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Dr. Virender Singh
Chief, Center for Agriculture-Horticulture Development (CAHD), Manar, Bhavnagar, Gujarat, India

Dr. PK Shukla
Ph.D. & IIT, BHU, Vice President, Pidilite Industries Ltd., Mumbai, Maharashtra, India

Prashant Bhil
Sr. Technical Officer, Center for Agriculture-Horticulture Development (CAHD), Manar, Bhavnagar, Gujarat, India

Sonu Kumar Ray
Sr. Scientist R&D, Center for Agriculture-Horticulture Development (CAHD), Manar, Bhavnagar, Gujarat, India

Dr. Nikunj Balar
Pidilite Industries Ltd., Mumbai, Maharashtra, India

Yuvrajbha Gadhvi
Pidilite Industries Ltd., Mumbai, Maharashtra, India

Narendrasinh Chauhan
Pidilite Industries Ltd., Mumbai, Maharashtra, India

Dr. Arunbhai Dave
Lokbharti University, Sanosara, Gujarat, India

Corresponding Author:
Dr. Virender Singh
Chief, Center for Agriculture-Horticulture Development (CAHD), Manar, Bhavnagar, Gujarat, India

Cultivation and feasibility of makhana (*Euryale ferox* Salisb.) in coastal high TDS conditions: A climate-resilient model for crop diversification and sustainable livelihoods

Virender Singh, PK Shukla, Prashant Bhil, Sonu Kumar Ray, Nikunj Balar, Yuvrajbha Gadhvi, Narendrasinh Chauhan and Arunbhai Dave

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Abstract
Makhana (*Euryale ferox* Salisb.), a nutritionally rich and economically important aquatic crop, is traditionally cultivated in freshwater ecosystems of eastern India, particularly Bihar. The present study evaluates the feasibility of cultivating makhana under coastal conditions in Bhavnagar, Gujarat, characterized by elevated Total Dissolved Solids (TDS >500 ppm), alkaline water, and saline influence. The study was conducted using a systematic field-based approach involving pond selection and preparation, substrate conditioning, controlled seed germination, nursery development, and transplantation under monitored conditions. Crop performance was assessed through regular monitoring of growth parameters and water quality throughout the cultivation cycle.
The crop exhibited successful establishment, consistent vegetative growth, normal flowering, and seed formation despite a progressive increase in TDS levels from approximately 520 ppm to 1200 ppm. No significant adverse effects on plant growth or reproductive development were observed under the prevailing conditions. Pilot-scale yield observations from a small experimental pond further supported the feasibility of cultivation under coastal high TDS conditions.
The study aligns with recent national initiatives, including the establishment of the National Makhana Board by the Government of India, as announced by the Hon'ble Prime Minister, aimed at promoting makhana cultivation and expanding its production beyond traditional regions. In this context, the findings demonstrate that makhana can sustain productive growth under coastal high TDS environments, indicating a broader ecological adaptability than traditionally recognized.
This study provides field-based evidence supporting the feasibility of makhana cultivation in saline-prone regions of western India. The results highlight the potential of utilizing underexploited coastal water bodies for aquatic crop production and contribute to the development of climate-resilient agricultural systems and diversification strategies.

Keywords: Makhana (*Euryale ferox*), coastal agriculture, high TDS, salinity tolerance, aquatic crop, crop diversification, feasibility study, climate-resilient agriculture

1. Introduction
Makhana (*Euryale ferox* Salisb.), commonly known as fox nut or gorgon nut, is an important aquatic crop valued for its nutritional composition, medicinal properties, and high market demand. The crop is rich in carbohydrates, proteins, minerals, and bioactive compounds, making it a popular functional food in both domestic and international markets. India is the leading producer of makhana, with cultivation largely concentrated in the freshwater wetlands of eastern states, particularly Bihar.
Despite its economic importance, the cultivation of makhana remains geographically restricted due to its perceived sensitivity to water quality parameters, especially salinity and Total Dissolved Solids (TDS). Traditionally, the crop is grown in low-salinity freshwater ecosystems with relatively stable hydrological conditions. This limitation has constrained its expansion into other regions, particularly those affected by saline water intrusion and fluctuating water chemistry. In recent years, increasing pressure on freshwater resources, coupled with the impacts of climate change, has intensified the need for developing alternative and resilient cropping systems.

Coastal regions, especially those located near estuarine zones, are often characterized by high salinity, alkaline soils, and elevated TDS levels, which restrict the cultivation of conventional crops. However, these regions also possess a significant number of underutilized water bodies that remain largely unproductive due to the lack of suitable crop options.

The coastal region of Bhavnagar district in Gujarat represents one such agro-ecological system, where saline water intrusion and elevated TDS levels pose major constraints to agricultural productivity. At the same time, the availability of waterlogged and low-lying areas provides an opportunity for exploring aquatic crop-based interventions that can utilize these otherwise underexploited resources.

In this context, the introduction of makhana in coastal high TDS environments represents a novel approach toward crop diversification and resource optimization. While existing literature primarily supports makhana cultivation under freshwater conditions, there is limited scientific evidence regarding its adaptability to saline or high TDS environments. Addressing this knowledge gap is essential for expanding the crop's geographical boundaries and enhancing its role in sustainable agriculture.

The present study aims to evaluate the feasibility of cultivating makhana under coastal conditions characterized by elevated TDS levels. The study focuses on systematic field implementation, including pond selection and preparation, substrate conditioning, controlled seed germination, nursery development, transplantation, and monitored crop management practices. Growth performance and water quality parameters were analyzed to assess the adaptability of the crop under these non-traditional conditions.

This study is positioned as a pilot-scale feasibility and adaptation assessment conducted under field conditions, rather than a full-scale agronomic or economic evaluation. The findings are intended to provide a scientific basis for further research, optimization of cultivation practices, and potential scaling of makhana cultivation in saline-prone and coastal agro-ecosystems. To the best of our knowledge, systematic field-level evaluation of makhana under coastal high TDS conditions in western India has not been previously documented.

2. Institutional Background and Research Context

The present study was carried out at the Center for Agriculture-Horticulture Development (CAHD), Gramdaxinamurti, Manar, Bhavnagar, Gujarat, India, which operates as a field-based research and extension platform under the Corporate Social Responsibility (CSR) initiative of Pidilite Industries Ltd.

The center was established with the objective of promoting sustainable agriculture, enhancing farmer livelihoods, and introducing innovative crop-based solutions in challenging agro-climatic regions, particularly in coastal and semi-arid environments. Over time, the center has developed into an integrated hub combining applied research, field demonstrations, capacity building, and value addition across agriculture and horticulture systems.

The institutional approach follows a research-to-field model, where experimental trials are directly linked with field-level validation and farmer-oriented implementation. The center undertakes systematic evaluation of high-value and alternative crops, with a focus on their adaptability under abiotic stress conditions such as salinity, water quality constraints, and soil limitations.

In addition to research activities, the center actively conducts farmer training programs, exposure visits, and skill development initiatives to facilitate the dissemination of improved agricultural practices. Supporting infrastructure such as soil and water testing facilities further enables scientific decision-making and resource optimization at the field level.

Within this framework, the introduction of makhana (*Euryale ferox*) in coastal Bhavnagar represents a targeted intervention aimed at evaluating the feasibility of aquatic crop cultivation under high TDS conditions. The study was implemented through a structured methodology involving pond selection, nursery development, transplantation, and systematic monitoring of crop performance.

This initiative demonstrates the role of CSR-supported agricultural platforms in facilitating applied research and field-level innovation, particularly in regions where conventional cropping systems are constrained by environmental limitations.

3. Materials and Methods

3.1 Study Area Description

The experimental study was conducted in the coastal region of Bhavnagar district near Alang, Gujarat, India. The region is characterized by semi-arid climatic conditions, high evapotranspiration rates, and saline water intrusion due to its proximity to the Gulf of Khambhat. The experimental units consisted of pond-based systems developed in low-lying areas with natural water accumulation.

The study was conducted on representative pond units under field conditions, with observations recorded from multiple sampling points within the pond.

The experimental pond used for the feasibility trial measured approximately 25 ft × 15 ft with a water depth ranging from 2.5 to 3.5 ft.

3.2 Pond Selection and Preparation for Feasibility Trial

Ponds for the feasibility trial were selected based on their ability to retain water throughout the crop cycle, accessibility for monitoring, and representation of typical coastal conditions with moderate salinity levels.

Selection criteria included:

- Water retention capacity for at least 5-6 months
- Presence of standing water during pre-monsoon period
- TDS levels above 500 ppm
- Accessibility for management and monitoring

Prior to transplantation, ponds were prepared through the following steps:

- Removal of unwanted aquatic weeds and debris
- Leveling of pond bed to ensure uniform water depth
- Strengthening of bunds to prevent water loss
- Initial water stabilization for 7-10 days
- Water depth was maintained between 30-60 cm during early establishment stages and gradually adjusted based on crop growth.

Fig 1: Selected pond site (left) and pond preparation activities (right) prior to transplantation.

3.3 Pond Conditioning and Substrate Preparation

Following initial pond preparation and water stabilization, pond conditioning was carried out to create a suitable substrate environment for makhana cultivation. Since makhana is a rooted aquatic crop that prefers soft and nutrient-rich bottom conditions, efforts were made to simulate a muddy substrate within the pond system.

Organic inputs such as agricultural waste-based manure and well-decomposed cow dung were incorporated into the pond. In addition, locally available clay soil was added to enhance the formation of a cohesive and soft sediment layer at the pond bottom. These materials were uniformly distributed and allowed to settle under water to develop a semi-muddy substrate conducive to root establishment.

The pond was maintained under static water conditions for a period of 5-7 days after substrate addition to allow proper settling and stabilization. This conditioning process facilitated the development of a nutrient-rich and soft bottom layer, which supported seedling anchorage and early growth under high TDS conditions.

Table 1: Pond Conditioning Inputs and Purpose

Input Material	Purpose
Cow dung manure	Nutrient enrichment
Agricultural waste manure	Organic matter addition
Clay soil	Formation of soft muddy substrate
Settling period (5-7 days)	Substrate stabilization

Fig 2: Pond conditioning and substrate preparation showing addition of organic inputs and development of muddy bottom layer

3.4 Seed Germination and Nursery Development

Makhana seeds were subjected to controlled germination under laboratory and nursery conditions to ensure uniform seedling development before field transplantation.

Seeds were first cleaned and soaked in water, followed by incubation under controlled conditions to initiate sprouting. Germinated seeds were transferred to nursery tanks/trays containing shallow water to support early growth.

Prior to germination, seeds were treated with commonly used fungicidal formulation to reduce the risk of fungal contamination and improve germination efficiency under controlled laboratory and nursery conditions.

Table 2: Seed Germination Parameters

Parameter	Value
Seed Source	Traditional growing region (Bihar)
Pre-soaking Duration	24-48 hours
Germination Environment	Controlled (Lab/Nursery)
Water Depth (Nursery)	5-10 cm
Germination Period	7-10 days
Germination Rate	80-85%

Nursery management practices included:

- Maintaining clean and shallow water conditions
- Protection from direct disturbances
- Periodic observation of sprouting and early leaf development

Fig 3: Seed germination under controlled conditions (left), nursery development (center), and early seedling growth (right) of *Euryale ferox*

Fig 4: Transplantation of nursery-grown *Euryale ferox* seedlings into prepared pond, showing manual placement and early establishment under controlled water depth.

3.5 Transplantation of Nursery Plants to Pond

Healthy and uniformly developed seedlings were selected for transplantation into prepared ponds. Transplantation was carried out carefully to minimize root disturbance and ensure proper establishment.

Table 3: Transplantation Parameters

Parameter	Value
Seedling Age	20-25 days
Leaf Stage	2-3 leaf stage
Water Depth at Transplant	30-40 cm
Plant Spacing	1.5-2.0 m
Survival Rate	85-90%

During transplantation

- Seedlings were gently placed in the pond bed
- Adequate spacing was maintained to allow leaf expansion
- Initial monitoring was done for 7-10 days to assess establishment

Fig 5: Vegetative growth of *Euryale ferox* under coastal high TDS conditions showing floating leaves at different developmental stages, with minor surface discoloration observed under field conditions.

3.6 Soil Analysis

Table 4: Soil Physico-Chemical Properties

Parameter	Value Range	Interpretation
Soil Texture	Sandy Clay Loam	Suitable for aquatic root anchorage
Organic Carbon (%)	0.65-0.72	Moderate fertility
pH	7.8-8.2	Slightly alkaline

3.5 Water Quality Monitoring

Water quality parameters, particularly Total Dissolved Solids (TDS) and pH, were monitored on a monthly basis throughout the crop cycle to evaluate their influence on crop growth and adaptability.

Table 5: Monthly Water Quality Trends

Month	Growth Stage	TDS (ppm)	pH	Observation
October	Transplantation	520	7.6	Good establishment
November	Vegetative	600	7.8	Stable growth
December	Leaf expansion	750	8.0	No stress
January	Flowering	900	8.1	Normal
February	Fruiting	1100	8.2	High tolerance
March	Maturity	1200	8.3	Stable growth

3.7 Cultivation Practices and Crop Management

Following successful transplantation, standard and adaptive cultivation practices were implemented to ensure proper establishment and growth of makhana under coastal high TDS conditions. Particular emphasis was placed on maintaining stable water conditions and minimizing environmental stress.

Water depth was maintained within the range of 30-60 cm throughout the crop cycle, with periodic adjustments based on plant growth stage and climatic conditions. During early establishment, relatively shallow water depth was maintained to support root anchorage, while deeper levels were gradually introduced during vegetative expansion and reproductive stages.

Weed management was carried out manually to remove competing aquatic vegetation that could hinder plant growth and nutrient availability. Care was taken to avoid disturbance to developing plants during weeding operations.

Nutrient management was primarily based on organic inputs and natural nutrient availability within the pond system. No intensive chemical fertilization was applied, considering the objective of evaluating crop adaptability under minimal external inputs.

Regular field observations were conducted to monitor plant health, leaf expansion, and overall crop vigor. Special attention was given to identifying any symptoms of salinity stress, such as chlorosis, reduced leaf size, or delayed flowering.

Table 6: Crop Management Parameters

Parameter	Practice
Water Depth	30-60 cm
Water Adjustment	Periodic based on growth stage
Weed Management	Manual removal
Nutrient Input	Minimal / organic
Crop Monitoring Frequency	Weekly
Major Stress Observed	No severe stress symptoms

3.8 Monitoring and Data Collection: Systematic monitoring was carried out throughout the crop cycle to evaluate crop performance and environmental conditions. Observations were recorded at regular intervals to capture both growth dynamics and water quality variations.

Growth parameters monitored included leaf diameter, number of leaves, flowering initiation, and seed formation. These parameters were recorded at weekly intervals to assess plant development and overall crop performance.

Water quality parameters, particularly Total Dissolved Solids (TDS) and pH, were measured on a monthly basis using standard water testing methods. These measurements were essential to understand the relationship between water chemistry and crop adaptability.

In addition to quantitative observations, qualitative assessments were also conducted, including visual inspection of plant health, presence of pests or diseases, and overall crop condition under varying salinity levels.

Table 7: Monitoring Parameters and Frequency

Parameter	Frequency	Method
Leaf Diameter	Weekly	Manual measurement
Flowering Stage	Weekly	Visual observation
Seed Formation	Weekly	Visual observation
TDS	Monthly	Water testing meter
pH	Monthly	pH meter
Plant Health	Weekly	Visual assessment

3.9 Growth and Yield Measurement

Growth and yield parameters of makhana (*Euryale ferox*) were systematically recorded throughout the crop cycle to evaluate plant performance under coastal high TDS conditions.

Growth observations were conducted at weekly intervals from transplantation to maturity. Key vegetative parameters included leaf diameter, number of leaves per plant, and overall canopy spread. Leaf diameter was measured manually using a measuring scale across the widest portion of fully expanded leaves. Visual assessment was used to evaluate plant vigor and the presence of any stress symptoms such as discoloration, chlorosis, or deformities.

Reproductive parameters, including days to flowering, flower emergence, and seed formation, were recorded through regular field observations. The time taken for flowering initiation was noted from the date of transplantation, and the progression from flowering to seed development was monitored.

Yield estimation was carried out at the maturity stage through manual harvesting of seeds from the pond. Collected seeds were cleaned and weighed using a standard weighing balance to determine raw seed yield. As the study was conducted on a pilot-scale pond, yield values were also expressed on an area basis by extrapolating observed production to a per-acre scale for comparative interpretation.

Table 8: Growth and Yield Measurement Parameters

Parameter	Method	Frequency
Leaf Diameter	Manual measurement (cm)	Weekly
Leaf Count	Visual counting	Weekly
Canopy Spread	Visual estimation	Weekly
Flowering Initiation	Days after transplanting	Once
Seed Formation	Visual observation	Weekly
Yield (Raw Seed)	Weight measurement (kg)	At harvest

4. Results

4.1 Crop Establishment and Survival

The transplanted makhana seedlings established successfully under coastal high TDS conditions. Initial observations during the first two weeks after transplantation indicated good plant anchorage and adaptation to pond conditions. The survival rate of transplanted seedlings ranged between 85-90%, indicating minimal transplant shock and effective acclimatization to the aquatic environment.

Uniform establishment was observed across the pond, with no significant plant mortality recorded after the initial stabilization period. Early-stage growth was characterized by the development of floating leaves and gradual expansion of plant coverage.

4.2 Vegetative Growth and Leaf Development

The crop exhibited consistent vegetative growth under varying TDS conditions throughout the crop cycle. Leaf development was progressive, with well-formed floating leaves covering a significant portion of the water surface during the vegetative stage.

Leaf diameter ranged between 60-90 cm under observed conditions, indicating satisfactory plant vigor. No major symptoms of physiological stress such as chlorosis, necrosis, or stunted growth were observed during the vegetative phase, even with gradual increases in TDS levels.

Table 9: Vegetative Growth Parameter

Parameter	Observation
Leaf Diameter	60-90 cm
Leaf Spread	Uniform
Plant Vigor	Good
Visible Stress Symptoms	No significant stress symptoms observed
Flower Initiation	65-75 days
Seed Formation	Successful
Survival Rate	85-90%

Fig 6: Vegetative growth of *Euryale ferox* under coastal high TDS conditions showing floating leaf expansion and canopy development at different growth stages

4.3 Flowering and Reproductive Development

Flowering was initiated approximately 65-75 days after transplantation. The flowering phase progressed normally, with consistent bud formation and successful transition into reproductive stages.

Subsequent observations indicated successful seed formation, suggesting that elevated TDS levels did not show any significant adverse effect on reproductive development under the conditions of the study. The crop maintained normal phenological progression from flowering to maturity. Flowering and early reproductive stages observed under field conditions are presented in Figure 7.

Fig 7: Flowering and reproductive development of *Euryale ferox* under coastal high TDS conditions showing flower emergence and early seed pod formation.

4.4 Water Quality Trends and Crop Response

Water quality monitoring revealed a gradual increase in Total Dissolved Solids (TDS) from approximately 520 ppm during transplantation to around 1200 ppm at the maturity stage. The pH levels remained slightly alkaline throughout the crop cycle.

Despite the increasing salinity levels, the crop maintained stable growth and development. No significant decline in plant performance was observed in response to rising TDS levels.

Table 10: Water Quality Trends and Observed Crop Response

Month	Growth Stage	TDS (ppm)	pH	Crop Response
October	Transplantation	520	7.6	Good establishment
November	Vegetative	600	7.8	Stable growth
December	Leaf expansion	750	8.0	No significant stress symptoms observed
January	Flowering	900	8.1	Normal development
February	Fruiting	1100	8.2	Tolerance observed
March	Maturity	1200	8.3	Stable performance

4.5 Yield Observation

Harvest observations confirmed successful seed production under coastal high TDS conditions at the pilot scale. The experimental pond, with dimensions of approximately 25 ft × 15 ft and a water depth ranging from 2.5 to 3.5 ft, yielded approximately 3-4 kg of raw makhana seeds during the harvest period.

When expressed on an area basis, the observed yield corresponds to an estimated range of approximately 350-450 kg per acre. This indicates that makhana cultivation under coastal high TDS conditions can achieve productive output comparable to conventional systems when scaled appropriately.

The yield performance observed in the present study reflects the feasibility of crop establishment and seed production under saline and elevated TDS environments, particularly under controlled management practices. As this study represents a pilot-scale feasibility trial, the results demonstrate the potential for yield optimization under improved agronomic practices and larger-scale implementation.

The observed yield, in conjunction with stable vegetative growth and successful reproductive development, reinforces the suitability of makhana as a viable aquatic crop for saline-prone and coastal agro-ecosystems. Harvesting operations under field conditions are illustrated in Figure 8.

Table 11: Yield Performance

Parameter	Value
Pond Dimensions	25 ft × 15 ft
Water Depth	2.5-3.5 ft
Pond Area	~0.0086 acre
Raw Seed Yield	3-4 kg
Estimated Yield (per acre)	~350-450 kg/acre
Crop Performance	Stable

Fig 8: Harvesting of makhana (*Euryale ferox*) under coastal conditions showing manual collection of seeds from pond during maturity stage.

4.6 Post-Harvest Handling and Processing Potential

Post-harvest handling and processing constitute an important component of the makhana value chain, as raw seeds require conversion into popped kernels for consumption and marketability. In the present study, harvested seeds obtained from coastal cultivation were subjected to preliminary handling and drying practices to assess their suitability for conventional processing methods.

Initial observations indicated that the seeds produced under moderate to slightly high TDS conditions were comparable in physical appearance and maturity to those obtained from traditional freshwater systems. The seeds were found to be structurally intact and suitable for standard post-harvest operations such as drying and roasting.

Although detailed quantitative evaluation of popping efficiency and recovery ratios was not undertaken within the scope of this study, the preliminary assessment suggests that seeds produced under coastal conditions possess the necessary characteristics for processing into popped makhana. The quality of processed makhana is known to depend on factors such as seed maturity, moisture content, and processing techniques, which require controlled experimentation for accurate evaluation.

These observations indicate the potential for integrating post-harvest processing with coastal makhana cultivation systems. However, systematic studies on processing efficiency, recovery percentage, product quality, and market acceptability are required to fully establish the commercial viability of makhana produced under high TDS environments. Preliminary post-harvest handling steps including drying, cleaning, and packaging are illustrated in Figure 8.

Fig 9: Post-harvest handling of makhana (*Euryale ferox*) showing drying, cleaning, and packaging of seeds under field conditions.

5. Discussion

The results of the present study demonstrate that *Euryale ferox* can be successfully cultivated under coastal conditions of Gujarat characterized by elevated Total Dissolved Solids (TDS), thereby challenging the conventional understanding of makhana as a strictly freshwater-dependent crop. The successful establishment, vegetative growth, flowering, and seed formation observed under progressively increasing TDS levels indicate a broader ecological adaptability of the crop than previously documented.

One of the key observations of the study was the ability of the crop to sustain stable growth and development even as TDS levels increased from approximately 520 ppm at transplantation to around 1200 ppm at maturity. This suggests that gradual exposure and relatively stable water conditions may play a critical role in enabling crop adaptation to saline environments. Similar responses have been reported in aquatic cropping systems, where acclimatization and controlled management enhance tolerance to abiotic stress factors such as salinity.

The absence of significant physiological stress symptoms, such as chlorosis, reduced leaf size, or delayed reproductive development, further supports the hypothesis that makhana possesses inherent tolerance mechanisms that can be effectively utilized under managed conditions. The maintenance of normal phenological progression, including timely flowering and successful seed formation, indicates that reproductive processes were not adversely affected within the observed TDS range.

The observed tolerance of makhana to elevated TDS levels in this study is consistent with reports on adaptive responses of aquatic crops under controlled salinity exposure. However, unlike conventional freshwater systems, the gradual increase in TDS observed in the present study may have contributed to physiological acclimatization, enabling sustained growth and reproductive development.

The yield obtained under coastal conditions remained consistent and sufficient to demonstrate the feasibility of cultivation under high TDS environments. The yield values were derived from a pilot-scale pond system and subsequently expressed on an area basis to facilitate comparison with standard cultivation systems. When considered alongside stable vegetative growth and successful reproductive performance, the results reinforce the suitability of makhana as a viable aquatic crop for saline-prone and coastal agro-ecosystems. It is important to note that detailed economic evaluation was beyond the scope of the present study.

The findings also highlight the importance of cultivation practices such as controlled water depth, proper nursery management, and careful transplantation in ensuring successful crop establishment under non-traditional conditions. These management interventions likely contributed to minimizing environmental stress and supporting plant adaptation under elevated TDS conditions.

From a broader perspective, the study underscores the potential of utilizing underexploited coastal water bodies for aquatic crop cultivation. In regions where conventional agriculture is constrained by salinity and water quality limitations, such interventions provide a practical pathway for resource utilization and crop diversification. The integration of makhana into such systems may contribute to the development of climate-resilient agricultural models suited to coastal and saline-prone environments.

It is important to emphasize that the present study represents a feasibility and adaptation assessment under field conditions. Further investigations on physiological responses to salinity stress, optimization of agronomic practices, multi-location validation, and long-term sustainability are required to establish standardized cultivation protocols. Additionally, systematic evaluation of post-harvest processing efficiency and economic viability remains an important area for future research.

6. Conclusion

The present study demonstrates that *Euryale ferox* (makhana) can be successfully cultivated under coastal conditions characterized by elevated Total Dissolved Solids (TDS), thereby extending its cultivation potential beyond traditionally recognized freshwater ecosystems. The crop exhibited satisfactory establishment, vegetative growth, flowering, and seed formation under progressively increasing salinity levels, indicating its adaptability to moderate high TDS environments when supported by appropriate management practices.

The findings highlight the feasibility of utilizing underexploited coastal water bodies for makhana cultivation, offering a practical approach for crop diversification in regions where conventional agriculture is constrained by salinity and water quality limitations. The ability of the crop to sustain stable growth and complete its life cycle under such conditions provides a strong basis for further exploration and scaling. The pilot-scale yield observations further support the feasibility and scalability of makhana cultivation under coastal high TDS conditions.

It is important to note that the present study represents a feasibility and adaptation assessment under field conditions. Further investigations on yield optimization, multi-location validation, physiological responses to salinity stress, and long-term sustainability are required to establish standardized cultivation practices. Additionally, systematic evaluation of post-harvest processing efficiency and economic viability remains an important area for future research.

The findings establish a foundation for expanding makhana cultivation beyond traditional freshwater regions into Gujarat, including waterlogged areas, ponds, fallow lands, and coastal and saline-prone agro-ecosystems, thereby supporting livelihood opportunities for farmers and rural communities.

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