and 35 mg per mini-cutting, respectively (Fig. 4G & 4H). The observed rooting performance of *C. erectus* under the experimental conditions supports the applicability of the mini-cutting technique for its propagation, with potential implications for conservation and mass propagation programs.

The propagation efficiency for *C. erectus* cuttings was 0.57 (57% of cuttings treated with 4000 mg/L IBA were converted into rooted plants; Fig. 5), indicating a moderate performance of this technique. When juvenile cuttings (mini-cuttings) treated with 6000 mg/L IBA were used, the efficiency index increased to 0.65. These results emphasize the distinct responses associated with each propagation strategy and highlight the importance of tailoring clonal propagation protocols to the species' biological and physiological traits to optimize success in conservation and restoration programs.

Discussion

This study demonstrates the response of *Conocarpus erectus* to vegetative propagation techniques and IBA treatments, providing insights into optimized strategies for propagation and conservation under different restoration scenarios. The contrasting behaviors observed between the two techniques underscore the importance of selecting propagation strategies that align with environmental stability and the desired degree of clonal uniformity or phenotypic plasticity.

Standard cutting showed a propagation efficiency of 0.57 (57% of cuttings treated with 4000 mg/L IBA formed roots), indicating a moderate yet consistent response under controlled conditions. This level of performance suggests that the cutting

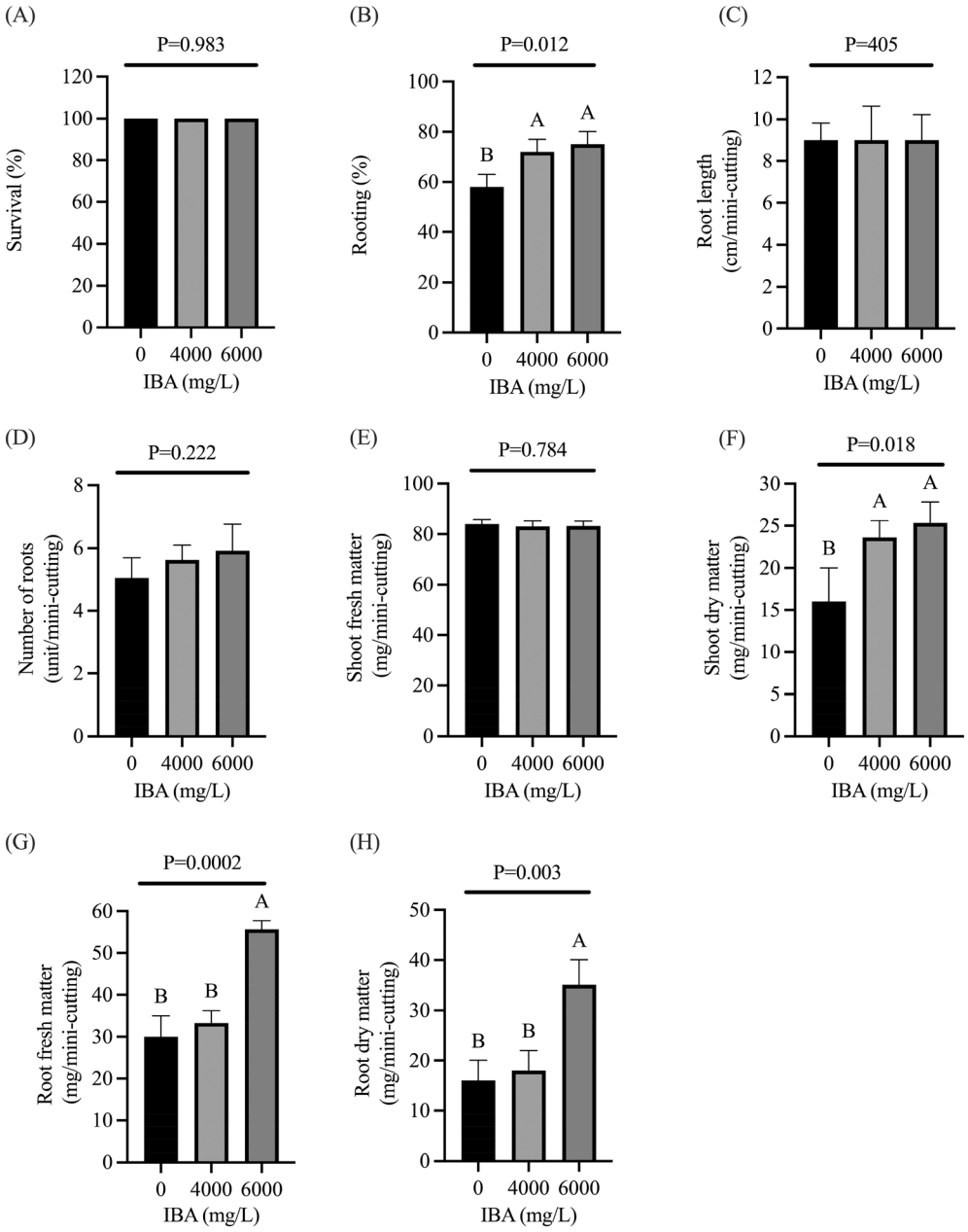


Figure 4. Effect of indole-3-butyric acid (IBA) concentration on the survival, rooting, and growth of *Conocarpus erectus* juvenile cuttings (mini-cutting). (A) Survival (%; $p = 0.983$); (B) rooting (%; $p = 0.012$); (C) root length (cm per mini-cutting; $p = 0.405$); (D) number of roots (units per mini-cutting; $p = 0.222$); (E) shoot fresh mass (mg per mini-cutting; $p = 0.784$); (F) shoot dry mass (mg per mini-cutting; $p = 0.018$); (G) root fresh mass (mg per mini-cutting; $p = 0.0002$); and (H) root dry mass (mg per mini-cutting; $p = 0.003$). Different uppercase letters indicate significant differences among treatments according to Tukey's test ($p < 0.05$). Bars represent mean + SE ($n = 4$).

technique is suitable for rapid propagation in relatively stable environments, where uniform clonal establishment is advantageous for site colonization and stand formation. The positive response of *C. erectus* to IBA concentrations of 4000–6000 mg/L corroborates the sensitivity of mature tissues to auxin stimulation, as previously reported for other woody species (Safaa et al. 2014; Stuepp et al. 2017*a*). Optimizing auxin dosage enhances rooting efficiency and vegetative rescue, supporting genotype recovery from remnant or fragmented populations.

In contrast, juvenile cutting (mini-cutting) reached a higher efficiency index (0.65), with mini-stumps maintaining 100% survival and continuous sprout production. These characteristics demonstrate the adaptability of *C. erectus* to mini-garden systems and reveal its potential for long-term and scalable propagation with cost-effectiveness (Filho et al. 2018; Silva et al. 2022;

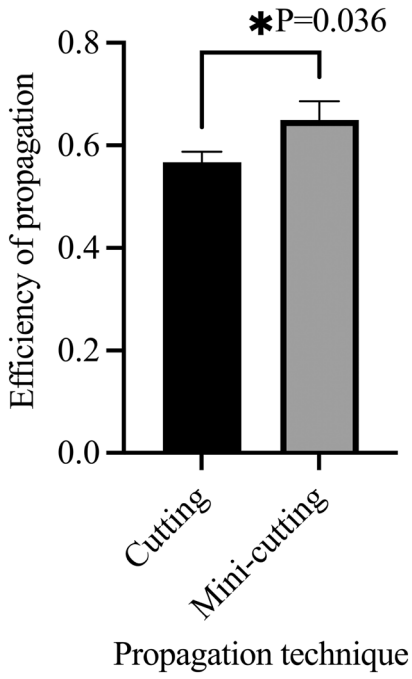


Figure 5. Propagation efficiency of *Conocarpus erectus* using cutting and juvenile cutting (mini-cutting) techniques. Asterisks indicate significant differences according to the *t* test ($p = 0.036$). Bars represent + SE.

Souza et al. 2023). The physiological vigor and phenotypic plasticity of juvenile propagules confer greater resilience to environmental variability, making this technique particularly suited for restoration in dynamic or heterogeneous coastal systems. The positive effect of IBA on rooting and biomass accumulation in juvenile cuttings confirms the role of auxin in promoting adventitious root formation and supports the use of exogenous hormonal regulation to enhance clonal propagation performance (Díaz-Sala 2021).

The effect of IBA was evident in both propagation techniques, with *C. erectus* exhibiting optimal rooting at concentrations between 4000 and 6000 mg/L. This response pattern was consistent across cutting and juvenile cutting (mini-cutting) systems, suggesting a conserved auxin requirement for root induction in this species. Similar concentration ranges have been reported for *C. erectus* stem cuttings (Safaa et al. 2014), reinforcing the notion that the species' sensitivity to exogenous auxin is relatively stable, regardless of propagule maturity.

The maintenance of high IBA demand even in juvenile propagules indicates that increased juvenility does not necessarily reduce the auxin threshold required for maximum adventitious rooting. However, the superior rooting index observed in juvenile cuttings compared with standard cuttings under the same IBA concentration reveals the positive influence of physiological vigor and juvenility on rooting efficiency. These results demonstrate that while auxin responsiveness in *C. erectus* appears species-specific and conserved, the regenerative potential of propagules is strongly modulated by their ontogenetic stage and physiological condition, which reflects distinct physiological and maturity sensitivities (Wendling et al. 2014; Stuepp et al. 2017*b*; Xavier et al. 2021).

From a conservation perspective, the integration of both techniques provides a flexible framework: standard cutting serves as a rapid-response strategy for in situ genotype rescue in stable environments, whereas juvenile cutting offers a sustainable ex situ alternative, functioning as a living germplasm bank for continuous clonal production. This framework strengthens genetic conservation and supports restoration planning across varying environmental conditions, improving the resilience of rehabilitated mangrove ecosystems.

Compared to other ex situ approaches, such as tissue culture or large field germplasm banks, cutting and juvenile cutting systems are cost-effective, genetically stable, and scalable (Abiri et al. 2020; Hanson & Ellis 2020). Moreover, this is the first documented use of the juvenile cutting technique for *C. erectus*, highlighting the novelty and applicability of this approach to mangrove propagation.

Effective in situ and ex situ conservation strategies are essential to prevent irreversible losses and to safeguard the critical ecosystem services provided by mangroves (Malik et al. 2015; Bindiya et al. 2023). Cutting and juvenile cutting techniques constitute a practical and compact alternative for establishing living germplasm collections aimed at conserving and multiplying genotypes.

In summary, our findings support the interpretation that standard cutting is a suitable rapid-propagation method for stable environments, favoring uniform clonal establishment, while juvenile cutting represents a long-term, phenotypically plastic strategy appropriate for changing or heterogeneous environments. The combined use of both techniques thus provides a biologically and operationally integrated model for mangrove restoration and conservation under diverse ecological conditions.

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LITERATURE CITED

Abdel-Rahman S, Abdul-Hafeez E, Saleh AMM (2020) Improving rooting and growth of *Conocarpus erectus* stem cuttings using indole-3-butyric acid (IBA) and some biostimulants. Scientific Journal of Flowers and Ornamental Plants 7:109–129. https://doi.org/10.21608/sjfop.2020.96213

Abdul-Hafeez EY (2020) Production of high quality air-layers from *Conocarpus erectus* L. in response to IBA and *Bacillus subtilis*. Egyptian Journal of Horticulture 47:29–39. https://doi.org/10.21608/ejoh.2020.21760.1125

Abiri R, Atabaki N, Abdul-Hamid H, Sanusi R, Shukor NAA, Shaharuddin NA, Ab Shukor NA, Ahmad SA, Malik S (2020) The prospect of physiological events associated with the micropropagation of *eucalyptus* sp. Forests 11: 1211. https://doi.org/10.3390/f11111211

Bindiya ES, Sreekanth PM, Bhat SG (2023) Conservation and management of mangrove ecosystem in diverse perspectives. Pages 323–352. In:

Sukumaran ST, Keerthi TR (eds) Conservation and sustainable utilization of bioresources. Sustainable development and biodiversity. Springer, Singapore. https://doi.org/10.1007/978-981-19-5841-0_13

Das S (2017) Ecological restoration and livelihood: contribution of planted mangroves as nursery and habitat for artisanal and commercial fishery. World Development 94:492–502. https://doi.org/10.1016/j.worlddev.2017.02.010

Dewir YH, Aldubai AA, El-Hendawy S, Alsadon AA, Seliem MK, Naidoo Y (2018) Micropropagation of buttonwood tree (*Conocarpus erectus*) through axillary shoot proliferation. HortScience 53:687–691. https://doi.org/10.21273/HORTSCI12987-18

Dias PC, Xavier A, Oliveira LS, Paiva HN, Correia ACG (2012) Vegetative propagation of angico-vermelho (*Anadenanthera macrocarpa* (Benth.) Brenan) half-sibs by mini-cuttings. Revista Árvore 36:389–399. https://doi.org/10.1590/S0100-67622012000300001

Díaz-Sala C (2020) A perspective on adventitious root formation in tree species. Plants 9:1789. https://doi.org/10.3390/plants9121789

Díaz-Sala C (2021) Adventitious root formation in tree species. Plants 10:486–489. https://doi.org/10.3390/plants10030486

Diniz C, Cortinhas L, Nerino G, Rodrigues J, Sadeck L, Adami M, Souza-Filho PWM (2019) Brazilian mangrove status: three decades of satellite data analysis. Remote Sensing 11:808. https://doi.org/10.3390/rs11070808

El-Mahrouk E-SM, Eldawansy SM, El-Tarawy AM, Ebrahim HMA, Eisa EA, Tilly-Mándy A, Honfi P (2024) Evaluation of the growth, enzymatic activity, electrolyte leakage, and phytoremediation efficiency of *Conocarpus erectus* under cadmium and lead stress. Frontiers in Plant Science 15:1466697. https://doi.org/10.3389/fpls.2024.1466697

Elster C, Perdomo L (1999) Rooting and vegetative propagation in *Laguncularia racemosa*. Aquatic Botany 63:83–93. https://doi.org/10.1016/S0304-3770(98)00122-3

Felice FEF, Araujo PCD, Pinheiro ES, Vergara C (2024) Mini-cutting technique for the propagation of a *Eucalyptus camaldulensis* clone selected in a semi-arid region. Forest Systems 33:20905. https://doi.org/10.5424/fs/2024333-20905

Filho JB, Di Carvalho MA, Oliveira LS, Konzen ER, Brondani GE (2018) Mini-cutting technique for *Khaya anthotheca*: selection of suitable IBA concentration and nutrient solution for its vegetative propagation. Journal of Forestry Research 29:73–84. https://doi.org/10.1007/s11676-017-0429-0

Goldberg L, Lagomasino D, Thomas N, Fatoyinbo T (2020) Global declines in human-driven mangrove loss. Global Change Biology 26:5844–5855. https://doi.org/10.1111/gcb.15275

Hanson J, Ellis RH (2020) Progress and challenges in ex situ conservation of forage germplasm: grasses, herbaceous legumes and fodder trees. Plants 9:446. https://doi.org/10.3390/plants9040446

Hernandez CT, Espino G (1999) Ecologia, produccion y aprovechemiento del mangle *Conocarpus erectus* L., en Barra de Tecoanapa Guerrero, Mexico. Biotropica 31:121–134. https://doi.org/10.2307/2663966

Kass L, Hunt R, Danfort S, Egan TP (2007) Reproductive biology of buttonwood, a polygamous population on San Salvador. Bahamas Naturalist Journal of Science 2:40–49. https://doi.org/10.21273/HORTSCI12987-18

Malik A, Fensholt R, Mertz O (2015) Mangrove exploitation effects on biodiversity and ecosystem services. Biodiversity and Conservation 24:3543–3557. https://doi.org/10.1007/s10531-015-1015-4

Matta TC, Pereira LS, Belmonte YCB, Chaves FO, Soares MLG (2025) Evaluating terrestrial laser scanning for structural characterization of mangrove forests in southeastern Brazil. Forest Ecology and Management 583:122567. https://doi.org/10.1016/j.foreco.2025.122567

Ochoa-Gomez JG, Acosta-Velázquez J, Anguamea-Valenzuela CA, Martinetto P (2021) Distribution and structure of *Conocarpus erectus* L.(Combretaceae) in the northern limit of the Pacific Ocean (Gulf of California). Ocean & Coastal Management 209:105645. https://doi.org/10.1016/j.ocecoaman.2021.105645

Rad HD, Assarehzadegan M-A, Goudarzi G, Sorooshian A, Birgani YT, Maleki H, et al. (2019) Do *Conocarpus erectus* airborne pollen grains exacerbate autumnal thunderstorm asthma attacks in Ahvaz, Iran? Atmospheric Environment 213:311–325. https://doi.org/10.1016/j.atmosenv.2019.06.010

Safaa MM, Youssef ASM, Ne H (2014) Effect of IBA, rooting media and planting date on vegetative propagation of button wood tree (*Conocarpus erectus* L.). Annals of Agricultural Science 52:123–132. https://doi.org/10.21608/assjm.2014.111283

Saintilan N, Khan NS, Ashe E, Kelleway JJ, Rogers K, Woodroffe CD, Horton BP (2020) Thresholds of mangrove survival under rapid sea level rise. Science 368:1118–1121. https://doi.org/10.1126/science.aba2656

Santos TO, Santana KVA, Santos HVS, Filho RNA, Holanda FSR (2019) Floristic and structural characterization of the mangrove forests in the estuary of the São Francisco River. Floresta 49:163–170. https://doi.org/10.5380/rf.v49i2.51884

Sidik F, Supriyanto B, Krisnawati H, Muttaqin MZ (2018) Mangrove conservation for climate change mitigation in Indonesia. WIREs Climate Change 9:e529. https://doi.org/10.1002/wcc.529

Silva AKV, Aguiar TS, Santos MEC, Araujo JKP, Freire AC, Salami G, Dias PC (2022) Vegetative propagation of *Mimosa caesalpiniifolia* by mini-cuttings technique. Revista Árvore 46:e4631. https://doi.org/10.1590/1806-908820220000031

Souza LS, Diógenes FEG, Silveira GVS, Silva CJ, Araujo PCD (2023) Mini-cutting as a technique to propagate *Tabebuia aurea*, an important tree found in tropical dry forests. Australian Journal of Crop Science 17:631–638. https://doi.org/10.21475/ajcs.23.17.08.p3892

Stuepp CA, Amaral BA, Ayub RA, Fragoso RO (2021) Pruning management of mini-stumps for mass propagation of blueberry. Pesquisa Agropecuária Brasileira 56:e02486. https://doi.org/10.1590/S1678-3921.pab2021.v56.02486

Stuepp CA, Bitencourt J, Wendling I, Koehler HS, Zuffellato-Ribas KC (2017*a*) Age of stock plants, seasons and IBA effect on vegetative propagation of *Ilex paraguariensis*. Revista Árvore 41:e410204. https://doi.org/10.1590/1806-90882017000200004

Stuepp CA, Wendling I, Trueman SJ, Koehler HS, Zuffellato-Ribas KC (2017*b*) The use of auxin quantification for understanding clonal tree propagation. Forests 8:27. https://doi.org/10.3390/f8010027

Su J, Friess DA, Gasparatos A (2021) A meta-analysis of the ecological and economic outcomes of mangrove restoration. Nature Communications 12:5050. https://doi.org/10.1038/s41467-021-25349-1

Tomlinson PB (1986) The botany of mangroves. Cambridge University Press, New York

Wendling I, Trueman S, Xavier A (2014) Maturation and related aspects in clonal forestry, part II: reinvigoration, rejuvenation and juvenility maintenance. New Forests 45:473–486. https://doi.org/10.1007/s11056-014-9415-y

Xavier A, Wendling I, Silva RL (2021) Clonal forestry: principles and techniques. Federal University of Viçosa, Viçosa, Minas Gerais, Brazil

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