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# Climate-Resilient Fish Farming and Household Adaptation in Flood-Prone Northeastern Bangladesh

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**Abstract:** Climate change is disrupting hydrological stability in northeastern Bangladesh, particularly affecting small-scale aquaculture in flood-prone areas like Osmaninagar Upazila. This study examines the adoption of climate-resilient aquaculture practices and their impacts on pond productivity, species diversity, and adaptive benefits for smallholder households. A cross-sectional study involving 300 randomly chosen pond-owning households was conducted, utilizing structured interviews to gather data on socio-demographics, pond characteristics, management and stocking methods, and production reports over the previous year. Analysis revealed substantial improvements in pond management following the adoption of climate-resilient practices. Initially, most households engaged in minimal pre-stocking management and relied on naturally recruited fish. Post-adoption changes included over 90% of households liming their ponds before stocking, approximately two-thirds using fertilizers regularly, and almost all constructing shrub or brush park structures for habitat enhancement. The average annual production from primary ponds increased from approximately 42 kg to 80 kg per household, with yields per decimal nearly doubling. Households with higher scores in practice adoption exhibited significantly greater productivity and species diversity ($p < 0.05$), incorporating carps, tilapia, and various nutrient-rich small indigenous species. Nevertheless, challenges persisted, including irregular fingerling supply, limited technical knowledge, and ongoing climate threats. The results suggest that climate resilient aquaculture can transform underutilized flooded ponds into productive and nutritious resources. However, sustaining these benefits depends on continuous technical support, improved input and service markets, and the integration of aquaculture into local climate adaptation frameworks.

**Keywords:** Climate-resilient aquaculture, Smallholder fish farming, Flood-prone ponds, Household adaptation, Northeastern Bangladesh, Small indigenous species

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## 1. Introduction

Aquaculture plays a vital role in Bangladesh's rural economy, considerably enhancing household nutrition, cash income, local employment, and the national food supply. The nation ranks among the foremost global producers of freshwater fish, with a significant portion of this production derived from small-scale ponds integrated into domestic properties **(FAO, 2020; Belton & Thilsted, 2014).** When managed efficiently, these ponds can yield continuous harvests year-round, provide nutrient-rich fish for women and children, diminish reliance on imported protein, and mitigate the impact of income variability or agricultural setbacks on households. In numerous lowland regions, aquaculture and fisheries are intrinsically interconnected, characterized by flood-induced transfers of water, nutrients, and fish among distinct ponds and naturally linked water bodies. This ecological opportunity has been increasingly eclipsed by climate instability, which is now significantly impacting production outcomes, household decision-making, and system viability **(Vo et al., 2021; Sunny et al., 2025a).**

The northeastern floodplains of Bangladesh, specifically the Sylhet region, are among the most climate-sensitive areas in South Asia due to their monsoon-driven hydrology, low elevation gradients, and proximity to transboundary watershed flows **(Ahmed & Diana, 2016; Shahid, 2012)**. Increased frequency of extreme precipitation events, flash floods, extended inundation, and variable water depth has resulted in significant siltation, dike erosion, and unrestricted fish movement during cultural cycles. Pond embankments frequently fail due to extended submersion, water turbidity escalates significantly with runoff, and abrupt flushing occurrences jeopardize water quality, dissolve stored feeds, and displace stocked fish. Amidst such uncertainty, numerous smallholders diminish stocking intensity or postpone stocking until late post-monsoon periods, frequently sacrificing 2-3 months of the profitable growing season. This risk-averse conduct diminishes both productivity and potential returns from aquaculture investments **(Haque et al., 2020; Sunny et al., 2025b).** At the household level, climate uncertainty interacts with structural obstacles, including shared ownership arrangements, poor financial liquidity, and restricted access to dependable advisory support, resulting in reluctance to transform ponds into systematic production units. For numerous households, the pond serves as a seasonal, opportunistic source of fish rather than a regulated livelihood activity. Households typically depend on naturally recruited fish, especially during concurrent flood seasons, rather than on planned stocking, feed planning, or nutrient cycling. This ecological recruitment offers dietary benefits, although it is exceedingly unpredictable and susceptible to hydrological variations. These trends indicate both climatic susceptibility and deficiencies in institutional coordination regarding small-scale aquaculture intensification **(Haque et al., 2024).**

Climate-resilient aquaculture has emerged as a localized adaptation strategy aimed at altering pond ecosystems to sustain productivity amid hydrological variability. The strategy prioritizes cost-effective, gradual modifications over capital-heavy intensification, rendering it appropriate for smallholders with constrained cash. Reinforcing pond dikes and raising critical margins reduces fish escape during flood surges; the application of lime stabilizes pH and diminishes disease prevalence; fertilizer application enhances phytoplankton proliferation; and the creation of bush-park refuges improves structural complexity within the pond, fostering periphyton growth and safeguarding fish during shock events **(Ekram-Ul-Azim, 2001; Boyd & Tucker, 2014).** The utilization of periphyton-based natural productivity replaces commercial feed inputs, facilitating productivity increases while reducing reliance on feed, typically the most expensive aquaculture input for low-income households.

An additional aspect of climate-resilient aquaculture is nutritional adaptation. Integrating small indigenous species (SIS) such as *mola, punti, tengra*, and shing into stocking systems enhances carp-based aquaculture and markedly elevates the availability of micronutrients, vitamin A, calcium, iron, and essential fatty acids **(Bogard et al., 2015; Thilsted et al., 2016**). SIS harvest transpires sporadically and in limited quantities, rendering them suitable for domestic use without undermining market-driven harvesting timelines. Consequently, climate-resilient aquaculture enhances both household dietary and economic resilience in the face of climate stress. Despite the implementation of such measures in many locations of Bangladesh, comprehensive peer-reviewed research targeting specific high-exposure areas is scarce. A significant portion of the current documentation originates from program-led rapid assessments, gray literature, demonstration summaries, or non-academic monitoring studies. These sources typically exhibit a deficiency in systematic sampling, statistical analysis correlating management techniques with result indicators, or comprehensive consideration of institutional restrictions. Moreover, scant research has examined the relationship between household perceptions of change and variations in production, as well as the enduring nature of constraints despite knowledge acquisition and initial implementation.

This study explores climate-resilient aquaculture practices among smallholder households in Osmaninagar Upazila, Sylhet District, an area notable for significant flood risk, a prevalence of household ponds, and an increasing interest in transforming these ponds from passive water bodies into adaptive economic resources. The analysis integrates pond-level activities within a wider livelihood framework and assesses the discrepancies between self-reported production trends and previous management strategies. The study additionally investigates how perceived obstacles associated with knowledge, climate shocks, and access to inputs persist in hindering sustainability post-adoption. This study offers localized empirical evidence from a flood-prone upazila, providing insights relevant to climate adaptation planning, aquaculture extension programming, pond rehabilitation initiatives, and nutrition-sensitive smallholder interventions. The results enhance the developing dialogue on climate-resilient aquatic food systems and provide a pragmatic approach to bolstering adaptation in areas where seasonal hydrological variability is the primary obstacle to aquaculture transformation.

## 2. Materials and Method

### 2.1 Study area

The study was conducted at Osmaninagar Upazila, Sylhet District, in the northeastern floodplain region of Bangladesh. Osmaninagar is distinguished by minimal elevation gradients, substantial yearly precipitation, episodic flash floods, and extended monsoon flooding, rendering it an appropriate environment for investigating climate-sensitive aquaculture systems. The region features multiple farmhouse ponds utilized for domestic reasons and opportunistic fish harvesting. Five unions: Umarpur, Tajpur, Paschim Poilanpur, Purba

Poilanpur, and Dayamir were chosen to exemplify varied hydrological characteristics, population density, road accessibility, and vulnerability to seasonal flooding. These unions have a significant incidence of families owning ponds, rendering them analytically pertinent for examining variations in the adoption of climate-resilient aquaculture activities under similar ecological conditions. Pond-based aquaculture in the region is mostly small-scale and family-operated, with pond dimensions typically varying between four and ten decimal units.

**2.2 Study Design and Sampling**

The study utilized a community-based cross-sectional methodology, focusing on household-level recollections of recent production cycles. Although the study provides comparison remarks between "before" and "after" management conditions, these remarks are based on respondent recollection, not panel monitoring. The objective was to ascertain household perceptions regarding alterations in pond management and outcomes following the adoption of climate-resilient measures. The sampling frame comprised households owning ponds within the designated unions. Village-level inventories of pond proprietors were compiled in collaboration with local leaders and mobilizers knowledgeable about household attributes. Simple random sampling was utilized to choose eligible respondents from these lists **(Sedgwick, 2015).**

Three hundred households were chosen for interviews, averaging about sixty households for each union. The sample size was large enough to allow for accurate predictions about adoption rates with reasonable confidence intervals. It also made it possible to compare important subgroups without adding to the sampling error. Households were eligible for the survey provided they owned or managed at least one pond for aquaculture purposes within the preceding 12 months. Households with newly excavated ponds without an operational cycle were excluded.

**2.3 Data Acquisition**

Primary data were gathered by face-to-face interviews with a structured, pretested questionnaire presented by trained enumerators. The instrument recorded socio-demographic attributes of household members, property ownership, occupations, and gender participation in pond-related activities. Comprehensive data about pond dimensions, water retention periods, embankment integrity, hydrological interconnectivity, and seasonal inundation was recorded. Participants detailed management measures conducted before stocking, including liming, fertilization protocols, pond rehabilitation, and the installation of bush or bamboo structures within the pond.

Stocking decisions were documented by recording fish species combinations, stocking frequency, estimated number of fingerlings, time within the production calendar, and average stocking costs. Households then submitted estimates of fish collected during the preceding production year, differentiating between cultivated fish and naturally recruited fish introduced by floodwater. Participants also remembered production patterns prior to the adoption of enhanced procedures to facilitate comparative analysis. Moreover, respondents detailed access to inputs, exposure to advisory information, obstacles encountered during production cycles, and disruptions associated with periodic flooding.

Data were gathered during the dry season to reduce access limitations and enhance memory precision. Prior to formal data collection, the questionnaire was administered to non-sample households to verify clarity, logical sequencing, and internal consistency. Enumerator training reinforced the need for neutrality in questioning, the avoidance of leading statements, accurate unit recording, and the validation of pond size, when possible, through physical verification or corroboration with family members.

### 2.4 Definition of Climate-resilient Methods

For the sake of analytical consistency, climate-resilient techniques were defined as pond management measures that improve ecological stability and survival chances during hydrological changes and are also affordable for smallholders. The practices encompassed the application of lime before stocking, utilization of organic or inorganic fertilizers to augment natural feed availability, establishment of structured brush-park refuges, stocking combinations featuring at least two resilient carp species alongside tilapia or small indigenous species, and regular maintenance of embankments. Adoption intensity was defined as a continuum rather than a binary condition. Households indicating no or only one practice showed low adoption, while those consistently implementing three or more practices exhibited high adoption levels.

### 2.5 Variables and Measurements

Quantitative metrics encompassed the annual estimated harvest volume from the primary pond, with distinct figures provided for farmed fish and spontaneously recruited fish. The yields were standardized according to pond size to calculate yield per decimal. Species richness was calculated based on household recollection of unique species gathered. The explanatory variables comprised pond size, adoption intensity, access to fingerlings, kind of extension exposure, perceived flood danger, and the number of household members engaged in pond-related activities. Documented alterations in productivity, fish accessibility for domestic consumption, and management simplicity were regarded as result perceptions rather than quantified causal impacts.

### 2.6 Data Analysis

The data were analyzed for consistency and absent values, thereafter undergoing descriptive analysis with conventional statistical tools. Means, ranges, and proportional distributions were calculated to depict household characteristics, pond attributes, management practices, input use, and production results. A comparison examination was undertaken between recalled historical conditions and current results to enhance inference despite reliance on recall-based measurement. Statistical significance was evaluated using paired t-tests for within-household changes, while one-way comparisons within adoption groups were analyzed by analysis of variance. Since the values are subjective estimates, statistical data should not be interpreted as conclusive causal inferences but rather as indicators of structured relationships that align with theoretical expectations and household decision-making processes.

To mitigate interpretive bias, the study focused on the correlation between practice adoption and developmental trajectory rather than on numerical precision. The focus was on family differences, which made it easier to see when aquaculture practices changed from opportunistic to strategic. The results are thus framed as a systematic cross-sectional analysis of household experiences rather than a controlled experimental assessment.

### 2.7 Ethical Considerations

Before the interview, enumerators elucidated the study's aims, voluntary participation, confidentiality of responses, and the possibility to withdraw at any moment. A verbal, informed agreement was acquired owing to the diverse literacy levels of the respondents. No identifying information was disclosed in the processed outputs. The study relied exclusively on self-reported household experiences without necessitating biological sampling, financial disclosure, or physical intervention, presenting minimal ethical risk.

## 3. Results and Discussion

### 3.1 Household and Pond Characteristics

Households surveyed in Osmaninagar exhibited varied livelihood profiles, with agricultural wage labor, small-scale farming, remittance-dependent income, and microenterprise being the predominant activities. The average household size was just above six individuals, consistent with rural home configurations in northeastern Bangladesh. While the majority of household heads were male, the responsibilities of fish feeding, minor harvests, and brush-park care engaged both adult women and older adolescents, illustrating the gender-integrated dynamics of aquaculture work within homestead settings. These gendered contributions have been recognized as essential for daily pond operations, especially in the absence of women as major decision-makers **(E-Jahan et al., 2010; Sunny et al., 2023)**.

**Table 1:** Socio-demographic characteristics of surveyed households

| Variable | Categories | % of households |
|---|---|---|
| Household head gender | Male | 83.7 |
| | Female | 16.3 |
| Mean household size | - | 6.2 persons |
| Primary occupation of household head | Day labor | 34.1 |
| | Small farming | 31.4 |
| | Small business | 18.9 |
| | Remittance dependent | 8.2 |
| | Other services | 7.4 |
| Education level of head | No formal schooling | 21.6 |

| Variable | Categories | % of households |
|---|---|---|
| | Primary completion | 39.8 |
| | Secondary completion | 29.1 |
| | ≥ Higher secondary | 9.5 |

Pond attributes indicated structural susceptibility to monsoon-induced hydrology. Pond sizes across families varied from 4.2 to 11.8 decimals, with average depth significantly diminishing during the late winter months due to partial evaporation. Numerous ponds maintained physical links with neighboring canals or inundated depressions during monsoon maxima, facilitating the ingress of wild fish while concurrently heightening the escape danger for stocked species. Participants often recounted previous seasons during which monsoon storms destroyed embankments or resulted in overflowing into adjacent plots. These trends align with extensive hydrological disturbances impacting domestic water bodies in the low-lying regions of Sylhet **(Haque et al., 2020)**.

**Table 2:** Pond features and physical attributes

| Indicator | Mean | Range |
|---|---|---|
| Pond size (decimal) | 7.6 | 4.2-11.8 |
| Average water depth in peak season (ft) | 5.2 | 3.8-7.1 |
| Water retention duration (months) | 8.3 | 6-12 |
| Ponds with seasonal canal/lowland connectivity | 68.5% | |
| Ponds with strengthened dikes | 54.7% | |

Before the adoption of enhanced methods, pond utilization primarily involved unplanned fish catch rather than systematic cultivation. Households often harvested once or twice annually, obtaining mixed assemblages predominantly composed of naturally recruited fish. Inputs were infrequently applied, stocking was irregular, and ponds were rarely limed or drained prior to production cycles. This management behavior reflects historical patterns in flood-maintained aquaculture environments, where biological recruitment replaces deliberate stocking yet provides less predictability or system regulation **(Allison & Bassett, 2015; Rana et al., 2024)**.

### 3.2 Adoption of climate-resilient practices

Adoption patterns exhibited structural transformation rather than trivial procedural modifications. Before the implementation of climate-resilient measures, only a minor percentage of families indicated consistent usage of liming, fertilization, or embankment reinforcement. Numerous accounts detail historical instances where brush materials were indiscriminately deposited into ponds, functioning as shade rather than as intentional habitat.

Following exposure to technical guidance, adoption significantly increased and occurred in a tiered manner **(Rahman et al., 2023).** Over 90% of households indicated they used lime prior to stocking, and roughly two-thirds fertilized ponds at various intervals using cow dung, urea, or a combination of fertilizers. Brush-park structures, typically fashioned from bamboo, native shrub branches, and trimmed betel-nut fronds, were intentionally in the corners of ponds or in deeper recesses. Households indicated an average of 11.6 brush clusters per pond, with variance spanning from 6 to 16 based on pond size and available biomass **(Hossain et al., 2024).**

Adoption gradients were apparent. Households that adopted three or more recommended practices generally dedicated efforts to pond maintenance, predator eradication, and synchronizing stocking cycles with anticipated monsoon periods. The farmers set clearer management goals and had higher expectations for how their crops would respond to changes. Conversely, households with limited adoption continued to depend significantly on naturally recruited fish, engaged in sporadic input applications, and were devoid of stocking schedules. These findings reflect conceptual models of behavioral change, indicating that the adoption of aquaculture occurs in stages influenced by accumulated knowledge, financial resources, and confidence **(Dey et al., 2013; Urbi et al., 2025).** Significantly, households did not implement techniques in isolation; liming, fertilizing, stocking diversification, and embankment reinforcement functioned synergistically, together influencing ecological stability.

**Table 3: Adoption of climate-resilient practices among households**

| Practice | % Households Adopting | % Adopting previously |
|---|---|---|
| Liming before stocking | 91.3 | 24.8 |
| Regular fertilization | 63.2 | 18.7 |
| Structured brush-park fully installed | 96.0 | 41.2 |
| Integration of ≥3 resilient species | 72.4 | 19.1 |
| Dike strengthening before season | 58.3 | 22.7 |

### 3.3 Stocking practices and species composition

Fish stocking behavior changed dramatically following the shift toward climate-resilient management. Historically, no more than one-fifth of households stocked fingerlings at recommended densities; currently, nearly all households stock fish deliberately. Stocking densities varied according to pond size, but across sampled households, reported densities ranged between 180 and 310 fingerlings per decimal for composite carp-tilapia culture, with gradual tapering toward smaller ponds. The timing of stockings also shifted. In late winter (February-March), households stocked more fish, which allowed for growth periods that missed the peak monsoon months when the risk of escape is highest **(Haque et al., 2017).**

Species composition also diversified. The most consistently stocked species included rohu (*Labeo rohita*), silver carp (*Hypophthalmichthys molitrix*), catla (*Catla catla*), and mrigal (*Cirrhinus cirrhosus*), followed by tilapia (*Oreochromis niloticus*) and grass carp (*Ctenopharyngodon idella*). About 5-61% of households also kept small native species, such as *mola* (*Amblypharyngodon mola*), *punti* (*Puntius sophore* complex), and *tengra* (*Mystus tengara*). Respondents perceived SIS culture as beneficial because species can be captured periodically in small quantities for immediate consumption **(BBS, 2015; Kuddus et al., 2021).** This result is consistent with substantial evidence indicating that SIS-carp integration improves dietary nutrient availability and bolsters resilience to temporary variations in water quality **(Bogard et al., 2015; Thilsted et al., 2016)**. The presence of structured bush-park zones further supported periphyton growth, effectively functioning as natural feeding surfaces. This ecological enrichment reduces feed dependency and stabilizes fish survival under climatic uncertainty.

**Table 4. Reported changes in fish production outcomes**

| Indicator | Before adoption (mean) | After adoption (mean) |
|---|---|---|
| Harvest from main pond (kg/year) | 41.8 | 82.6 |
| Yield per decimal (kg) | 4.6 | 9.1 |
| Share of stocked fish (%) | 7-12% | 31-42% |
| Species richness (count) | 6.8 | 10.7 |

**3.4 Production outcomes**

Production outcomes reflected clear upward transitions but displayed heterogeneity across adoption intensity. Before improved management, households recalled annual yields of 33-48 kg from their main ponds, with little differentiation between ponds of similar size. Yield per decimal ranged between 3.8 kg and 5.2 kg under traditional systems, dominated by naturally recruited fish. Following the adoption of climate-resilient practices, reported output levels increased substantially. Households indicated average yields ranging from 72 to 91 kg per pond, which translates to approximately 7.9-10.4 kg per decimal.

Importantly, yield gains, not absolute values, represent the analytically meaningful point. Households with higher adoption intensity frequently attributed improved performance to consistent liming, timely stocking, reduced fish escapes due to strengthened dikes, and establishment of bush-park refuges that provided shelter during flood pulses. Where fertilization was regular, households described noticeable plankton blooms during early growth phases, followed by gradual settling into greenish, stable water conditions. Such transitions mirror classic ecological responses documented in fertilized earthen pond systems **(Boyd & Tucker, 2014; Sazzad et al., 2024)**.

Although numeric estimates derive from recall, directional patterns remain meaningful. High-adoption households consistently reported nearly 40-55% greater yields than minimal-adoption households. Informal significance testing indicated that yield differences by adoption category were statistically distinguishable at $p < 0.05$, even after normalizing the pond area. Yields of naturally recruited species also increased, partly due to ecological structuring inside ponds; however, the contribution of stocked species increased disproportionately. These findings reinforce the conceptual claim that resilience-focused pond design complements, not replaces, ambient flood-linked fish recruitment **(Higano et al., 2022; Ferdushi et al., 2019).**

### 3.5 Adaptation-linked livelihood and nutritional implications

Households described production improvements not merely as yield increases but as shifts in food and income strategies. Increased harvesting frequency allowed intra-household consumption of small fish, often by women and children. Such patterns resonate with nutrition-sensitive aquaculture frameworks positioning small-scale harvests as micronutrient entry points in rural diets **(Belton & Thilsted, 2014; Tiva et al., 2025a)**. Households also recovered greater proportions of stocked carp during harvest events, enabling partial sale into local market chains at stable seasonal prices. Respondents further emphasized the psychological dimension of resilience, reporting greater confidence to invest in feed, labor time, and structural maintenance when outcomes felt predictable. This shift aligns with decision-based resilience theories, where perceived reliability drives planning and productive investment.

### 3.6 Persistent constraints and institutional frictions

Despite meaningful adoption, three broad constraint categories remained salient. First, uncertainty in fingerling quality affected stocking outcomes. Households frequently reported receiving variable-sized or physically weak fingerlings, often sourced from itinerant traders rather than accredited hatcheries. Quality inconsistency threatens post-stock survival and undermines willingness to intensify culture. Similar constraints are documented nationally, where aquatic seed markets remain weakly regulated **(Hasan & Ahmed, 2002; Akhter et al., 2025)**.

Second, knowledge limitations persisted. Many respondents claimed partial understanding of disease symptoms, water turbidity responses, and correct fertilizer timing. Households expressed interest in advisory access beyond initial training sessions. This observation illustrates a prevalent trend in extension programs, characterized by a reduction in instructional depth following initial adoption events **(Dey et al., 2013; Mahmud et al., 2025)**.

Third, climate risk is still structurally unavoidable. Even with improved embankments, unpredictable rainfall intensities, delayed peak monsoons, and runoff events continue to challenge the stability of ponds. Respondents viewed major flood seasons as unavoidable risk periods, indicating resilience, not immunity. Finally, multiple-ownership ponds created fragmented decision authority, complicating labor division and investment allocation. Shared ownership, while culturally common, lowers adoption intensity due to unclear cost-benefit distribution. These constraints highlight that climate-resilient aquaculture requires institutional strengthening, not merely technical instruction.

## 4. Conclusion and Policy Recommendations

These findings from Osmaninagar Upazila indicate that converting smallholder ponds from passive, flood-prone waterbodies into climate-resilient aquaculture systems is both feasible and significant when management is deliberate and ecologically informed. Households implementing systematic measures, including liming, regular fertilizing, reinforced embankments, and organized refuges, observed significant enhancements in production stability, species richness, and harvest predictability. The transformations were not only technical alterations in ponds but also behavioural changes influenced by confidence, investment timing, and synchronization with seasonal hydrology. As households started to regard ponds as intentional livelihood assets instead of mere incidental storage, the survival rates of supplied carp increased, naturally recruited species thrived, and harvesting became more regular and nutritionally significant. Despite production numbers being based on self-reported recollection, their alignment with ecological processes and documented management alterations significantly bolsters their reliability.

The study indicates that climate-resilient aquaculture is not a singular technical solution that, once implemented, remains self-sustaining. Structural hurdles persist due to constraints concerning fingerling quality, the lack of standardized advice services, and erratic flood timing. Many homes continue to operate with an inadequate understanding of disease management, water treatment, and nutritional limitations. Furthermore, co-ownership of ponds complicates investment decisions, exacerbating inconsistent adoption trends even across identical geographic contexts. Enhancing resilience necessitates institutional fortification, in addition to modifications in farm-level practices. Dependable availability of high-quality fingerlings, preferably backed by hatchery-level traceability and seasonal distribution systems, would diminish mortality rates and enhance the propensity to intensify aquaculture practices. Advisory communication should transition from singular training sessions to ongoing, seasonally relevant information that assists farmers in adapting to specific climatic occurrences rather than broad concepts.

Future resilience improvements will rely on integrating these systems into local adaptation strategies. Incorporating pond calendar recommendations with early flood-risk notifications, utilizing union-level extension agents or digital advisory groups, would directly affect stocking schedules and anticipated losses. Promoting the integration of nutrient-rich tiny indigenous species with commercial carps can enhance dietary resilience and market adaptability, especially during periods of crop scarcity. A sustained emphasis on cost-effective ecological enhancements, rather than capital-heavy aquaculture development, is the most feasible approach for households with variable liquidity. Nonetheless, climate-resilient aquaculture in Osmaninagar exemplifies a pragmatic approach to minimizing climate exposure instead of evading production risk. When maintained through integrated input systems, adaptive advisory services, and localized planning, these techniques can significantly enhance livelihood resilience, nutritional access, and the productive utilization of homestead ponds. These results demonstrate that adaptation in smallholder aquaculture is influenced not solely by technology, but by a steady reconfiguration of ecological practices, decision-making processes, and institutional support that allows households to maintain productivity under persistent environmental unpredictability.

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**Author Contribution**

The authors were involved in the creation of the study design, data analysis, and execution stages. Every writer gave their consent after seeing the final work.

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**A statement of conflicting interests**

The authors declare that none of the work reported in this study could have been impacted by any known competing financial interests or personal relationships.

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