Design and development of assistive products for harvesting of aquatic food-crop (water-chestnut): A user- centred design approach

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

DOCTOR OF PHILOSOPHY

By

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Declaration

I hereby declare that the work contained in this thesis entitled “**Design and development of assistive products for harvesting of aquatic food-crop (Water-chestnut): A user-centred design approach**” has been carried out by me, a legitimate student of Department of Design at Indian Institute of Technology Guwahati, Assam, India under the guidance of Prof. Sougata Karmakar at the Department of Design, Indian Institute of Technology Guwahati, Assam. This work is done for the award of Doctor of Philosophy. It has not been submitted elsewhere for another degree or diploma.

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Certificate

This is to certify that the work contained in this thesis titled "Design and development of assistive products for harvesting of aquatic food-crop (Water-chestnut): A user-centred design approach" submitted by **Mr. Jitesh Singh Chauhan** to the Indian Institute of Technology Guwahati for the award of the degree of the Doctor of Philosophy has been carried out under my supervision. This work has not previously been submitted for a degree or certificate from another institution.

Place: IIT, Guwahati

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Dedicated to My Parents

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Executive summary

The increasing population has enhanced the demand for food, employment, and shelter for the coming generation. The agriculture sector is one of the vital sectors that plays a crucial role in meeting these needs. The government and research scientists have been striving to support farmers by providing the necessary facilities and means to enhance productivity. Numerous technological interventions have been witnessed till date, aimed at enhancing various aspects of agricultural practices such as timely cultivation, reducing laborious tasks, improving cultivation methods, and optimizing post-harvest operations.

Crops are produced in both terrestrial and aquatic environments (ponds, reservoirs, and lakes). Judicious use of terrestrial and aquatic resources for crop cultivation is crucial in meeting global demand for a diverse range of food products. India has vast land under water logged conditions, and these areas can be used for the cultivation of aquatic crops such as water chestnut, foxnut, and lotus stem. The cultivation practices of any food-crop involve some common steps: preparation of the field, sowing or transplanting, intercultural activities, harvesting, and post-harvest operations. Among these practices, harvesting is the most crucial and pivotal phase of the cultivation process.

A thorough literature review was conducted on the design and development of various crop harvesters from different electronic databases (Scopus, Web of Science, and Google Scholar). Following literature review, it was found that the reported research and development activities pertaining to harvesting aids, specifically for the harvesting of aquatic crops, are exceptionally low. In case of terrestrial crops, different types of harvesters ranging from manual to robotic have been developed to enhance the productivity of the farmers. The design and function of these crop harvesters are context-specific, depending upon the farmer's requirements, land capacity, and the crop's or fruit's physical properties. From the literature, it was also found that substantial research has been carried out on the importance of aquatic crops and their medicinal value but research on the cultivation practices, tools and techniques used, and challenges in the cultivation of aquatic crops has not been explored.

A preliminary study was done to determine the status of the cultivation methods, tools, and challenges in the cultivation of aquatic crops. Initial interaction with the farmers revealed that the cultivation process of aquatic crops encompasses several common stages, including water-body cleaning, sowing and transplanting, inter-culture, and harvesting. Farmers have reported discomfort while walking on marshy land, which is often covered with water. Maintaining

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balance during walking over the marshy surface/humus becomes challenging as their fe(
and get stuck. Moreover, there is a risk of cuts and injuries from sharp objects (e.g; broken shell of snails/ mollusks) present in the water-body. The challenges intensify when the farmers venture into deeper areas where the water level rises above their chest. Using a boat is also impractical as it hinders their ability to perform agricultural activities effectively. In some cases, farmers depends on frugal designs to float on water bodies. However, these improvised floating arrangements are often fabricated using makeshift techniques, resulting in physical difficulties, uncomfortable postures, and even accidents due to imbalance. Additionally, these makeshift floating devices lack durability, requiring farmers to create new ones each season.

Therefore, based on the literature review and initial field survey, a prominent research gap is noticed in aquatic crop cultivation, particularly in the design and development of assistive products for harvesting purposes. To address this gap, the current research plans to investigate the challenges faced by farmers during the harvesting of one of the aquatic crops i.e., water chestnut crops. By understanding the specific problems encountered by farmers in harvesting activities, this study seeks to contribute to the development of appropriate solutions/interventions that can enhance the efficiency and effectiveness of harvesting practices. The research endeavours to bridge the existing knowledge gap and provide valuable insights in terms of design interventions for cultivation of aquatic crops, benefiting farmers and the overall agricultural sector.

In the present thesis, research gaps have been presented in the form of a schematic diagram, and various research questions have been mapped to the identified research gaps. Please find below a list of research questions. To initiate the research, following a hypothesis has been postulated: 'Harvesting of aquatic food-crops can be facilitated by developing requirement specific assistive products (which help in reduction of manual effort and enhance occupational health and safety) in activities that are not only directly but also indirectly associated with the harvesting process.'

- RQ 1: What are the local tools and techniques used for harvesting aquatic crops?
- RQ 2: What problems are faced by aquatic farmers?
- RQ 3: What should be the design criteria for developing tools to be used in harvesting aquatic crops?
- RQ 4: What would be the effect on efficiency and productivity with the use of a developed technique?

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Hence, the research is aimed at identifying challenges faced by aquatic farmers in harv aquatic food crops (water-chestnut) and providing appropriate/feasible solutions that can enhance productivity and reduce drudgery.

To achieve the aim, the following objectives were set:

Objective 1: To study the various steps involved in the cultivation of the water chestnut crop, with special emphasis on harvesting.

Objective 2: To identify the problems associated with the harvesting of water chestnut.

Objective 3: To identify the most appropriate and feasible solution to address the various problems associated with the harvesting process of water chestnut.

Objective 4: To design and develop the targeted solution and conduct field testing for studying effectiveness.

To fulfil the first objective, a detailed survey was conducted at three sites that were purposely selected from the north-eastern districts of Assam, India. Farmers with experience spanning more than five years were interviewed. The consent of the farmers was obtained before the field study. Ten (10) farmers from each site were selected for interviews. The various stages/ steps for cultivation of aquatic fruit crops as described by the farmers were studied, and with the help of interviews and uncontrolled observation. It was found that the most challenging task was cleaning water bodies (before transplanting) and harvesting the fruit. The physical properties of the plant were also considered, and it was found that the plant expanded uncontrollably and created a web of plant branches. The farmers need to remain inside the adverse aquatic environment for 5-6 hours a day, they suffer from various health-related issues, including body pain, itching, and swelling in different body parts. The underwater images of the water chestnut plants make us understand the challenges faced by farmers with the traditional floating device and why they face difficulty maneuvering through the webbed plant branches floated on and within water bodies.

It was found that for the harvesting of the water-chestnut crop, the farmers must deal with three major challenges, i.e., difficulty with the traditional floating device, repetitive plucking activity, and continued water contact/ submersion.

Farmers use locally made floating-aid to float on the water bodies and perform different cultivation activities in the water bodies. Several issues have been identified with the current design and functionality of the floating-aid used by the farmers. Wooden planks or bamboo

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utilized to connect the two air-filled containers are prone to breakage due to weatherin continuous submersion in water. Thread or tying rope used to secure the bamboo or wooden planks to the containers becomes loose and flimsy after just a few days of use. This compromises the stability and durability of the overall structure, posing a constant concern as sudden dismantling or component failure can lead to imbalance and toppling. Furthermore, the locally made floating device suffers from design flaws, such as its flat shape and sharp corners, which often cause entanglement with the mesh or web created by the plants' branches. This entanglement hinders smooth movement and operation of the device. Moreover, farmers have reported experiencing significant discomfort while using these devices, resulting in pain in their knees, thighs, and backs. These issues collectively highlight the need for improvements in the design, durability, and user comfort of the floating aids used in aquatic crop cultivation.

Another challenge with harvesting is the repetitive nature of plucking activity. During the process of fruit plucking, farmers often resort to using their bare hands without the assistance of any plucking aid. This practice leads to pain and discomfort in their fingers and wrists, as the repeated twists and turns of the hands during plucking activities strain the muscles and ligaments. The continuous exertion eventually results in muscle fatigue and a feeling of numbness. Additionally, a common complaint among farmers is the sticking of dirt on their thumb nails. Compounding the issue is the fact that water chestnut fruits float on the water surface, making the fruits susceptible to the accumulation of a black layer of dirt from the water. Consequently, there is a pressing need for the development of suitable plucking aids or tools that alleviate the strain on the hands, prevent dirt accumulation, and enhance the efficiency and comfort of the fruit plucking process for farmers.

Another difficulty with harvesting is the extended periods of stay in water bodies, which can have detrimental effects on the skin and overall health of farmers. The cultivation of aquatic crops in wetland areas requires farmers to remain in prolonged contact with water without adequate protective measures. This exposes them to various diseases and problems. The pond environment itself, with its muddy and thorny conditions, further adds to its unhygienic nature. Farmers are bound to stay immersed in stagnant water up to their waist or neck, resulting in swelling, skin infections, itching, and injuries.

Unfortunately, these challenging cultivation methods contribute to the gradual decline of cultivation practices of valuable aquatic food-crops, pushing it towards the brink of extinction. In

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this regard, various design interventions were developed and tested that could assist the fa in the harvesting activity.

A product design method was employed to develop a floating device, which involved understanding the needs of the farmers, generating multiple concepts, and selecting the most suitable one. The prototype was fabricated with the help of FRP material, and it was found effective in terms of comfort and productivity for the farmers. The design criteria were based on the needs of the farmers, as well as water-chestnut plant properties. Following three iterations, final working prototype was tested for the harvesting rate, heart rate, and perceived discomfort of the farmers, and it was found that there was a significant increase in the harvesting rate (fruit harvested/ hr) and a reduction in the working heart rate and perceived discomfort that were measured using a heart rate monitor and a Borg CR 10 rating, respectively.

An assistive-aid was developed to facilitate the plucking of fruit. This aid was designed to assist farmers in maintaining a neutral thumb joint angle, allowing them to perform the task for extended periods without much discomfort. Utilizing 3D printing technology, the aid was created and subsequently tested with farmers. The results showed a reduction in physical exertion of the hand, which was confirmed through electromyography (EMG) analysis. The EMG analysis demonstrated that the muscular effort was lower when using the plucking-aid compared to bare-handed plucking. This indicates that the aid effectively reduced the strain on the hand muscles, providing farmers with a more ergonomic and efficient approach to fruit plucking.

A cost-effective piece of wader type personal protective equipment (PPE) was designed to safeguard farmers from water contact and waterborne insects. The term "low cost" emphasizes the affordability of this PPE when compared to related products on the market. To ensure accessibility and economic feasibility, the PPE (wader) was developed using locally available materials. This approach aimed to address the needs of small-scale farmers by providing them with a practical and affordable solution for protection during harvesting activities.

The key findings of the study include that the cultivation of water-chestnut crops is challenging as the various stages of cultivation take place in stagnant water bodies. Out of various stages, cleaning the water bodies and harvesting the fruits are particularly time-consuming and physically demanding tasks. The primitive and makeshift tools used by farmers require interventions as they are not properly designed. The distinct properties of aquatic plants necessitate different designs, materials, and working mechanisms for agricultural tools. Farmers face varying water levels across the water bodies, which fluctuate with the seasons, leading to

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submersion of partial or full body. This causes skin diseases and discomfort. To address the challenges faced by the farmers in the harvesting process, three innovative products were developed: a durable floating device made of FRP material, a plucking aid with a reduced thumb bending angle, and a low-cost wader for protection against water insects and unhygienic water contact. These products aim to facilitate aquatic farmers in the cultivation process and overcome the limitations of traditional practices.

The present research demonstrates the design and development of innovative products that facilitate the harvesting process for aquatic crops. It is important to note that facilitating harvesting goes beyond directly developing products associated with the process itself. In addition to a plucking aid designed for manual harvesting, two other products indirectly assist in the process: a floating device and a low-cost wader (PPE). The innovative floating device reduces manual efforts by enabling easy maneuverability through the water chestnut plant clusters, eliminating the need for removing entangled branches as required with traditional devices. It also offers better balance, comfortable working posture with back support and a reduced abduction angle of thighs. The plucking aid reduces repetitive force exertion and muscle fatigue while facilitating easy plucking with less muscular effort. Furthermore, the low-cost wader serves to protect farmers from direct contact with unhygienic water bodies during harvesting, minimizing potential health hazards associated with prolonged exposure to water and providing protection against insects and snakes. These design interventions contribute to reducing drudgery and enhancing productivity in harvesting activities for aquatic farmers.

The novelties of the current research have been described in the discussion section, in bulleted points. Key contribution of the thesis has been described in terms of a. contribution of knowledge base, b. methodological perceptive and c. contribution to the society.

It is expected that the current research outcome will be immensely useful to the farmers involved in the cultivation of water-chestnut as well as to the new farmers who want to start cultivation of these crops by utilizing the unused water-bodies. The developed and field-tested assistive products for the farmers were found effective in the harvesting of water-chestnut crops. The current research is novel in the domain of aquatic agriculture as it addresses challenges faced by farmers from the perspective of productivity and OSH by developing context-specific design solutions through user-centered design approach.

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1 Introduction

1.1 Current scenario

Increasing population is a major challenge for the world, and it has enhanced demand for food, shelter and employment. According to World bank, there will be 9.7 billion people on the planet by 2050. (FAO, 2009; Le Mouël & Forslund, 2017; Randive et al., 2021; Wudil et al., 2022), and it is also predicted that agricultural production must expand by 70% in order to meet the world's growing food demand (Bruinsma, 2009). On the other hand, United nation has set targets to end hunger, double the agriculture production and end the malnutrition by year 2030 (Mugambiwa & Tirivangasi, 2017). Moreover, agriculture development is considered an important tool to end poverty (Irz et al., 2001; Majid, 2004).

Unfortunately, industrialization and urbanization have reduced the land available for agricultural cultivation. According to the United Nations Convention to Combat Desertification (UNCCD), every year 3.3 million of agricultural land is lost due to urbanization (Shagun, 2019). The cultivable land is reducing because of rapid infrastructure development and natural disasters like floods, earthquakes, and Draught (Basumatari et al., 2023; De Haen & Hemrich, 2007; Ward et al., 2020). Land-based development is possible, it may exacerbate climate change, accelerate the extinction of species, and jeopardize the provision of other ecosystem services (Amundson et al., 2015; Shukla et al., 2019). The shrinkage of land would affect the production of agriculture and farmers earning. We need to think of a sustainable plan to provide food and employment to the increasing population especially in the rural area without harming the natural resources.

Many technical interventions are being made in order to overcome the obstacles. Precision agriculture (Fresco & Ferrari, 2018), conservation agriculture (Kassam et al., 2019), modern greenhouse, mechanization, and automation at various levels have been used to boost agricultural productivity. The majority of agro-technologies have been created for terrestrial agriculture, and approaches for growing water crops have never benefited from the advancement of technology. (Chauhan & Karmakar, 2021). Alternatives should be explored to increase food/ crop production to fulfill the rapidly growing crisis in the coming future.

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Agriculture is a time-bound practice with different kinds of challenges. However, the a tools and technological intervention play a vital part in boosting the productivity and efficiency of the farmers. Mechanization is the use of tools and machines in agriculture to assist farmers in completing labor-intensive activities (Sims & Kenzle, 2006). It reduces the drudgery in farm activities with appropriate tools or implements designed. Agriculture is combination of different practices, among the practices harvesting operation in agriculture production that is labor-intensive, costly, and require care for handling consumable part (Joshi et al., 2015; Sola-Guirado et al., 2018). Basically, harvesting refers to the collection of useful parts of a plant. The process of harvesting and threshing is widely recognized as a critical operation that significantly impacts both the quality and production costs (Alizadeh & Allameh, 2013; Noordin et al., 2016; Pandirwar et al., 2014).

Aquatic food crop production is a significant source of income for farmers in many countries like India, China, and other Asian countries (Chauhan et al., 2022). The aquatic crops are cultivated on stagnated water bodies such as ponds, and reservoirs. Aquatic crops have been used for their medicinal value since the ancient time (Swapna et al., 2011). They have numerous health advantages; therefore, consuming them frequently will be beneficial for a healthy existence. Additionally, the terrain where water is present for the majority of the year and the water table is at or near the surface. The rising of the subsoil water table causes waterlogging, which affects nearly all over-irrigated lands. The aquatic crops are cultivated in the wetland, such as pond, reservoirs and other stagnant water-bodies. In the world total area under wetland is nearly 250 million hectares (Dempsey, 2014; Gardner & Finlayson, 2018). While in India the area under wetland is 4.8 million hectares (GOI 2018).

Considering the enormous amount of wasteland in waterlogged areas, there is an opportunity to cultivate aquatic crops as an alternative form of agriculture in certain areas. This approach allows for the proper utilization of the land and presents a means to generate revenue for farmers.

1.2 Literature review

1.2.1 Alternative agriculture

Alternative agriculture refers to a broad range of farming and agricultural practices that deviate from conventional or mainstream methods (Knapp & van der Heijden, 2018; Skrzypczyński et al., 2021). It encompasses various approaches and techniques that aim to address the limitations and

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challenges associated with traditional agricultural systems. Alternative agriculture emphasizes sustainability, environmental stewardship, and social considerations.

1.2.1.1 Hydroponics

Hydroponic cultivation presents a practical solution to address various challenges, particularly in urban landscapes, where it offers the opportunity to supply fresh food while mitigating agricultural soil loss (Touliatos et al., 2016). Additionally, traditional agricultural systems consume excessive amounts of water, posing a risk to future water supplies (Barbosa et al., 2015). The unsustainability of these systems, both environmentally and economically, emphasizes the pressing need for innovative agronomic methods like closed-loop hydroponics. The Floating Raft System (FRS) has proven to be the most effective hydroponic method for growing leafy plants like lettuce, basil, rocket, and radish. (Ciriello, Formisano, El-Nakhel, et al., 2021; Tomasi et al., 2015). Compared to conventional soil-based cultivation, FRS offers numerous advantages, including accelerated growth cycles, improved water use efficiency, reduced labor costs, increased unit production through higher planting density, consistent and repeatable growth conditions, reduced incidence of soil-borne pathogens, and the ability to overcome limitations like high salinity, heavy metal contamination, and suboptimal soil conditions (Ciriello, Formisano, Pannico, et al., 2021). On the other hand, the hydroponic cultivation brings various challenges such as high initial setup costs, technical knowledge and expertise, power dependency and water and nutrition management (Gumisiriza et al., 2022; Khan et al., 2020).

1.2.1.2 Roof top agriculture

Growing food within cities, often known as urban agriculture, is one way to contribute to mitigating issues like climate change, increasing food demand, rainfall water loss and generating revenue (Deksissa et al., 2021; Gulyas & Edmondson, 2021). Urban agriculture is defined as the cultivation of crops within or adjacent to a city. In point of fact, urban agriculture may bestow a multitude of advantages onto a metropolis. For instance, it can help alleviate the oppressive heat that settles over urban areas during the summer months, it can facilitate the formation of compact human communities that foster increased opportunities for interpersonal connection, it can facilitate the expansion and financial success of modest enterprises, and it can contribute to the assurance of adequate supplies of food (Amos et al., 2018; Kingsley et al., 2019; Nyelele & Kroll, 2020). The capacity for all inhabitants in a city to have access to food, with the goal of reducing the population's dependency on food that must be brought in from the surrounding countryside. Urban agriculture is hampered by the fact that there are rarely any open areas with soil where plants may

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be grown in most cities. Fortunately, there is a practice known as rooftop agriculture wher are grown. The growing of food atop city building roofs can aid in resolving this issue. Depending on the cultivation technique and the plants cultivated, different amounts of water, soil, or other resources may be required for rooftop agriculture.

Rooftop farming can also have advantages for buildings. For instance, the presence of plants on rooftops can provide insulation, helping to regulate temperatures inside the building. This reduces the building's heating and cooling expenses as well. Additionally, rooftop agriculture may shield the roof from the sun, rain, and wind and lessen city noise pollution (Barathi & Vidjeapriya, 2022; Mahmoud et al., 2017; Shin & Kim, 2019).

1.2.1.3 Seafood

Seafood production, particularly aquaculture or fish farming, can be considered a part of alternative agriculture. Aquaculture involves the cultivation of aquatic organisms such as fish, shellfish, and aquatic plants in controlled environments like ponds, tanks, or ocean enclosures. It provides an alternative to traditional wild capture fisheries and contributes to global seafood production (Lusher et al., 2017; Naylor et al., 2000).

In addition to fish farming, alternative seafood production methods include:

- Shellfish farming: This involves the cultivation of shellfish such as oysters, mussels, clams, and scallops. Shellfish farming can have environmental benefits, as these filter-feeding organisms improve water quality by removing excess nutrients and contribute to coastal ecosystem health (Crawford et al., 2003; Souchu et al., 2001).
- Seaweed and algae farming: Seaweed and algae cultivation, known as marine-culture, is gaining attention as a sustainable and nutritious source of food and other valuable products (Buschmann et al., 2001; Trono Jr & Largo, 2019). Seaweeds can be farmed in coastal areas or offshore, providing ecosystem services like carbon sequestration and habitat creation.
- Integrated multi-trophic aquaculture (IMTA): IMTA is an approach that combines multiple species within the same aquaculture system to create symbiotic relationships (Buck et al., 2018; Ridler et al., 2007). For example, fish farming can be integrated with seaweed or shellfish cultivation, where the waste products from one species serve as nutrients for another, minimizing environmental impacts and enhancing overall system productivity.

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Alternative agriculture practices in seafood production focus on reducing the eco footprint, ensuring animal welfare, minimizing the use of antibiotics and chemicals, and adopting responsible feed and waste management practices (Ahmed et al., 2020; Green et al., 2022).

1.2.2 Aquatic food crops and its prospects

Aquatic food crops are used worldwide for food, fiber, and feed stock; some crop in India that are cultivated commercially listed below (scientific name is mentioned in parentheses)

1.2.2.1 Water-chestnut (*Trapa bispinosa*)

Water-chestnut commonly known as '*Singhara, panifal and pani-singhara'* is grown as a food crop in India, China and European countries (Swapna et al., 2011). In India it is grown in almost all state of northern India, Uttar Pradesh, Madhya Pradesh, Bihar and Orissa and other low-lying areas where water accumulate after the rain fall (Kundu, 2017; Singh, 2017). Karg, (2006) said that during the prehistoric era people relied on water chestnut if other crops failed. The water chestnut kernel is rich in protein (up to 20%), starch (52%), tannins (9.4%), lipids (up to 1%), sugar (3%), and various minerals. It is also an excellent source of fiber, vitamin B, calcium, potassium, iron, and zinc. In addition, it possesses numerous curative and supplementing properties. Therefore, they are commonly known as calming foods and are ideal for beating the summer heat. In addition, a mixture of water chestnut powder and water is an effective cough remedy (Jana, 2016; Kundu & Joshi, 2012). This crop requires water temperature of 12-15 deg C necessary for the fruit to germinate while 20 deg C is required for development of the flower. Harvesting of nut is usually done at the month of September and continues up to January this gives yield about 2500-3500 kg per ha. Harvesting of the crop is done manually and no appropriate tool and technique is available for the harvesting of this crop. Figure 2 showing farm of water chestnut crop.

1.2.2.2 Foxnut (*Euryale ferox*)

It is a significant aquatic crop that is related to the Nympheaceae family and is also known as Makhana, Gorgon nut, and Foxnut. For its proper growth, the required air temperature is 20 - 35 degree Celsius, Humidity is 50 - 90 percent. Makhana cultivation provides livelihood to many poor farmers particularly in Bihar and Manipur. It is commercially cultivated in the part of North Bihar, Manipur parts of Madhya Pradesh and West Bengal. Kumar et. al. (2011) found that the area under Foxnut cultivation is about 13000 ha. Makhana has many health benefit (Das et al., 2006).

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1.2.2.3 Indian lotus (*Nelumbo nucifera*)

Lotus is also national flower of India. It is the native crop of India, China and Japan (Rai et al., 2006). Some varieties of Indian lotus are used as a vegetable and have many medicinal benefits. Seeds are used to treat tissue inflammation (Swapna et al., 2011). Lotus stem is a great source of Vitamin C, and minerals in Zinc, Magnesium, Copper. It is also rich in dietary fiber and low saturated fats. It is a delicate, trailing or floating perennial aquatic plant that grows in ditches, marshes, wet rice fields, and moist soil adjacent to freshwater bodies of water. In rural India, it is also frequently used as a green leafy vegetable (Prasad et al., 2005).

1.2.2.4 Some other aquatic food in the world

- Nori, Zicai, and Gim, which belong to the genus *Porphyra spp*., are types of edible seaweeds (Rao et al., 2007). While fresh seaweeds have been consumed as a food source in Asia for centuries, their popularity and availability have grown worldwide only in recent times.
- Water mimosa, scientifically known as *Neptunia oleracea*, is a legume that exhibits the unique ability to thrive as a floating plant in open water or take root in moist soil as the water levels recede. The young plants of this species are commonly harvested, cooked, and consumed as nutritious green vegetables, likely rich in protein (NRC, 1976). Water mimosa cultivation is particularly prevalent in Thailand, where it is grown extensively along riverbanks and in borrow pits.

1.2.3 Occupational health and safety in agriculture

Occupational stress is caused by a variety of risk factors, including physical, organizational, psychological, and sociocultural issues at work (H. Lee et al., 2011; López-aragón et al., 2018). Neglecting workplace safety and stress can have an invisible but sometimes significant impact on the economy. Musculoskeletal injuries are the main workplace risks for employee motivation and high-quality output in India. In the field of agriculture, there are various occupational hazards that pose risks to farmers and agricultural workers. These hazards can have detrimental effects on their health and well-being (Eijrond et al., 2022; Hayden et al., 2022; Sharma et al., 2021).

Farmers manage hefty workloads while frequently adopting awkward stances and dealing with some issues at work (Kumudini & Hasegawa, 2009; Sharma et al., 2021). According to Gangopadhyay et al. (2005), preadolescent agricultural workers had pain in a variety of bodily areas, most notably the low back, knee, shoulder, hand, and neck region, as a result of working in

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an unnatural position for extended periods of time in the agricultural field. Nwuba and Kaul also looked at the hoe farmer's posture while working. Workers reportedly experienced low back strains that were harmful to their health. The most prevalent musculoskeletal condition in agricultural work is low back discomfort. Farmers frequently have low back pain, which seems to be related to the amount of posture that requires back bending as well as carrying and lifting large loads when performing various agricultural tasks (Walker-Bone & Palmer, 2002).

The prevalence of WMSDs (Work-related musculoskeletal disorders) among agricultural occupations has been the subject of numerous studies. For instance, one study in sugarcane plantations discovered that workers experienced physical illness symptoms, such as back pain, muscle cramps, lumbar pain, and shoulder pain (Sriwong & Inmuong, 2013). Another study on a rubber plantation found that the prevalence of musculoskeletal problems was 87.7% and 65.11%, respectively, in the 12 months and 7 days prior to the study (Plykaew et al., 2013). Musculoskeletal symptoms are caused by a variety of factors, including personal factors (Meyers et al., 2000, 2004), such as gender, age, and working conditions involving repetitive motion, forceful exertion, and prolonged work (Jain, Meena, & Dangayach, 2018; Stankevitz, Schoenfisch, Silva, et al., 2016), as well as uncomfortable postures like body bending, kneeling, twisting the body or the arms, and raising the hands above the head (Kwatra et al., 2017; Zeng et al., 2017). Additionally, unsuitable working conditions, environmental elements including vibrations, and excessive work hours can all contribute to musculoskeletal complaints (Solecki, 2011). Due to injuries and illnesses in many sections of the body, musculoskeletal diseases (MSDs) are most frequently encountered in the back and arms.

Moreover, in agricultural practices, the harvesting task was found to be the most risky (Jain, Meena, Dangayach, et al., 2018a; Rani et al., 2016) in terms of health hazards and safety issues. Occupational hazards due to manual labor, repetitive tasks, and use of improper tools and techniques have also been reported for Malaysian oil palm fruit harvesters (Ng et al., 2015), Sri Lankan rubber tappers (Stankevitz, Schoenfisch, de Silva, et al., 2016), Latino sweet potato farmworkers (Kearney et al., 2016), Indian manual-working rice farmers (Ojha & Kwatra, 2014; Pal et al., 2016), Cambodian fruit farm workers (Thetkathuek et al., 2018), Iranian apple harvesting laborers (Thamsuwan & Johnson, 2015), Brazilian banana harvesting workers (Merino et al., 2019), and labor-intensive agricultural workers in general (Lantin, 2016). Despite the risk potential of MSS, no previous studies have reported the prevalence of MSS or associated risk factors among water-chestnut farmers in India.

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Limited research has been conducted on the occupational hazards associated with crops, particularly water-chestnut crops. Few articles have been identified that specifically discuss the challenges associated with the cultivation of lotus stem (Parmanad & Sahu, 2019), kelp weed (Zhang et al., 2017), and foxnut (A. Kumar et al., 2021). While most studies have focused on the occupational hazards related to terrestrial crops, leaving a significant research gap in understanding the challenges faced by farmers cultivating aquatic crops. In particular, the specific occupational hazards and risks encountered by farmers engaged in water-chestnut cultivation have received less attention. Therefore, there is a need for further investigation to identify and address the occupational hazards specific to the cultivation of aquatic crops, with a particular emphasis on the water-chestnut crop and the challenges faced by farmers in this domain.

1.2.4 Technological intervention in the design and development of farming aid

In the present time, agricultural harvesting is not limited to the traditional type of manual operations (Araújo et al., 2021; Lu et al., 2020). The use of machinery in respective operations is rather common which reduces the time and human efforts (Jelani et al., 2008). Another reason for the increase in agricultural machinery is the commercialization of this industry as well as the shortage of labour (Bing-fu, 2007; Brotons-Martinez et al., 2018; Gupta et al., 1996). From tillage to harvest, different types of machinery are available to perform the respective operations with ease.

Agriculture constitutes a significant part of the low-middle-income country like India (Emerick, 2018). The agricultural practices are broadly divided into tillage, sowing, irrigation, crop management, inter-culture, and harvesting. In India, the climatic variation due to vast geographical diversity is responsible for harvesting different crops, vegetables, and fruits to a particular region (Shah, 2014). For example, due to the ample rainfall and adequate climatic conditions in the Northeastern part of the country, rice and Pineapple cultivation practices are common. For the past few years agriculture is becoming a center of attraction for many researchers as despite wide range of research opportunities in agricultural practices, the climatic change, unproductive land, and urbanization leads to decrease in the cultivable agricultural land (Beacham et al., 2018; Thornton et al., 2018). The increasing population rate created high demand and the need to facilitate farming practices (GOI, 2016). The operations like tillage, sowing, and harvesting should be focused exclusively on sustainable work practices. Many tools and implements are designed to reduce the operation time and drudgery of the operator.

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1.2.5 Design and development of crop harvester

In the extensive literature research in four data bases (Web of Science, Scopus, J-Gate, and Google Scholar), it was found that a total of 96 articles were dealing with the design and development of the agriculture food crop harvester. These articles highlight different design criteria and the working of harvesters. The harvesters can be grouped based on the level of mechanization (Manual, Semi-Mechanical, Mechanical and robotic), energy source (Fossil, Electric and Human) and crop types (Chauhan & Karmakar, 2021). The Categorization of articles was done based on the crop classification (FAO, 2010), which has been shown in Table 1.

Table 1. Number of harvesters developed based on crop classification

Crop type	**Crop classification**	**No. of harvester designed**
Terrestrial crops	Cereals	12
	Vegetables and melons	16
	Fruit and nuts	22
	Oilseed crops	18
	Root/tuber crops	11
	Beverage and spice crops	4
	Leguminous crops	3
	Sugar crops	7
	Total	**93**
Aquatic crops	Root crop (lotus)	1
	Weed (kelp)	1
	Fruit and Nuts (makhana)	1
	Total	**3**

Different crops possess distinct physical properties and require specific harvesting methods. The successful collection of edible or consumable parts necessitates the use of appropriately designed harvesters. Cereal crops such as maize, sorghum, barley, and wheat, for example, have varying geometries that impact the design of the harvester. On the other hand, root crops grow their edible parts beneath the soil, requiring a different type of harvester compared to cereal crops, where the edible parts are located above the soil. Additionally, the size of a farmer's landholding also influences the choice of harvester. Farmers with large landholdings would typically opt for larger harvesters rather than smaller ones. These factors contribute to the need for different types of harvesters in agricultural practices.

These harvesters were designed and developed to address majorly three challenges. Firstly, it helps to increase the harvesting rate because manual harvesting by hand consumes high time, which reduces the total yield. Harvesting at an appropriate time avoid loss in total production and enhance total productivity (Baneh et al., 2012). Secondly, it addressed the issue of labor scarcity. When crops reach their peak harvesting period, the demand for labor intensifies, leading to a

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shortage of available workers. Consequently, harvesting operations are delayed. agricultural activities pose a significant risk of musculoskeletal disorders, amplifying the need for preventive measures. (Jain, Meena, Dangayach, et al., 2018b; Khayer et al., 2017; Osborne et al., 2012). Crop harvesters are crucial in order to lessen laborious crop harvesting. Harvesters for terrestrial crops benefit from an ergonomic modification that reduces fatigue and improves performance. It was found that only three articles were for the aquatic crop and 93 articles for the terrestrial crops, as shown in Table 1.

1.2.6 Ergonomic considerations for human-centered design of agriculture tools and farming-aid

Using agricultural tools and implements can improve productivity and lessen laborious tasks associated with cultivation. Different kinds of tools have been created to aid in cultivation and boost productivity. These instruments may be robotic, mechanical, semi-mechanical, or manual. Despite advances in robotics and machinery in many fields, many farmers still carry out their work entirely by hand. These tasks can occasionally be very monotonous and stressful, causing farmers to compromise their health.

Getting useful technologies into farmers' hands will play a significant role in determining the future of agriculture. Increasing awareness of safety and health issues among farmers, farmworkers, society, and governments should be a top priority in farming (Castillo et al., 1998; Chatterjee, 2020). Due to their lack of resources and knowledge barriers, the vast majority of farmworkers in small landholdings are not well positioned to comprehend the research implications of ergonomics in agriculture. A nation frequently imports agricultural equipment and technologies that were made with the users of another nation in mind. Many times, the technologies developed and found to be successful in one country become the cause of increased injuries and health risks in another due to differences in the anthropometric and physiological parameters of people between countries.

Agriculture is expanding and developing, and this is why it places a strong emphasis on the producers and the production base. The fundamental focus on improving life and living in agriculture is sustainable food security and the livelihood of the majority of people (Ayyappan & Chand, 2012).

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1.2.7 Design thinking

Diverse stakeholders are brought together to participate in the design-thinking process, which aims to establish and maintain a shared understanding of the design problem in order to facilitate collaboration and facilitate the collective investigation of potential solutions to a shared challenge. (Barcellini et al., 2015; Gardien et al., 2014). In addition to this, co-design affords participants the chance to investigate and think critically about the local needs and concerns of their respective stakeholders, which, in turn, leads to an improvement in the innovation's design and delivery as well as the likelihood of its successful implementation (Khalid, 2006). This diversity and inclusiveness are the dimensions of co-design, which prioritizes the involvement of stake-holders (Molla et al., 2018).Through the co-design process, these stakeholders are involved in each step, from the initial conception of the product to the design and testing phases.

Over time, numerous iterations of design thinking models have emerged, but the origins of this approach can be traced back to Professor John Arnold (1913–1963). Notably, Arnold encouraged his engineering students at MIT to envision designing products for extraterrestrial beings rather than their peers, challenging their perspectives. In 1957, Arnold relocated to Stanford University, where he established the engineering design school. One of his students, David Kelley, went on to establish the renowned design firm IDEO and the D.school at Stanford University. Kelley's Stanford model of Design Thinking comprises five crucial phases: Empathise, Define, Ideate, Prototype, and Test (Kelley, 2001).

1.3 Research Gap

It is found that sufficient research has been carried out in the domain of design and development of terrestrial crops harvesting. On the other hand, there is a lack of research for the development of harvesting-aid for aquatic food crops. Farmers of aquatic food crop deal with many potential problems with the traditional method of cultivation. Based on the literature review, Figure 1 illustrates a diagrammatic representation of the identified research gap.

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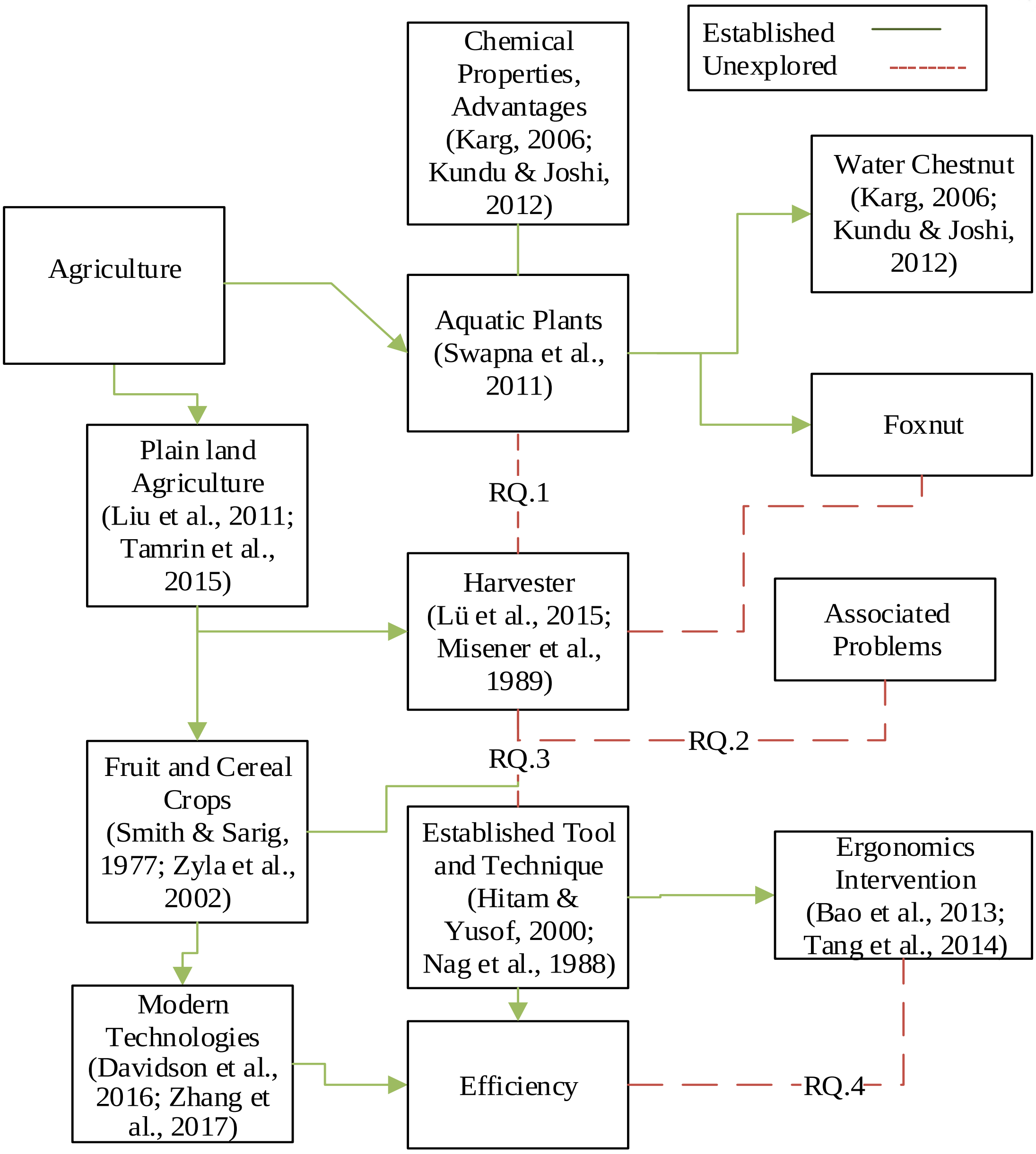

Figure 1. Identified research gaps for the present research topic

1.4 Research question

Based on the above research gaps, and initial interactions with the farmers, a set of research questions were raised as listed below.

- RQ 1: What are the local tools and techniques used for harvesting aquatic crop?
- RQ 2: What problems are faced by the aquatic farmers?
- RQ 3: What should be design criteria for developing tools to be used in harvesting aquatic crop?
- RQ 4: What would be the effect on efficiency/productivity with the use of developed technique?

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1.5 Preliminary field study

The cultivation process of aquatic crops has some common process such as cleaning of waterbodies, sowing/transplanting, interculture, and harvesting. For these process farmers have to go inside the water bodies for more than 5 hours without any standard tool also shown in Figure 2. Farmers also reported discomfort in walking in marshy land, as the water bodies is covered with marshy land, and it is very difficult to keep balance while walking. Foot get sink in marshy land and get stuck, many times it requires high force to pull the leg and move forward in these water bodies. Many times they get cut in leg due sharp objects in the water body. The major challenges come when they go in depth, when the water level is high (above the chest level). The use of boat is also difficult as they cannot perform the agriculture activities while sitting on the boat. Farmer sometimes use frugal design to float on water. Due to improper fabrication through 'Jugad' technique, they have to face many physical difficulties (awkward posture and discomfort) and even accident due to imbalance. These floating arrangements are also not durable and thus the farmers need to make a new one during every season.

Figure 2. Water chestnut cultivation in Kamrup, Assam

1.6 Problem statement

From the field study, it was observed that the agricultural worker engaged in harvesting of aquatic food-crops are socio- economically deprived and thus incapable of acquiring costly design interventions. Generally, for harvesting of aquatic crops (water chestnut, foxnut, lotus, etc.) workers are bound to remain inside water for the duration of 5 to 6 hour. Due to prolonged stay inside the water and humus, workers suffers from various skin diseases, which varies from simple swelling and white skin to fungal and bacterial infection. As this harvesting work requires repetitive hand and fingers movement along with force exertion the worker become fatigue very soon. Moreover, they do not have appropriate tool/ equipment for harvesting. These workers also do not use any personal protective equipment/measures. Thus, the need of the hour is to

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develop appropriate tools, technique along with personal protective equipment to save the w
from drudgery along with enhancing their performance and productivity. Unavailability of appropriate anthropometric and biomechanical databases of the targeted users hinders the design and development of any intervention. Another important challenge for designer/ engineer in developing tool and technique for harvesting aquatic food crop is the selection of appropriate/correct material. Intended design intervention should also be crop specific as the physical properties of the crop and its location/ position in aquatic body are also different.

1.7 Motivation and justification of choosing the research

From the literature review it is clear that design and development in terrestrial agriculture is very common. It has been found that wide range of technological intervention are available for the terrestrial crop cultivation that could assist the farmers to fulfil the work demand with ease and in time. On the other hand, there is lack of research and development in the field of aquatic agriculture. There are numerous waterbodies available that can be used for the cultivation of these crops. In this regard, the current research planned to explore the challenges in cultivation of water-chestnut, and possibilities with suitable solution and design interventions that can be taken to the real world setting and benefit different stake holder involved.

1.8 Aim and objective

- **Aim**

To identify challenges faced by aquatic farmers in harvesting of aquatic food crop (water-chestnut) for providing appropriate/feasible solutions which can enhance productivity and reduce drudgery.

- **Objectives**

Objective 1: To study the various step involved in the cultivation of water chestnut crop, with special emphasis on harvesting.

Objective 2: To identify the problems associated with harvesting of water chestnut.

Objective 3: To identify most appropriate and feasible solution to address the various problems associated with harvesting process of water chestnut

Objective 4: To design and develop the targeted solution and field testing for studying effectiveness

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1.9 Hypothesis

To proceed further in research, the following hypothesis has been formulated.

Harvesting of aquatic food-crops can be facilitated by developing requirement specific assistive products (which help in reduction of manual effort and enhance occupational health and safety) in activities that are not only directly but also indirectly associated with the harvesting process.

1.10 Research plan

The graphical depiction of the entire research procedure concerning the topic "Design and Development of Assistive Products for Harvesting of Aquatic Food-Crop (Water-chestnut): A User-Centered Design Approach" is illustrated in the provided Figure 3.

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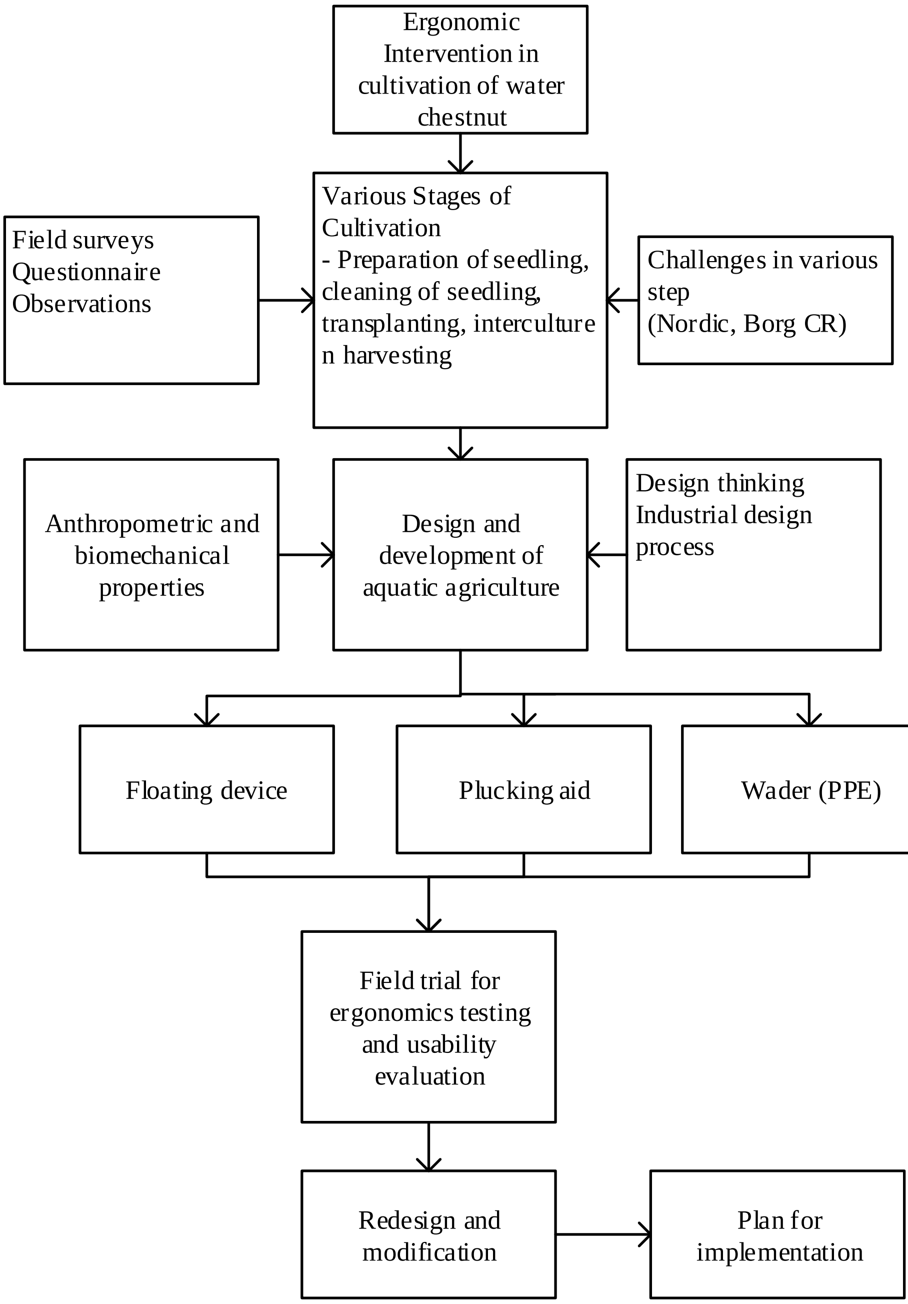

Figure 3. Overall flow of the research

1.11 Framework of the thesis

According to the research workflow, the thesis document is segmented into six distinct chapters. The thesis workflow is succinctly explained in Figure 4. The research inquiries, goals, and hypotheses tackled within each separate chapter are succinctly outlined in Table 2.

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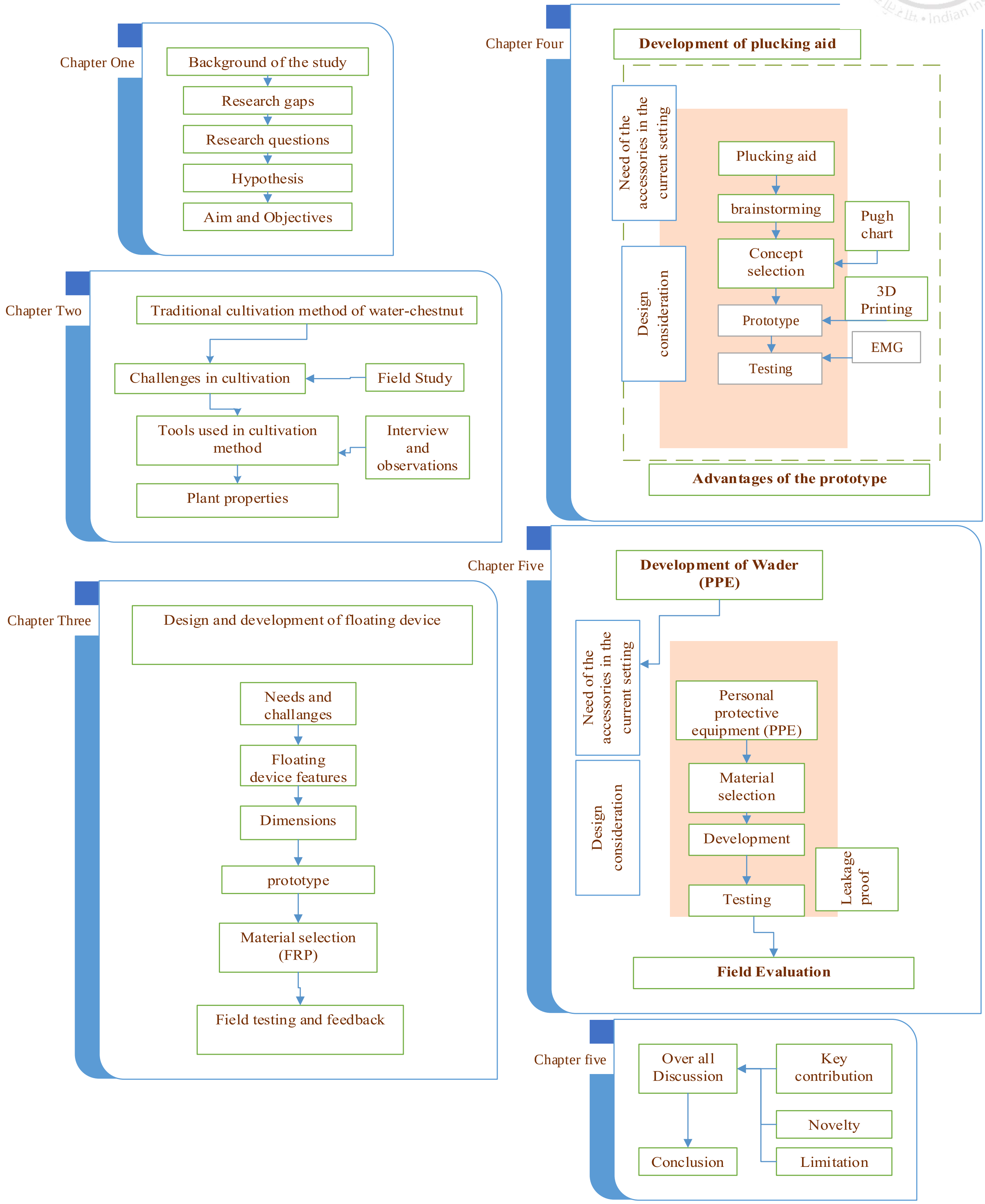

Figure 4. Thesis workflow and content of various chapters

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Table 2. Research questions, objectives, hypothesis - organized in various chapters and publications

<table>
<tr><th>Chapter</th><th>Research Questions</th><th>Objectives</th><th>Hypothesis</th><th>Publications</th></tr>
<tr><td>2</td><td>RQ-1: What are the local tools and techniques used for harvesting aquatic crop?
RQ-2: What problems are faced by the growers?</td><td>Objective 1: To study the various step involved in the cultivation of water chestnut crop with special emphasis on harvesting

Objective 2: To identify the problems associated with harvesting of water chestnut
Objective 3: To study the physical properties of the water chestnut plant.</td><td rowspan="3">Harvesting of aquatic food-crops can be facilitated by developing requirement specific assistive products (which help in reduction of manual effort and enhance occupational health and safety) in activities that are not only directly but also indirectly associated with the harvesting process.</td><td rowspan="3">Chauhan, J. S., & Karmakar, S. (2021, January). Urge for human-centered design intervention for harvesting aquatic food crops. In International Conference on Research into Design (pp. 59-69). Springer, Singapore.

Chauhan, J. S., Singh, H. J., & Karmakar, S. (2022). Traditional Cultivation Practices of Water Chestnut in Northeast India (Assam): A Field Survey. In International Conference of the Indian Society of Ergonomics (pp. 369-381). Springer, Cham.</td></tr>
<tr><td>3,4 &5</td><td>RQ-3: What should be design criteria for developing tools to be used in harvesting aquatic crop?</td><td>Objective 3: To identify most appropriate/ feasible solution to address the various problems associated with harvesting process of water chestnut</td></tr>
<tr><td>3,4 &5</td><td>RQ-4: What would be the effect on efficiency/productivity with the use of developed technique?</td><td>Objective 4: To design and develop the targeted solution and field testing for studying effectiveness</td></tr>
</table>

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1.12 Outline of the thesis

A brief summary of the study divided into five chapters in the thesis is as follows:

Chapter–1: This chapter focuses on the need for development in agriculture, there are various factor associated with the development of the agriculture as well as farmers' safety such as ergonomics, tool and implement design. In the literature review it was found that there is a paucity in the area of aquatic crop cultivation for the development of farmers. While for the terrestrial crops different types of harvesters and harvesting aid were developed. The research questions, the aim of the present research, objectives to achieve the aim, hypotheses, and framework of the thesis are also presented in this chapter.

Chapter–2: This chapter describes the details of cultivation method of water-chestnut crop that involve the preparation of seedling, cleaning of the field, transplanting harvesting of fruit and cleaning of fruit. The chapter also discuss the challenges in the cultivation of the crop by the farmers. The study is required to understand the plant property.

Chapter–3: This chapter discusses the development steps of the floating device. In this chapter product design method is demonstrated that was used for the development of floating device. Different design is explored and selection of suitable design using Pugh chart has been done. The chapter also describes the prototype development stages using FRP material and field evaluation of the floating device.

Chapter–4: This chapter discusses the process for the design and development of a plucking aid. The chapter highlights the need of the intervention and design criteria for the plucking aid. The dimension of the plucking aid is based on the thumb anthropometric data of the farmers. The chapter describe the application of 3D printing technology for the fabrication of small products.

Chapter- 5: This chapter discusses the need and development of wader, the material used in the development, and the field trials. Because of long stay in the unhygienic water bodies, farmer develop swelling, infection and other skin diseases. In this chapter a low-cost wader (PPE) is developed with the locally available material.

Chapter- 6: This chapter presents the overall summary and discussion of the study. Limitations, major findings, and key contributions of the thesis are also presented here.

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2 Traditional cultivation practices of water chestnut in Northeast India

Abstract

In the majority of Indian states, water chestnut is cultivated for its use as a food crop. Despite having high economic significance and medicinal value, traditional cultivation practices are still followed by Indian farmers. Aquatic food crop cultivation practices, like water chestnut, have not received the attention they deserve due to their informal character and are not seen as mainstream economic operations. As a result, there has been no progress made toward the modernization of the following agricultural farming technique. The cultivation method being less documented and not available readily it could not catch the attention of agricultural researchers for their involvement. Hence, the purpose of this study was to gather information on the traditional cultivation technique of water chestnuts and to identify any difficulties encountered. In order to accomplish the task, a comprehensive survey was carried out in three locations in the northeastern districts of Assam, India. It was observed that five stages of water chestnut cultivation are consistent across all sites: seedling preparation, cleaning of water-bodies, transplanting, inter-culture, and harvest. It was also determined that operations of gathering and cleaning up the water bodies was tiresome and time-intensive. As a result of the fact that the farmers are required to work in an unfavorable aquatic environment for five to six hours every day, they experience a variety of health problems, the most common of which are soreness, itching, and swelling in the lower body. The research findings would make it easier to explore potential future research directions for boosting productivity, improving livelihood, and encouraging researchers to develop intervention ways that would ease the burdens of farmers in their daily work. The current research results would make it easier to explore potential future research directions for boosting production, improving livelihood, and inspiring researchers to develop intervention ways for reducing the drudgery of farmers.

2.1 Introduction

The agricultural food crop water chestnut (*Trapa bispinosa*) is grown all over the world, including India, China, Europe, and Africa (Guo et al., 2017). it is widely grown in Uttar Pradesh, Bihar,

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Madhya Pradesh, and the north-eastern regions of India (Chandana et al., 2013). Evidence s that during the 4th and 1st millennia BC, this plant served as a nutritional food (Karg, 2006). Many Indian farmers rely on income from water chestnut cultivation as their primary source of income. The fruit also contains a variety of therapeutic properties, including anti-inflammatory, antioxidant, immunomodulatory, nootropic, and anti-diabetic effects (Chandana et al., 2013). The water chestnut is an abundant source of starch (50%) and having protein (10%) which is similar to the cereals crop (Babu & Dwivedi, 2012; Karg, 2006).

The modernization of aquatic agriculture has not received its due attention. While there is a significant amount of investigation being carried out in the field of terrestrial agriculture, very few studies have been carried out in the field of aquatic agriculture. Apart from hardship, low profit, and health hazards, there might be numerous reasons for not giving due importance to aquatic agriculture as the potential food source as well as mainstream economic activities. Due to lack of literature related to cultivation method among agriculture researchers, engineers, and scientists, aquatic agricultural practices have not been modernized or mechanized.

The traditional cultivation of water chestnut is followed by agriculture workers in an unorganized or informal manner in different parts of India, especially north-eastern states. The tacit knowledge of this farming process is not documented well, and it is not easily accessible to members of the scientific community such as agricultural scientists, engineers, and research researchers. As a result, there has been very less intervention to improve farming techniques using current knowledge and cutting-edge technology. With this context, it is felt by the current authors that there is a need for proper documentation with appropriate visuals to describe the traditional cultivation technique of water chestnut. Therefore, the purpose of this article is to clearly describe the step-by-step traditional water chestnut cultivation procedures as well as the difficulties and potential areas for intervention in the future to make the cultivation practice more effective, and user-friendly.

2.2 Methodology

Data were gathered from three separate sites of water chestnut farms located in the north-eastern district of Assam state, India. The size of the farms that were greater than one and half bigha (>2000 m^2). Three locations were selected for the study from the Kamrup rural district of Assam. In order to gain an understanding of cultivation steps, time required in each step, tools and techniques used, seasons for cultivation, plant's physical characteristics, as well as challenges, the field survey was conducted using the explorative research method, which included unstructured interviews using an

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open-ended questionnaire, direct observations, and documenting (photography and videog (physical challenges, safety concerns, adverse climatic conditions, etc.). Figure 5 shows a schematic diagram that summarizes the survey method.

2.2.1 Farmers details

Farmers with more than five years of experience in the field were interviewed. Before beginning the field study, the consent of the farmers was obtained. There were ten (10) farmers chosen from each location for interview. The farmers ranged in age from 18 to 60 years old, were economically underprivileged (monthly income of about 8,000 rupees), and were illiterate to semi-literate (maximum schooling).

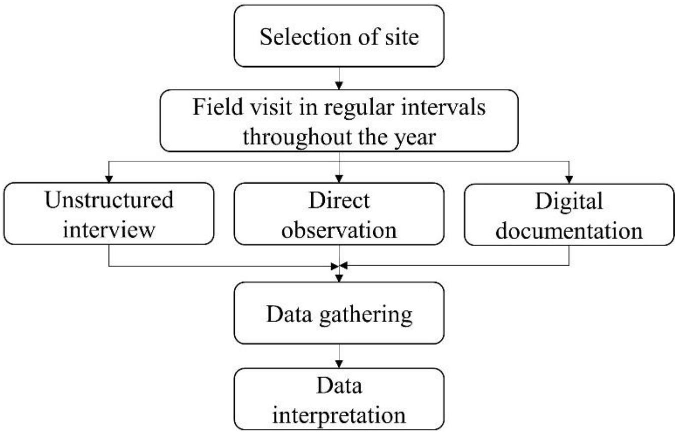

Figure 5 Methodology adopted for the study

2.3 Results from field survey

2.3.1 Different steps/ phases of water chestnut cultivation

The cultivation of water chestnuts can be divided into five distinct procedures or phases, commencing with seedling preparation and ending with harvesting. Figure 6 shows the steps followed in the cultivation of the crop.

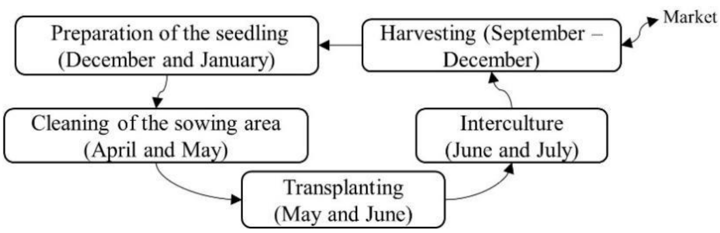

Figure 6 Cultivation step of water chestnut

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2.3.2 Preparation of seedling

In the month of December, fully matured water-chestnut fruits collected from last harvest are sown in an already cleaned water body. The sowing process is entirely manual, and the farmers sow the seed (matured chestnut) in the soft humus clay below the water with their bare-hands as the depth of the water remains low during the month of December- January. Within three months, the seed germinates and develops into a seedling also shown in Figure 7. These plants have propensity to spread/expand so the whole waterbody get covered with the plants gradually.

(a) Seedling of water chestnut (b) Segregation of seedling by the farmers

Figure 7. Seedling separation

2.3.3 Cleaning of the waterbodies

Cleaning of waterbodies is carried out in the month of April and May. Before transplanting the seedlings, the water bodies must be cleansed as they are covered with various kinds of water weeds floating on the surface. The farmers/ workers work for about six hours daily to clean the water bodies. The removal of floating weeds and the uprooting of weeds that are situated at the bottom of the water are both included in this cleaning process for the weeds. Farmers tie the bottom of their pants or trouser with a rope before entering water bodies to prevent insects from getting inside (Figure 8).

Figure 8. Farmers tie the bottom of their pant before entering into water-bodies

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The farmers use bamboo to push the weeds toward the bank of the waterbody and pi up as indicated in Figure 9. Then, with the aid of their hands, they remove the weeds from the water body. With the exception of the sickle for cutting small trees, there is no particular tool for this type of cleaning operations. Farmers reported that they suffer from pain/ body-ache in shoulder, hand and leg after performing such activities.


(a) Surface weed cleaning


(b) Throwing of weed with hands


(c) Inside water weed cleaning


(d) Inside water weed (*Gaaj*)

Figure 9. Cleaning of water bodies

Cleaning up weeds that are submerged in the water is far more difficult and time-consuming than cleaning up weeds that are floating on the water's surface. Farmers push the weeds with one leg and then collect them with their bare hands to remove the underwater weeds. Farmers reported that there isn't even a tool or work accessory available for this specific task.

2.3.4 Transplanting

Seedlings from the waterbody are taken out for transplanting. The stem section of water chestnut seedlings is quite long. Farmer goes inside the waterbody and brings the seedlings by pulling toward the bank/dyke with the help of hand. Seedlings are individually trimmed to approximately 5 feet in length to ensure uniform size for transplantation. Excess sections of the stems are discarded. Subsequently, the seedlings undergo a washing process to eliminate any insects or unwanted materials adhered to them. Once washed, the entire cluster of seedlings is enclosed within a fishing net for convenient transportation to larger water bodies for transplantation also shown in Figure 10. It's worth noting that, similar to the preceding stages, this phase is entirely manual.

During transplantation, farmers utilize their right big toe and index toe to grip the seedlings and insert them into the mud of the water bodies for growth. This task is relatively quick, requiring

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just a day for three farmers to plant three bigha (1bigha = 1400 m^2) of land. Seedlings are t
spaced 1 to 1.5 meters apart in both rows and columns.

(a) Taking seedlings to the field (b) Manual transplanting of the plants

(c) View of field after transplanting (d) View of field at time of harvesting

Figure 10. Various stages of transplanting process

2.3.5 Inter-culture

Weed removal from waterbodies is done at regular intervals after seedling transplantation. It is done to prevent weeds from interfering with the water chestnut plant's growth. This cleaning procedure is known as inter-culture. Cleaning continues until the water-chestnut plant covers the entire pond and blocks the sunlight from reaching the water's bottom.

2.3.6 Harvesting

The farmer used to tie the bottom of their pants or trousers with a tiny rope before entering the waterbody to harvest, covering the majority of their body with a shirt and pants to prevent water insects like leaches from getting inside their clothing.

While engaged in harvesting, farmers utilize a floating utensil or vessel also depicted in Figure 11 (a, b, & c) to collect and store the harvested fruits. Additionally, they employ a net to transfer the fruits from the filled vessels. The harvesting process is repeated five to six times between the months of September and December.

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Each plant requires the farmer to inspect and turn it to assess fruit readiness. If the deemed mature for harvesting, the farmer plucks it and places it in the floating vessel before moving on to the next plant.

(a) Entering of farmer in field

(b) Harvesting in the field

(c) Utensil to keep fruit

(d) Plastic net to transfer fruit from utensil

Figure 11. Activities associated with harvesting

Harvesting in high water level - When the water level rises above chest level, farmers resort to using either a boat or a makeshift floating structure crafted from lightweight materials like wood or bamboo. These harvesting aids, often constructed using locally available resources and employing an improvised approach, lack standardization the floating structure is also shown in Figure 12.

Figure 12. Locally made floating structure to facilitate harvesting in high water-level

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The task of harvesting of the crop can be divided into following seven sub-tasks. (a) Farmers face the challenge of navigating through densely covered water bodies entangled with a mesh of water-chestnut plant stems. To progress, they carefully maneuver individual plants on both the left and right sides, creating a pathway through the vegetation. (b). Reach – The farmer needs to approach each plant. (c). Pick –Farmer has to pick/hold the leafy portion (by left hand, generally) of each plant and lift it manually above the water surface, one at a time. (d). Search – The farmer is required to visually examine and search for mature fruits by gently rotating the plant using a twisting wrist motion. (e). Plucking –With the help of thumb and finger of the right hand farmers pluck the fruit. (f). Keeping –After plucking, they keep it in the floated vessel. (g). Transfer- Once the vessel becomes filled, they transfer the harvested fruits into the net and then proceed with an empty vessel to continue the filling process.

2.4 Challenges in the cultivation

From the field study it was found that the farmer faces many challenges in the cultivation of the crop. The major challenges identified are the disadvantages of locally made floating devices, ill effect of staying in water bodies, problem associate with the boat harvesting, and difficulties in bare-hand plucking of the fruit. A detail discussion of challenges is provided in the following section.

2.4.1 Disadvantages of locally made floating device

The farmers use locally made device for harvesting the fruit when water level is high, shown in Figure 13.

- The wooden planks/ bamboos used for connecting the two containers become easily breakable due to weathering and for regular immersion in water.
- The thread/ tie rope used to tie the bamboo/ wooden plunks with the containers become loose and flimsy after being used for a few days.
- The durability of the overall structure is always a matter of concern. Due to sudden dismantle/ breaking down of the components leads to sudden imbalance and thereby toppling.
- Due to the flat shape and sharp corners of locally made floating aid, it gets entangled into the mesh/ web created by the plants stems.

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- High discomfort was reported by the farmers, which leads to pain in knees, and back portion while using these devices.

Figure 13. Farmer using locally made floating devices

2.4.2 Ill-effect long duration submerging inside stagnant and unhygienic water bodies

Prolonged exposure to water can lead to various skin and health issues. Given that aquatic crops thrive in wetland environment, farmers often find themselves in prolonged contact with water without adequate protective measures. This can result in a range of common diseases and problems, which are outlined below:

- Swimmer's itch is an allergic condition that occurs when the motile and infectious stage of avian schistosomes penetrate the skin of an individual. Flatworm parasites that cause swimmer's itch are commonly found in water bodies (Rudko et al., 2019)
- Cercarial dermatitis is a waterborne non-communicable skin condition caused by Schistosoma cercariae released by aquatic snails. Cercarial dermatitis appears worldwide, but may be caused by different Trematode species (Tracz et al., 2019)..
- Cyanobacteria, also known as blue-green algae, are commonly found in freshwater lakes and reservoirs throughout the world can affect the skin (Stewart et al., 2006)
- Water bodies can have harmful insects and reptiles like snakes and leeches (Jonk) inside the muddy soils (Parmanad & Sahu, 2019) .
- Hot tub rash (pseudomonas Dermatitis) is caused in humans due to contact of contaminated water for a long period of time
- The pond environment is unhygienic due to mud, thorns/prickles.

Farmers are compelled to remain submerged for extended periods (up to their waist or even neck) within stagnant and unsanitary water bodies, leading to swelling in limbs, skin infections,

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bodily discomfort, and injuries. Consequently, these valuable crops are gradually facing th of extinction due to the challenging cultivation methods.

2.4.3 Problem associated with harvesting using boat

Farmers using the boats for harvesting water chestnut have to opt crouched posture for long duration. Due to the long duration they develop pain in the knee and lumbar area. A farmer performing the harvesting task of water chestnut on a boat as shown in Figure 14. Lumbar degenerative kyphosis (LDK) constitutes a subset of the flat-back syndrome and primarily arises from distinctive lifestyles, including extended periods of crouched posture while engaged in agricultural tasks and conducting daily activities on the ground (Novaes et al., 2017). Manual harvesting of aquatic plants using a boat leads to harmful body posture (C. Lee et al., 2017).

Figure 14. Harvesting of water chestnut on boat

2.4.4 Difficulties in bare hand plucking

Farmers pluck the fruit with bare hands without and plucking aid because of it, pain and discomfort in finger and wrist due to repeated twists and turns of hands during plucking activities. Hand muscles become fatigue and feeling of numbness occurs. Along with it, most of the farmer complained about the sticking of dirt on the thumb nail also shown in Figure 15. The water chestnut fruit float on the water surface due to this, a black layer of dirt of water sticks on the fruit’s surface.

Figure 15. Dirt in thumb nail

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2.5 Discussion

Researchers must possess an understanding of the plant's physical attributes to effectively intervene in the water chestnut cultivation process. The physical characteristics of the water chestnut plant differ from those of terrestrial plants. Thriving in stagnant water bodies such as lakes, ponds, and marshlands, this plant's roots embed into the soil beneath the pond's surface. Upon full maturation, the crown or upper part of the plant measures approximately 40 to 50 cm in width. The crown portion always remains on the surface of the water because of air sacks are attached with the leaves as shown in Figure 16. The fruit of the plant grows near the stem and just below the leaf of the plant.

Figure 16. Water chestnut plant with air sack and fruit

The investigation revealed that the water chestnut plant possesses an elongated stem, and owing to this characteristic, along with a floating crown at its top, the plant exhibits resilience to elevated water levels in aquatic environments. This distinct attribute enables the water chestnut crop to grow well even in regions, which are prone to high levels of flooding.

The water chestnut farmers encounter many issues linked to occupational health. Farmers claimed that they have to spend a lot of time in the water, which results in numerous skin and health issues. The majority of farmers (65%) said they were ignorant of such protective equipment, and others mentioned the expensive price of this equipment as reasons why they do not use it. Forty percent of farmers who spent extended periods of time in the water without wearing protective gear complained of limb swelling, skin infections, and itching in various body regions. Farmers have reported that they have been unable to continue their work as a result of such diseases, which has resulted in economic loss and increased medical bills. Similar problems were reported in the cultivation of makhana, where farmer has to go deep inside the water to collect the makhana seeds (Khadatkar et al., 2015).

68 percent of farmers reported back pain as a result of prolonged uncomfortable posture. Water chestnut cultivation has a high labor need, and it has been noticed that farmers must assume

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unnatural body postures to meet this requirement. Every stage of the cultivation process i[n] frequent bending. Farmers have to frequently bend their upper bodies while placing mature fruits within the soil in seedling preparation. In most water bodies, the depth gradually increases from the corner to the center, making it difficult to remove surface weed. Farmers must therefore choose an inconvenient posture depending on the depth level to accommodate their working environment. Similar positions have been linked to discomfort in various body areas when manually picking mussels (an aquatic plant) from a boat (Novaes et al., 2017).

Ninety percent of farmers reported that it took a lot of force to drive water weed with bamboo during cleaning. The explanation for such response could be the resistance of water to human movement which creates an environment difficult to walk in water than in air. Also, they need bamboo to push the weed. As a result, farmers need to battle two forces, including water resistance and weeds pushing bamboo. This task is quite demanding and depletes energy quickly.

Approximately 78% of the farming population reported feeling uncomfortable while strolling in mercy land. Due to the fact that the entire field is covered in mercy land, and it is quite impossible to keep balance while walking. Foot gets trapped in watery surface and becomes stuck, it often takes a lot of power to pull the leg free and continue forward in these water bodies.

Around 32 percent of farmer reported numbness and pain in their hand in the process of harvesting. Each plant must be harvested from the top (crown), as they float on the water's surface. They hold the plant in one hand while plugging the fruit with the other hand's finger and thumb. Forearm pronation and supination were frequently seen while holding the plant with hand in search of mature fruit to harvest. The water chestnut fruit is located below the crown piece; therefore, this is done to see the fruit. This action was carried out frequently as it was repeated with each plant.

Around 12 percent of farmer reported the instances of insect bite and 10 percent of farmer reported cut in leg due sharp object in the past. The water bodies usually have muddy water and farmer cannot see the bottom surface that can have any sharp object as well as harmful insect. The pond environment is unhygienic due to mud, thorns/prickles (Novaes et al., 2017). Water bodies can have harmful insects and reptiles like snake and leech (Jonk) inside the muddy soils (Parmanad & Sahu, 2019).

Following the field study, different insights into the various cultivation phases were acquired. According to farmers, there are disparities between the various stages of cultivation in terms of each farmer's ability to work, the amount of physical effort required, the tools and work accessories accessible, and the difficulties the farmers confront (as shown in Table 3).

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Table 3. Comparison of working capacity, physical demands, tools used and challenges faced in differe
of the cultivation process

Cultivation practices	Area (Bigha/ person/ day)	Physical exertion	Tool /accessories used	Challenges	Standard tool available	Remark
Seedling preparation		less	no	Adoption of awkward posture	no	
Cleaning	0.06	high	Bamboo, sickle	Immersed in water for long duration, itching unsafe situation (cut, insect bite, etc.), pain in shoulder, hand and leg,	costly machines	Needs intervention in terms of hand-tools and personal protective measures
Sowing	1	less	no		no	
Interculture		medium		Adoption of awkward posture, immersed in water		
Harvesting	0.10	high	Boat, locally made floating structure	Repetitive hand movement, awkward posture, water contact for long duration and fear of insect bite.	no	Needs intervention in terms of hand-tools, personal protective measures, appropriate floating devices etc.

Despite the fact that the water chestnut plant has high medicinal value and source of income for the farmers, these crops are on way to extinction. The lack of popularity in water chestnut cultivation can be attributed to various factors such as challenging cultivation techniques, unfavorable and unhealthy farming conditions, limited market demand, absence of tools and work accessories that could aid in cultivation, among others.

Following an in-depth field study and extensive interactions with farmers, the research findings have led to the identification of key requirements for improving the cultivation process of aquatic crops. It has been observed that a floating device is highly desirable to enhance efficiency during cleaning and harvesting activities in water-bodies. The floating device would offer better maneuverability and ease of use, thereby reducing the labor-intensive efforts required by the farmers.

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Additionally, there is a pressing need for a reliable personal protective equipment (PI can safeguard the farmers from potential hazards in the water bodies, including waterborne insects and other contaminants. Such a PPE would not only protect the farmers' health but also contribute to maintaining better hygiene during prolonged exposure to unhygienic water conditions.

Furthermore, to address the challenges faced during manual plucking, an innovative plucking aid is crucial. This plucking aid would be designed to optimize the thumb joint angle, reducing the strain and fatigue experienced by the farmers during the plucking process. By providing a more ergonomic solution, the plucking aid aims to enhance the farmers' comfort and productivity, resulting in improved overall harvesting efficiency.

2.6 Conclusion

Water chestnut cultivation holds remarkable potential as a significant source of livelihood. Within the cultivation journey, tasks like cleaning and harvesting emerge as particularly challenging and time-consuming. Regrettably, aquatic farmers lack standardized tools and equipment for the various activities linked to water chestnut cultivation. A significant portion of these tasks is carried out using bare hands and legs. The study underscores the pressing need for interventions across all stages of water chestnut cultivation, especially in the intricate cleaning and harvesting phases. While the implementation of robotics or large machinery isn't practical due to the aquatic farm's scale and the associated costs, there's a clear opportunity for manual or semi-mechanical tools and implements to aid farmers in various cultivation processes. The focus should be on user-centered design interventions that prioritize local manufacturability and maintenance while considering human factors in the different stages of aquatic crop cultivation.

In this chapter, physical properties, growing environment and steps involved in the cultivation of the water chestnut has been discussed, to get insight of the problem faced by the growers. Insights of the current research would be helpful in the development of tools or techniques to address various challenges faced by the farmers and reduce the drudgery of the cultivators. Scientific community should come forward to carry out research and development activities in the domain of aquatic agriculture most specifically water chestnut for improvement of cultivation practices. These initiative would to address the drudgery of the farmers and ensure enhancement of the overall productivity, and safety.

In conclusion, the research underscores the necessity of developing and implementing these three vital tools - the floating device, the personal protective equipment, and the plucking aid - to

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mitigate the challenges faced by farmers engaged in the cultivation of aquatic crops interventions hold the potential to revolutionize the agricultural practices in water-bodies and significantly enhance the well-being and productivity of the farmers.

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3 Design and development of a Floating Device for Aquatic Agriculture Workers of Northeast India: A systematic design process

Abstract

The cultivation of aquatic food crops presents unique challenges due to the need for farmers to work in water-bodies. In order to address the labour-intensive nature of these cultivation practices and improve overall productivity, the design and development of a floating device specifically tailored for aquatic farming was undertaken. This research aimed to create a cost-effective and efficient solution that would enhance the productivity and reduce the physical strain on farmers. The development process involved extensive exploration of unique design concepts and materials suitable for the fabrication of the floating device. The prototype was built and tested in real field conditions to evaluate their performance and functionality. The feedback received from farmers played a crucial role in refining the design and optimizing its effectiveness. Key factors considered during the design phase included stability, maneuverability, and durability of the floating device. The final design of the floating device offers improved comfort and safety for farmers, allowing them to carry out harvesting activities with greater ease and efficiency. Additionally, the device promotes land use efficiency by enabling cultivation in waterlogged areas and wetlands that were previously underutilized. This research contributes to the advancement of sustainable agricultural practices by providing a practical solution for the cultivation of aquatic food crops. The developed floating device offers promising opportunities to enhance productivity, reduce physical exertion, and improve the livelihoods of farmers engaged in aquatic farming.

Keywords: aquatic farming, innovation, human factors, design, agriculture, MSD

3.1 Introduction

The farmers grow the water-chestnut crop in the water bodies. The cultivation of water chestnut is completely different from the any other terrestrial crops. The farmers use different primitive tools for performing agricultural activities in the aquatic settings, one such aid is floating device.

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Farmers also reported discomfort in walking in marshy land, as the water bodies is c with marshy land, and it is very difficult to keep balance while walking. Many times, they get cut in leg due sharp objects in the water body. The major challenges come when they go in depth, when the water level is high (above the chest level). The use of boat is also difficult as they cannot perform the agriculture activities while sitting on the boat. Farmer sometimes use frugal design to float on water. Due to improper fabrication through ‘Jugad’ technique, they have to face many physical difficulties (awkward posture and discomfort) and even accident due to imbalance. These floating arrangements are also not durable and thus the farmers need to make a new one during every season. The aquatic farmers need a standardized floating device which is affordable, long-lasting, and suitable for their required aquatic agricultural tasks/ activities.

As the growing environment is water the tools and technique are different from what the farmers use for the cultivation of terrestrial crop. Farmer faces many challenges in the cultivation of the aquatic crop. The cultivation of these crops includes several processes, such as seedling preparation, water body cleansing, transplanting of seedlings, inter-culture, and fruit harvesting. One of the difficulties is that they have to remain in pond for long hours without any sort of safety equipment or harvesting tool. That could cause several of infections. They have to stand and work in an uncomfortable position when bending and selecting the plant or plucking the fruit, and it is difficult to maintain balance while walking since the water bodies are covered in marshy land.

3.2 Need of the floating device

Agricultural activities in water bodies are challenging due to the unique environmental and working conditions. One of the main challenges is the need to harvest crops by going near each plant. This can be difficult when the plants are dispersed throughout the water body and require a lot of time and effort to reach. Additionally, when the water level is high, it becomes even more challenging to reach every corner of the farm to perform agriculture activities. In such scenarios, a floating aid is used to help farmers perform these activities more efficiently. These floating aids are designed to float on the water surface at high water levels, enabling farmers to move around the farm and access every corner easily.

The use of a floating aid in water-chestnut cultivation activities provides several benefits. Firstly, it enables farmers to sit/support on the aid and perform agriculture activities more efficiently, saving time and effort. Secondly, it allows farmers to access areas of the farm that would be difficult to reach, such as areas with high water level.

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One of the major challenges that farmers face is the difficulty in walking on marshy la ground can be soft and muddy, making it challenging to maintain balance while walking. Additionally, the foot can easily sink into the mud, requiring a significant amount of force to lift and move the leg, leading to fatigue and exhaustion. This difficulty in walking can be particularly challenging when farmers need to move from one plant to the other to perform agriculture activities such as harvesting or inter-culture. In such cases, farmers may need to exert a considerable amount of effort to move around the farm, leading to fatigue and a decrease in productivity. A floating aid can help alleviate these challenges by providing a stable and buoyant platform for farmers to sit on while performing agriculture activities. The floating aid allows farmers to move around the water bodies with ease, reducing the amount of effort required to walk and perform agriculture activities. This, in turn, reduces fatigue and improves overall efficiency.

While fishing is also performed in water bodies, a similar type of device is required for performing agriculture activities. In the case of fishing, a boat is generally used, which provides a stable platform to catch fishes. However, for aquatic cultivation, boat would not be helpful, because the farmers have to adopt awkward posture to pluck the fruit. On the other hand, a floating aid is preferred as it is more maneuverable and can access more areas of the farm.

In conclusion, the use of a floating aid is essential for performing agriculture activities in water bodies especially for aquatic crops. It enables farmers to move around the water bodies more efficiently, access every corner of the farm, and ensure balance and comfort while working. Additionally, it provides a stable platform from which to perform agriculture activities, making it more efficient and less labour-intensive. Therefore, the use of floating aids is critical for the success of agriculture activities in water bodies, and efforts should be made to design and construct these aids to be as efficient and effective as possible.

3.3 Challenges in the current floating device

Floating aids are structures designed to provide buoyancy and stability to farmers in aquatic environments. These aids constructed using various materials and designs, with the aim of providing a stable and durable structure capable of withstand human weight in the aquatic environment. However, certain design and construction factors can compromise the durability and functionality of these aids, rendering them ineffective or even dangerous to use.

One of the key issues with the traditional floating aids is the use of wooden planks or bamboos to connect the two containers. These materials are prone to weathering and breakage due to regular

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immersion in water, compromising the overall structure of the floating aid. Wooden plan bamboos are also susceptible to rot and decay, further weakening the structure over time. This can lead to sudden collapse or toppling of the floating aid, potentially causing harm to the farmers. Therefore, it is essential to consider the type of materials used in the construction of floating aids, ensuring they can withstand prolonged exposure to water and environmental factors.

Another issue with the design of floating aids is the use of thread or rope to tie the bamboo or wooden planks with the containers. These materials can become loose and flimsy with use, adding to the structural instability of the floating aid. The use of thread or rope can also lead to corrosion or rusting, further compromising the durability of the overall structure. Durability of the overall structure is always a matter of concern when it comes to constructing floating aids. Sudden dismantle or breaking down of components can lead to sudden unbalance and toppling of the structure, causing potential harm or damage. Therefore, it is essential to ensure that the design of the floating aid is well-balanced and structurally sound, with all components securely fastened and resistant to wear and tear.

One additional issue with the locally made traditional floating aids floating aids is the shape and sharp corners. The flat shapes with sharp corners can lead to entanglement in the mesh or network created by plant stems, further compromising the functionality and effectiveness of the floating aid. This can make it difficult to move or adjust the position of the floating aid, leading to further damage or instability. Therefore, it is crucial to consider the shape and design of floating aids, ensuring they are streamlined and free from sharp edges or corners that can snag on plant stems or other obstacles.

In conclusion, the design and construction of floating aids requires careful consideration of numerous factors, including the materials used, the type of connectors used, and the overall structural soundness of the device. The use of robust and durable materials, along with well-designed connectors and regular maintenance, can help ensure the longevity and functionality of floating aids. Additionally, the shape and design of the aid should be carefully considered, with a streamlined and obstacle-free design being preferred. By addressing these design and construction issues, it is possible to create effective and safe floating aids that can withstand the rigors of the aquatic environment.

Considering above points the current study has been done to know the challenge in the cultivation and to design and develop a floating device for the farmers so that they can perform various cultivation practices. In the literature it was found that most of the research were done

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towards the design and development of the terrestrial crop and there is lack of research design and development of the aquatic crops. The present research aimed to design and develop a floating device to facilitate aquatic agricultural activities, reduce the farmer's drudgery and can be used in cultivation process by the farmers of the aquatic crops on high level as well as low water level in the water bodies.

3.4 Methodology

3.4.1 Development process of the floating device

In the current research, the 'Design Thinking' method introduced by the Stanford D'School (Brown, 2008) has been used to design and develop the floating device. The process of 'Design Thinking' has five steps that include Empathize, Define, Ideate, Prototype and Test (as shown in Table 4).

Table 4. Design thinking steps in context of development of floating device

Empathize	Define	Ideate	Prototype	Test
• Farmer selection • Interview • Plant properties • Current tools and devices used	Farmer use primitive tools to float on the water bodies that were not durable, comfortable and had high chance of failure/breaking. Hence to solve these problem a floating device was required.	Concept generation (brainstorming) and concept selection (Pugh chart)	• Digital prototype was made using Solidworks • Posture analysis through DHM was done • alpha and beta prototype were made	• Perceived discomfort • Productivity • Feedback and modification

3.4.2 Selection of farmers

A total of 30 adult farmers who cultivate water chestnuts and range in age from 18 to 60 years old were purposefully chosen from three separate locations in North Guwahati, Assam, India. Five years of minimum cultivation experience, good health, and the absence of any long-term illnesses were the inclusion criteria for the selection of farmers. These agriculture tasks are primarily performed by the male employees. Therefore, only male farmers were chosen as research participants. Ethical clearance from the institute ethical community were taken from

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the Institute. It was an anonymous survey, and the survey's participation was entirely vc without any incentives.

The subjects received a thorough explanation of the experimental plan and their role in the study, and they have provided consent to participate in the study. The methodology was reviewed and recommend by the Human Research Ethics committee of Indian Institute of Technology, Guwahati. Personal and demographic data such as place of birth, gender, height, weight, and education, as well as job experience (years), daily working hours, working conditions, job satisfaction, and perceived musculoskeletal pain, were gathered through questionnaire-based interviews and direct observation of the various cultivation processes. A thorough investigation of body part discomfort was also conducted using a modified Nordic questionnaire (Kuorinka et al., 1987), which took into account data on job stress, work environment, and body part discomfort.

3.4.3 Interview with the farmers to identify the current scenario, problem and needs identification

Focus groups, consumer surveys, and interviews are the techniques frequently produce qualitative information about customer preferences and wants (Geyer et al., 2018; Horvat et al., 2019). Such information is helpful during the opportunity identification stage to comprehend consumer wants and create product concepts. The explorative research method was adopted for the field survey that included unstructured interviews using an open-ended questionnaire, direct observations, and documenting (photography and videography) to get an insight of challenges in cultivation process, problem faced with the locally made floating device. In the interview we also focused on the need of the farmers for the suitable design.

3.4.4 Study of plant properties

Various plant properties needed to be considered in order to assess the feasibility of the developed product, including its shape and size. In the study, plant properties such as length, width, and growing environment of the plant were studied for the design of floating device. Under water images of the water chestnut field were taken with the help of a camera and a waterproof protecting cover. The image was helpful to understand the growth of plant under the water.

3.4.5 Different types of devices used for the cultivation

Various online data bases were explored for the tools and devices used in the cultivation of aquatic crop specifically for the water chestnut. The purpose was to study the differences and similarities

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between different available tools and implements, and to identify challenges and s improvement in the design of new product.

3.4.6 Concept generation

In this research for concept generation, we had used brainstorming methods. It is believed that more the ideas the better would be the success of the product because different feature can be combined from different ideas (Wentworth & Osborn, 1955; Yang, 2009). Limited time was provided for concept generation because it resists the designer to analyse the concept at the ideation phase (Wentworth & Osborn, 1955). Steps of brainstorming were followed for the concept development. The problems were communicated to the designer group, tasking them with the development of suitable concepts.

3.4.7 Concept selection

A crucial step in the product development process is concept selection. After generating maximum number of concepts, Pugh chart method was used for selecting the suitable concepts. Pugh chart is a standard method used by many researchers for concept selection in the past (Arunachalam et al., 2014; Nair et al., 2022; Verma & Karmakar, 2021).

3.4.8 Creation of mock-up

Before creating the prototype, a virtual mock-up of the chosen floating device/ concept was created. SOLIDWORKS (V16) software was used to produce a three-dimensional, solid CAD model, and the SOLIDWORKS platform was also used to create and assemble numerous product components. All the components of the floating device were drawn in two dimensions and given measurements (in mm).

3.4.9 Prototype development

The choice of material is a crucial step in the product development process since it affects a product's functionality and ability to be produced at a reasonable cost. It is generally acknowledged that a manufactured product's ultimate cost is mostly decided during the design phase.

The fabrication of the floating device was achieved with the help of Fiber Reinforce Polymer (FRP). The FRP product is waterproof, lightweight, and easy to develop. The creation of any novel FRP product typically entails a three-step process. Firstly, a pattern is crafted, which serves as the blueprint for subsequent steps. Next, a mold is meticulously prepared based on the pattern, allowing for the production of the desired product.

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3.5 Field Evaluation of developed floating device.

The field evaluation of the developed floating device was conducted during September-October 2022. The farmers were asked to harvest water-chestnut fruit using two methods viz. by use of developed floating device and existing traditional device.

3.5.1 Perceived Discomfort rating

Body part discomfort and overall discomfort ratings were determined using modified version of Bishop-Corlett body map and the Borg CR 10 scale (Borg, 1990). At the end of each task, participating farmer rated body part discomfort and whole-body discomfort. The subject rated the scale ranged from 0 to 10 (0 – no discomfort and 10 – extremely discomfort).

3.5.2 Physical exertion estimated by heart rate

The study was conducted in the water-chestnut farm, and heart rate was measured using polar heart rate monitor (Polar RS800CX). A comparison of heart rate for a farmer while using the newly developed floating device and traditional floating device was done in actual field condition. Physiological parameter (heart rate) of subject was recorded before starting the task, during the task and after the task.

The experiment procedure was explained to the farmers. The farmers were told to take rest for 5 min before the start of the experiment and their resting heart rate was measured. In next step, farmers were told to perform the harvesting activity with the traditional floating device for 30 min and the working heart rate of the farmer was recorded. After the harvesting activity, the same farmer was asked to take rest until he had achieved the resting heart rate. The same steps were repeated with the new floating device.

3.5.3 Productivity

The performance parameter of the floating device, specifically the harvesting rate (number of fruits harvested per hour), was measured for the farmers using both the traditional and newly developed floating devices. The harvesting rate was compared between the traditional and newly developed floating device with the 10 farmers. The farmers were told to harvest the fruit for 1 hour with traditional device and the same farmer was asked to harvest the fruit with new floating device next day. Care was taken that the farmer should harvest new area of the field where harvesting is not done before, so that the density of fruit would remain the same. The weight of harvested fruit was measured and recorded for the comparison.

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3.5.4 Usability testing and farmer's feedback

User feedback was collected to check the efficacy of the developed product. Fifteen farmers volunteered to participate in the study. The novel floating device- usability was evaluated using the System Usability Scale (SUS) (Brooke, 1996). A fresh group of fifteen (15) male farmers (who did not participate in the previous survey) were selected for usability evaluation and gathering feedback regarding the developed prototype. The developed prototype was given to the farmers individually for their use and interactions. Their feedbacks were collected along with the rating on SUS. The SUS scores were interpreted in terms of adjective rating and acceptability (Bangor et al., 2008, 2009; Verma & Karmakar, 2021).

3.6 Results

3.6.1 Demographics or the personal information of the farmers

The average age of farmers was 40.9 (± 9.84) years. The average weight of the farmer was found to be 66.3 (± 9.65) kg. 43.3 percent of the farmer were illiterate further 26.6, and 30 percent of the farmer took education up to primary and secondary levels respectively.

Table 5. Demographic details of farmers

Variables	Mean (SD)
Age	40.9 (9.84)
Weight	66.3 (9.65)
Education	freq (%)
Illiterate	13(43.3)
Primary	8(26.6)
Secondary	9(30)
Marital Status (freq)	freq (%)
Married	24(80)
Not married	6(20)
Smoking (freq)	freq (%)
Yes	7(23.3)
No	23(76.6)

Table 6. Work related details

Variables	Mean (SD)
Cultivation area (Bigha)*	5.9 (3.38)
Work experience (years)	14.6 (6.4)
Working hours per day	5.2 (1.5)
Number of breaks in a day	1.2 (0.4)
Maximum depth of Pond (ft)*	7.1 (1.7)

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Job Satisfaction	freq (%)
Low	22 (73.3)
Moderate	6(20)
High	2 (6.6)

(1bigha = 1400 m^2, 1ft = 0.3 m)*

3.6.2 Discomforts in various parts of the body

The percentages of the participants with body parts discomfort at the neck, shoulder, upper back, elbow, wrists lower back, hips, knees and ankles during the last 12 months were 45%, 62 %, 22%, 40%, 54%, 74%, 60%, 58% and 20% respectively. The pain affected their normal activities both at work and outside their work. During the last 12 months, the numbers of participants whose normal activities were disrupted due to discomfort at the neck, shoulder, upper back, elbow, wrist, elbow, lower back, hips, knees and ankle/feet were 32%, 48%, 10%, 10%, 40%, 70%, 32%, 40% and 20% respectively. The occurrence of discomforts/ pain in various body parts of the participants and thereby, disruption of their regular activities at the workplace or outside the workplace has been shown in Figure 17.

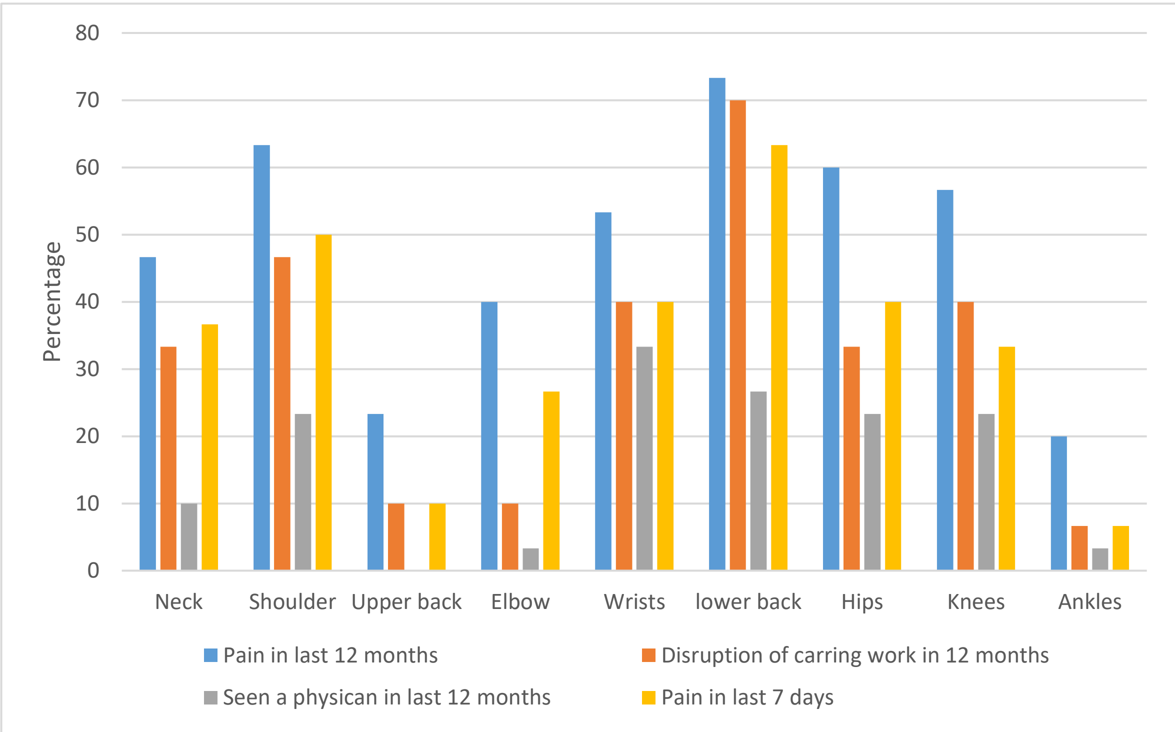

Figure 17. Body parts discomfort and disruption of work as reported by the participants

3.6.3 Tools used in harvesting activities

Figure 18 shows the tools and techniques employed by farmers during water-chestnut fruit harvesting include fastening the lower part of their pants before entering the water body, carrying

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a floating utensil and a plastic sack, and utilizing a locally crafted floating device. These collectively facilitate their efforts in harvesting water-chestnut fruits from the aquatic environment.

Tie the lower part of pant   Floating utensil   Plastic sack   Locally-made floating device

Figure 18. Tools and technique used in the harvesting of water-chestnut

3.6.4 Floating device used in other parts of country for harvesting

The Figure 19 shows several floating devices that have been identified and used in other regions of the country. In certain areas, a small boat is also favoured, although its usage often requires uncomfortable postures and frequent breaks. Other alternatives include utilizing earthen pots or plastic containers attached to bamboo. However, these options have their limitations, as they lack durability and often encounter obstacles due to the presence of plant branches.

Figure 19. Floating device used in different regions of the country

The major problem that was found in the harvesting is the design and discomfort due to the frugal design of the floating device. The structure of the device is made from bamboo stick and oil tin. They cut the bamboo in 1 m length and divide it into two equal parts from the middle. Farmer tie the bamboo and the oil tin with the help of rope. The oil tins were fastened at both end of the bamboo. It was found that major challenge was in the whole cultivation process was in case of harvesting and cleaning of pond. Harvesting is the main component of any crop production. It requires utmost care and handling of fruit the farmer has to pick each plant and hold the, the fruit contain thorn that can be harmful for the farmer.

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3.6.5 Under water plant Images

The process of capturing plant images involved the use of a waterproof cover to protect the mobile camera. The underwater plant images have been shown in Figure 20. These images turned out to be pivotal in shaping the design of the prototype. By meticulously documenting the plant's physical characteristics, growth patterns, and how it interacts with its environment, the images provided valuable insights for the development of an effective and efficient floating device. The plant was taken out carefully from water, Figure 21 shows the water chestnut plant expansion under the water.

Figure 20. Under water plant image

Figure 21. Plant image to showing expansion (left), Digital representation of plant under water (right)

3.6.6 Farmers needs

Need identified for the development of the new floating harvester-

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- The floating device should have smooth surface so that the farmer can manouver in the waterbodies.
- The farmer should get sufficient buoyancy to remain afloat on the water's surface.
- The width should be less than 50 cm as the space to walk in the water bodies with the standing crop
- The device's length should be designed to enable the farmer to reach the front end easily and address any obstacles encountered during movement.
- As the activity is performed for 5-6 hours a day, a comfortable sitting posture and a back rest is required.
- The device can be used in the high as well as low water level.
- Ensuring the device's water resistance is of utmost importance
- Easy to carry, as the device needs to be conveniently transported between various locations.

3.6.7 Concept generation

Taking into careful consideration the distinct needs of the farmers engaged in water chestnut cultivation, a range of innovative concepts were generated also shown in Figure 22. These concepts aimed to address the challenges faced by the farmers in various stages of water chestnut cultivation, including cleaning, harvesting, and overall manoeuvrability in water bodies.

Figure 22. Concept through brainstorming

Among the various concepts generated, a few were selected for further exploration and feasibility, the selected concept were shown in Figure 23.

	A floating base to accommodate the farmer and an attachment to lift the water-chestnut plant.
	Advantage 1. comfortable sitting posture

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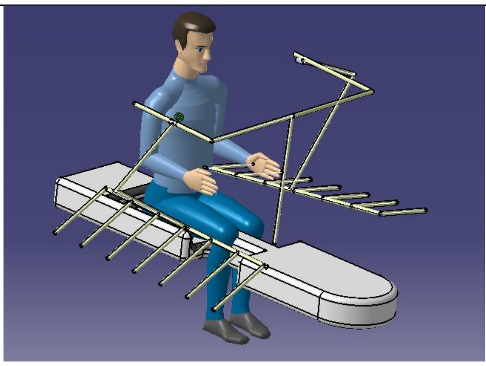
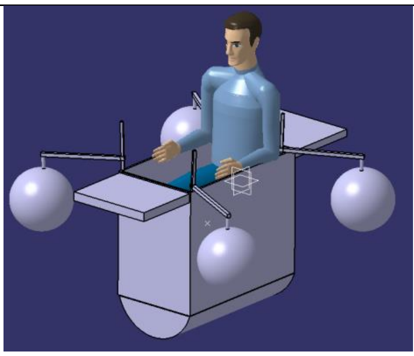
	2. Free movement 3. attachment to lift the plant
	Disadvantages 1. Balance would be difficult as the centre of buoyancy will be below the centre of gravity
	A small boat like structure supported with four balls.
	Advantage 1. Balance would be good 2. Protection from water-insect
	Disadvantages 1. Difficult to manoeuvre 2. Awkward posture while plucking 3. High puling force due to water and plant resistance
	A floating base, which has two balls that are attached in front and back.
	Advantage 1. Good balance 2. Ease in manoeuvrability 3. Good posture
	Disadvantages 1. No protection from water contact and insect
	A frame like structure with detachable front and back attachments
	Advantage 1. Ease in manoeuvrability 2. Good posture
	Disadvantages 1. More hindrance by the plant, hence difficult in maneuverability 2. Bad thigh support
	Advantage 1. Safety from water insect

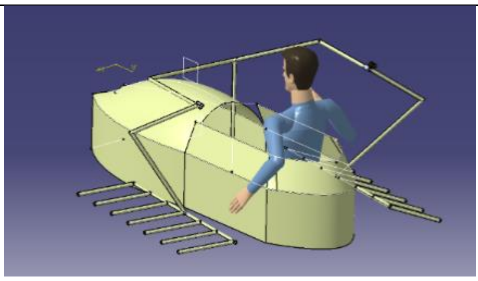
	Disadvantages 1. Difficult in manoeuvrability 2. Awkward working posture 3. Heavy weight

Figure 23. Different digital concepts

The device cannot help in saving the farmer from the contact of water. The water contact of the farmer can be avoided with the use of special designed Personal Protective Equipment such as Wader. This PPE is a kind of half body suit could be used to save from water contact and adverse effect of water.

3.6.8 Concept Selection

During the concept selection process, careful consideration was given to the needs and criteria expressed by the farmers. A systematic approach, such as the Pugh chart shown in Table 7, was utilized to evaluate and compare different concepts based on their alignment with the farmers' requirements.

Table 7. Pugh chart matrix for comparative analysis

Design Criteria	**Weight**	**Design Concepts**					
		1	**2**	**3**	**4**	**5**	**6**
Balance	**3**	**0**	+	+	**0**	+	+
Less Hindrance by plant	**3**	**0**	--	++	+	++	-
Buoyancy	**3**	**0**	+	**0**	**0**	**0**	+
Working posture	**3**	**0**	-	**0**	**0**	**0**	**0**
Low cost	**2**	**0**	+	**0**	++	**0**	**0**
Portability	**2**	**0**	**0**	**0**	+	**0**	**0**
Safety	**2**	**0**	-	+	++	+	**0**
Ease of use	**1**	**0**	**0**	**0**	**0**	-	**0**
Comfort	**3**	**0**	+	+	**0**	-	-
	+	**0**	**11**	**14**	**7**	**11**	**6**
	-	**0**	**11**	**0**	**0**	**4**	**3**
Total		**0**	**0**	**14**	**9**	**7**	**3**

3.6.9 Prototype development

Based on the field study following dimensions of the floating device is made shown in Figure 24.

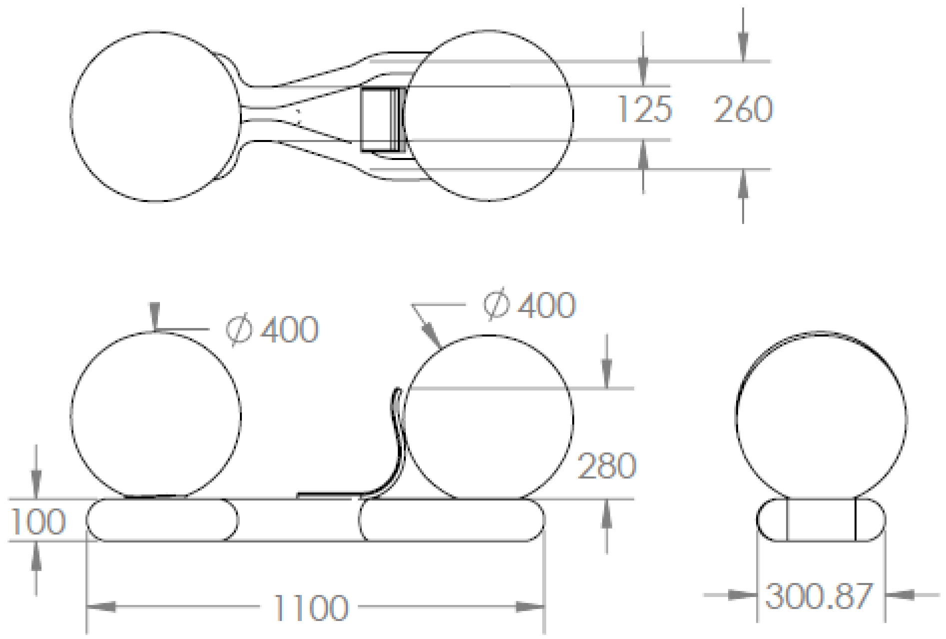


Figure 24. Dimensions (in mm) of the floating device

3.6.9.1 Buoyancy force calculation

Archimedes' principle states that the upward buoyant force that is exerted on a body immersed fully or partially in a fluid, is equal to the weight of the fluid that the body displaces. A man of 70 kg with the weight of the floating device of 5-7 kg will require displacement of 35 to 40 liters' water to generate buoyancy force for floating on the water body. In this condition, the device will be submerged up-to height 26 cm from the bottom of the floating device to maintain the equilibrium between downward weight (human and device) and upward buoyancy force.

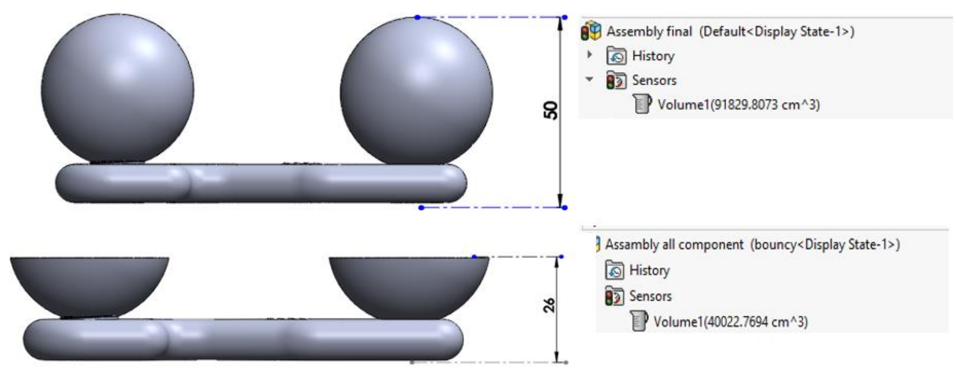


Figure 25. Volume displaced by the floating device

The floating device alone can displace a total volume of 91 litre (91800 cm3) when fully submerged at a depth of 50 cm, and it displaces 40 litre of water at a depth of 26 cm also shown in Figure 25.

3.6.9.2 Development of alpha-prototype

The alpha prototype is the initial version of the product that is created during the inital stages of development. Its primary purpose is to test and validate the core functionality and basic design concept. The fabrication of the alpha prototype involves translating the product's design specifications into a tangible form. The fabrication of the prototype was done with the help of scrap materials, the image of alpha prototype has been shown in Figure 26.

Figure 26. Alpha prototype of the floating device and its field-testing

3.6.9.3 Development of beta prototype

Once the alpha prototype has undergone testing and necessary improvements, the next step is to create a beta prototype. The beta prototype is an enhanced and more refined version of the product compared to the alpha prototype. It incorporates the modifications and enhancements suggested during the alpha testing phase.

The fabrication process of a Fiber Reinforced Polymer (FRP) product involves several steps to ensure the creation of a high-quality and durable final product. The fabrication process is also shown in Figure 27. Here is a general overview of the FRP manufacturing process:

Design and Pattern Development: The first step is to develop a design for the desired FRP product. This involves conceptualizing the shape, size, and specifications of the product. Once the design is finalized, a pattern or Mold is created. The pattern serves as a template for the subsequent manufacturing steps.

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Mold Preparation: Using the pattern, a Mold was prepared. The Mold can be made of materials such as metal or composite materials. The Mold was carefully crafted to replicate the exact shape and dimensions of the desired FRP product.

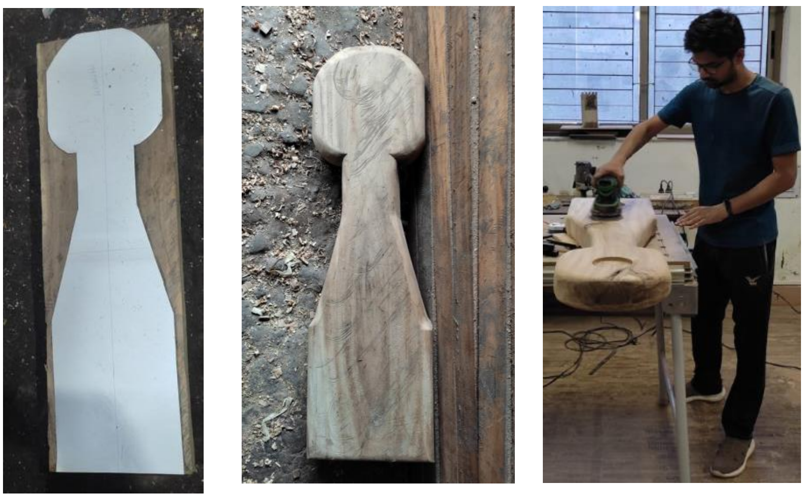
Material Preparation: The FRP material consists of a combination of a polymer matrix, typically resin, and reinforcing fibres such as fiberglass, carbon fibre, or aramid fibre. Here, fiberglass was used for the development of floating device. The resin was mixed with a hardener or catalyst to initiate the curing process. The reinforcing fibres were typically pre-impregnated with the resin to ensure proper adhesion and distribution.

Layup: In this step, the reinforcing fibres are laid onto the Mold surface in a specific pattern or orientation. This process is known as layup. The fibres were manually placed on the Mold.

Resin Infusion: Once the reinforcing fibres are in place, the resin is applied to impregnate the fibres and bond them together. The resin is carefully distributed to ensure complete saturation of the reinforcing fibres, eliminating any air pockets or voids.

Curing: After the resin infusion, the curing process begins. The product was left to cure at an appropriate temperature and for a specific duration. This allows the resin to harden and bond with the reinforcing fibres, forming a solid and robust composite structure.

Demoulding and Finishing: Once the curing was completed, the FRP product was carefully demoulded from the Mold. Any excess material or flash was trimmed or removed.



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(a) Wooden piece with required dimension for making pattern

(b) Shape is given to the wooden piece with the help of cutout

(c) Smoothing the surface of wooden base with sand grinder

Mold preparation with the help of wooden pattern

Drying of Mold

After drying product is started to develop

Joining the upper half and lower half of the product

Final prototype of base

Preparation of Mold with the help of pattern

Preparation of product with the Mold of the ball

Fixing the Mold

Figure 27 Fabrication process using FRP and initial testing of prototype

Figure 28. Initial prototype and testing with farmers for feedback

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3.6.10 Iteration in the prototype after feedback

Once the initial prototype was developed also shown in Figure 28, it underwent preliminary trials to gauge its performance. Based on the invaluable feedback received from the farmers who participated in these trials, a series of three iterations were subsequently carried out. These iterative phases aimed to enhance the design, functionality, and overall effectiveness of the prototype, taking into account the practical insights provided by the farmers. This iterative approach not only enabled the identification and rectification of any shortcomings but also facilitated the incorporation of user-centric improvements, resulting in a refined and more efficient final product. The collaborative process between the researcher, and the farmers throughout these iterations played a pivotal role in achieving a prototype that aligns closely with the practical requirements and preferences of the end users.

1. Reducing the thickness of the base – Upon analysis, it was determined that a reduction in thickness would not only enhance the device's balance but also result in cost savings due to reduced material usage. Additionally, this modification would contribute to a decrease in the overall weight of the floating device, further improving its maneuverability and usability.

2. Covering the front portion of the prototype – The existing gap between the ball and base at the front was identified as a hindrance, as it allowed plants to become entangled. By introducing a cover in this area shown in Figure 29, the obstruction caused by plant entanglement would be minimized, subsequently reducing the effort required by the farmers during operation.

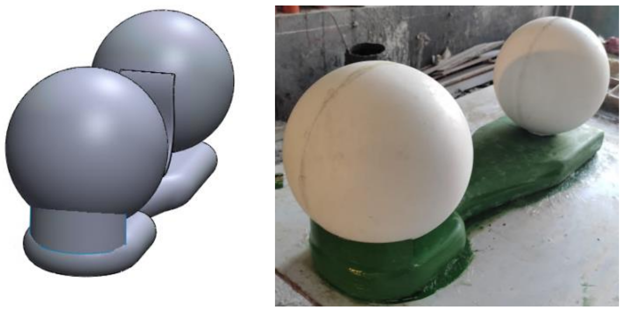

Figure 29. Iterations in the prototype (covering front gap)

3. Reducing the length of the prototype – Feedback from farmers highlighted that they encountered difficulties in maneuvering and turning the device during task performance. Addressing this concern, a shorter prototype design was developed (reducing the length

by 10 cm) to enhance the device's agility and maneuverability in the water bodi final prototype after modification also shown in Figure 31.This adjustment aimed to create a more user-friendly experience for the farmers by increasing their control and ease of movement during the harvesting process.

Figure 30 Iterations in the prototype (length reduction)

Figure 31. Developed floating device after iterations

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3.6.11 Usability testing and feedback from users

An SUS score of 72.25 was acquired, reflecting a "good" and "acceptable" usability rating. Ratings for different SUS items can be found in Table 8.

Table 8. System usability scale

Items	User-1	User-2	User-3	User-4	User-5	User-6	User-7	User-8	User-9	User-10	AVG
1. I think that I would like to use this product frequently.	4	3	4	3	3	2	4	4	5	4	
2. I found the product unnecessarily complex.	2	1	1	2	1	2	2	1	1	3	
3. I thought the product was easy to use.	4	3	5	4	3	2	2	1	4	3	
4. I think that I would need the support of a technical person to be able to use this product.	2	1	2	2	1	1	2	1	1	2	
5. I found the various functions in this product were well integrated.	2	3	3	2	4	2	2	3	2	1	
6. I thought there was too much inconsistency in this product.	1	2	2	1	2	1	1	2	1	3	
7. I would imagine that most people would learn to use this product very quickly.	4	5	4	4	5	4	4	3	4	4	
8. I found the product very cumbersome to use.	2	2	1	2	3	1	3	2	3	2	
9. I felt very confident using the product.	3	4	3	4	4	4	5	2	4	4	
10. I needed to learn a lot of things before I could get going with this product.	1	1	1	2	1	1	1	2	1	1	
SUS RAW	29	31	32	28	31	28	28	25	32	25	
Final SUS	72.5	77.5	80	70	77.5	70	70	62.5	80	62.5	72.25

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3.6.12 Field trials

The developed prototype was tested in the actual field condition with the farmers. Initially the first impression of the farmers was reported, and they were happy to see the product and exited to test the prototype in the field. The performance of the developed product was measured in terms of productivity (harvesting rate i.e., kg/hour), heart rate and body part discomfort.

3.6.12.1 Productivity/ performance of the aquatic farmers

The performance of the developed floating device was found satisfactory under the prevailing field conditions. Field evaluation of developed and traditional floating device was done with 10 farmers. The average harvesting rate increased by 15 percent with the developed floating device compared with the harvesting with the traditional floating device. The harvesting rate of individual farmers (shown in Figure 32). The increase in productivity was possible because of the developed floating aid has increased the comfort and maneuverability in the water-chestnut field. The waterbodies get covered with the expansion of the water-chestnut plant because of it the plant stem provide a hindrance to the motion of the tradition floating device. While the developed floating device has smooth surfaces and round curves, and it can easily get past to the dense covering of water-chestnut crop. Wilcoxon signed-rank showed that the harvesting rate (kg/hr) with developed floating device was significantly higher ($Z = -2.70$, $p<0.05$) than the traditional one.

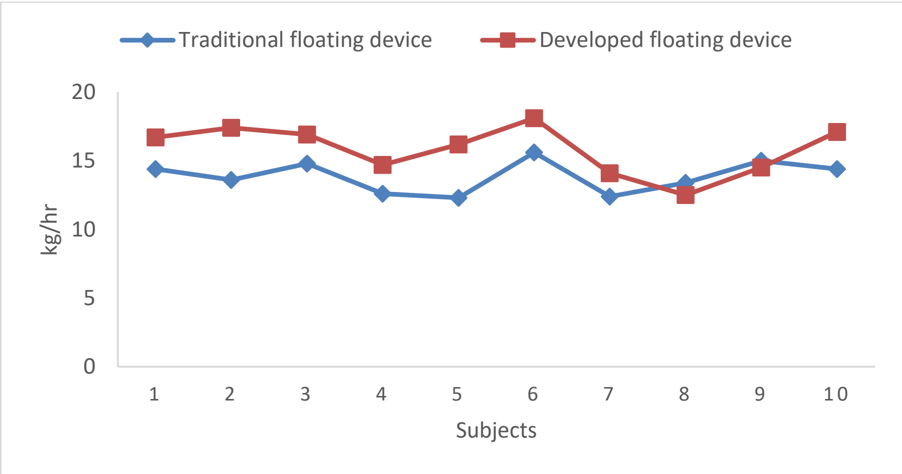

Figure 32. Comparison of harvesting rate

3.6.12.2 Physical exertion estimated by heart rate

Heart rate monitoring is a valuable tool in assessing physical exertion and energy expenditure. By tracking heart rate during different activities or work tasks, researchers can gain insights into their cardiovascular effort and adjust their workload accordingly. Maintaining an appropriate heart rate

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range ensures that energy is utilized effectively without excessive strain on the cardiov system.

The average resting heart rate of 10 farmers was 78.5 (± 7.5) beats/min, while the average working heart rate with the traditional floating device was found to be 117.75 (± 5.4) beats/min. On other hand, the average working heart rate during harvesting with the developed floating device was found to be 108.4 (± 4.2) beats/min. Wilcoxon signed-rank test showed that the working heart rate during the use of developed floating device was significantly less ($Z = -3.34$, $p<0.05$) in comparison to the use of traditional floating device. Individual heart rate data has been depicted in Figure 33. This indicates that use of developed floating device require less physical exertion and thereby leads to lesser increase of heart rate.

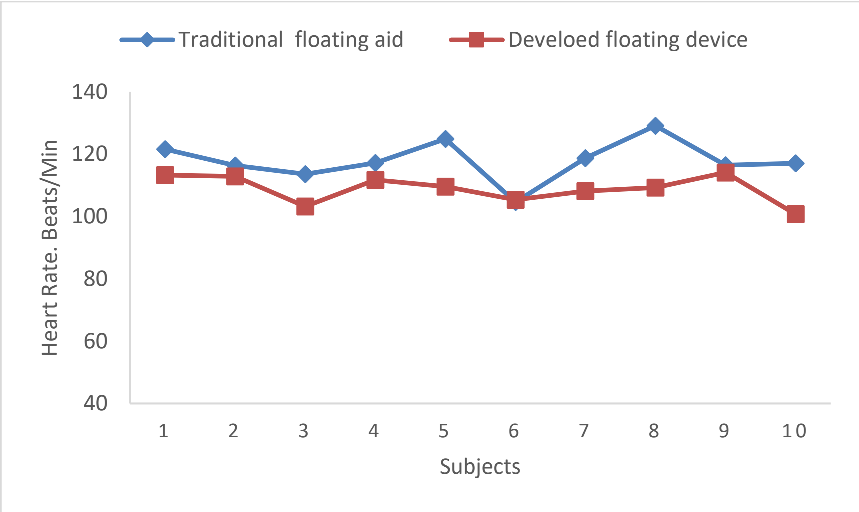

Figure 33. Response of heart rate while using traditional and new floating device

3.6.12.3 Perceived discomfort

Body part discomfort ratings were determined using a modified version of the Borg CR 10 scale (Borg, 1990). At the end of task, participating farmers (n=30) rated body part discomfort and whole-body discomfort. The mean value of body part discomfort (shown in Figure 34). The farmers rated the scale ranged from 0 to 10 (0 – no discomfort and 10 – extremely discomfort). The body part discomfort score for newly developed floating device and traditional floating device were 25.90 (±6.45) and 36.20 (± 7.69), respectively.

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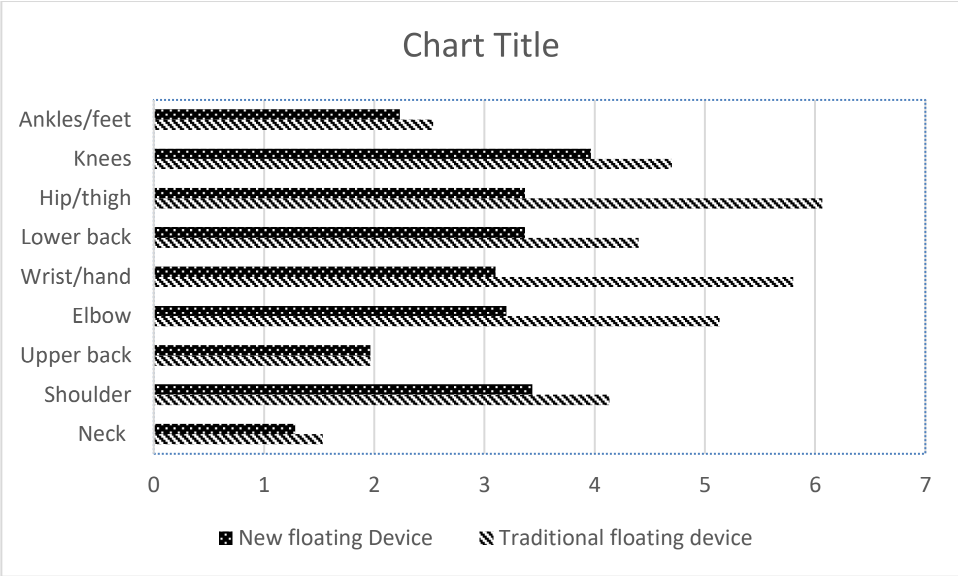

Figure 34. Mean values of perceived discomfort score (Borg CR 10) during harvesting with traditional and developed floating device

3.7 Discussion

Insights from field studies and interviews with farmers shed light on the need for intervention in the harvesting process. Farmers involved in harvesting the crop often use primitive tools and have limited education, and comes under low-income group, leading to a marginalized lifestyle. Consequently, high-tech, and costly interventions may not be suitable for supporting farmers in harvesting water chestnut fruit. Farmers encountered various difficulties with traditional floating devices, primarily due to their poor design, which led to musculoskeletal problems. Previous literature also highlighted the importance of redesigning harvesting tools to assist farmers and reduce muscle fatigue and strain (Mohamaddan et al., 2021; Nourani et al., 2017).

Farmers using boat for harvesting water chestnut have to opt crouched posture for long duration. Sitting in a crouched posture for extended periods of time can indeed lead to pain and discomfort in the legs and back. This is particularly relevant to farmers who may spend significant amounts of time in physically demanding positions, such as bending or squatting while performing tasks like planting, weeding, or harvesting (Novaes et al., 2017). The crouched posture can place excessive strain on the muscles, tendons, and ligaments of the legs and back, leading to muscle fatigue, joint stiffness, and even musculoskeletal disorders over time (Bell, 2002; Patial et al., 2022). The pain experienced can range from mild discomfort to more severe symptoms that may interfere with daily activities.

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In the case of terrestrial crops, harvesting tools directly interact with the plant or increase productivity (Abdulkarim et al., 2017; Nourani et al., 2017). However, for aquatic crops like water chestnut, harvesting productivity is enhanced by using floating devices that do not directly interact with the plant. Instead, it provides support and float in water bodies, thereby increasing farmers' productivity. The study of plant properties played a key role in the design of floating device.

The advantages and benefits of the developed device were compared with other prototypes related to aquatic crops. The field trials demonstrated positive results, with an increase of 14 percent in farmers' productivity when using the developed device. The device also incorporated a backrest to provide support to the lumbar region, enabling farmers to sit for longer durations, despite the physically demanding and tiring nature of the job.

With the use of the new floating device, the perceived discomfort was also reduced because of the comfortable posture and the farmers do not have to do extra efforts for removing of mess of plant that get entangled with the traditional floating device. The effect of the developed floating device could also be seen in the heart rate comparison of farmers while using the floating device. With the use of developed device, farmers save time from removing plant that create hindrance in the locally made device. The design of the floating board is such that it provides comfortable posture and easy leg movement due to the curve/ cut in the board. The board is made smooth with no sharp corners to provide less hindrance and easy maneuverability.

In the traditional floating device, the use of bamboo or brick provide discomfort in the thighs. Due to compression for long duration the farmer observe pain in the thighs (Harney & Patijn, 2007), sometime the pain is so high that the farmer feels the numbness in the leg. The numbness is cause due to the pressure in the tissue and of the cell body. Tissue compression is also reduced with the use of new floating device which also reduces the pain of the farmers in the thighs and hence the duration of work increases.

The movement of the device inside the water bodies is achieved with the hands of the farmer as they require to stop frequently to harvest the crop. Hence a manual floating device is enough for the harvesting the water-chestnut fruit, they do not require any mechanical intervention in the harvesting of the crop. The device would help them to float in the water and perform activities like cleaning, harvesting while the water level is high (above the chest level) with ease of movement in water bodies. The ergonomic design of the device would ensure better working posture and reduce

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drudgery. The current innovative floating device has improved the productivity and harvesting of aquatic farmers.

The result shown the positive response from the farmers and they have accepted the device happily. The design of the device is such that, it is smooth durable and comfortable. The smoothness of the device provide help in navigation of the farmer from one point to another in the field. As the field is filled by the plant stem and root it is covering all over the pond the navigation become difficult, and the plant provide hindrance to the motion of the farmer. The material of the device is plastic, and it is reusable. The back rest of the device is to provide comfort to the farmer while harvesting. In the traditional design there was no backrest support for the farmer. Absence of backrest leads to discomfort among the farmer, and they have complaint about the same. The bouncy provided by the device is sufficient for the load of 90 kg.

Based on the study following guideline can be made for development of a floating device that could be used for the cultivation of aquatic crop that has similar plant properties as water-chestnut.

- The device should have smooth corners and no pointed or sharp edge.
- The material should be light weight so it can have small size and sufficient buoyancy
- The material should be water resistant and has high resistance to corrosion.
- Minimum volume displacement by the device should be 30 litre considering the half body submerged.
- Back rest would enhance the performance and comfort of the farmers.

Limitations and future scope

The pond environment is unhygienic due to mud, thorns/prickles, the device cannot help in saving the farmer from the contact of water. The water contact of the farmer can be avoided with the use of special designed Personal Protective Equipment such as Wader.

3.8 Conclusion

The farmers of aquatic crops still rely on the traditional tools and technique for the cultivation of the crop. Ergonomic design intervention is required to assist the farmers in the cultivation process. These assistive tools would increase the productivity of the farmers and proper utilization of wetland areas. The design and development of a floating device with participatory approach helped to find a suitable solution for the context specific problems. The study of plant properties and expansion under water is one of the key factors on finalizing the design of the floating device. The

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systematic product design process incorporated in the study can act as a reference for researchers coming from different domain of educational background. The developed device reduced the body pain and discomfort among the farmers and improved safety.

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4 Design and development of a plucking-aid for water chestnut harvesting

Abstract

The plucking task requires repetitive hand and fingers movement that involves an uncomfortable thumb joint angle along with force exertion that leads to pain and numbness in the thumb tip and wrist. In addition, during the plucking dirt/ algae accumulation in nail often causes infections. Keeping in view the aim of the study is to design and develop a plucking aid to pluck the fruits with ease in turn leading to an increase in productivity. Following the field-survey to identify the challenges and users' requirements, various design ideations were done through brainstorming. The most feasible and effective concept was finalized through the Pugh chart. Finally, a prototype was devolved using 3D printing and field-trials were performed for usability evaluation and further refinement. Amongst five feasible concepts, the best one was prototyped and found suitable for the intended purpose. Farmers rated the use of the aid highly satisfactory as it provides normal thumb joint angle that reduces pain in the thumb and wrist. Furthermore, it was also found beneficial in protecting the nails from dirt. Innovative design with due considerations of anthropometry and biomechanical properties of the thumb finger of the targeted users ensured better fit and comfortable movement during plucking activity. The use of nail-like projection of the aid significantly reduced force exertion leading to a reduction of muscular fatigue at the thumb.

Keyword: Design thinking; harvesting; aquaculture; product design; repetitive task;

4.1 Introduction

Musculoskeletal disorders (MSD) are prevalent among the working-age population and encompass conditions affecting both passive (bones, joints) and active bodily structures (muscles, tendons, ligaments, peripheral nerves) (Jain, Meena, Dangayach, et al., 2018b; Punnett & Wegman, 2004; Syuaib, 2015). Given that MSD constitutes a significant portion of compensable occupational ailments globally, extensive endeavors have been undertaken to identify potential risk factors for MSD

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development and prevention within workplace environments (Palmer, 2011). In occu demanding manual-intensive tasks like agriculture, manufacturing, construction, or services, MSD exhibits notable prevalence (Silverstein et al., 2002; Veiersted et al., 2008).

The agricultural labour involves extended hours of work, postures demanding agility, and repetitive motions, all of which may contribute to muscular discomfort, termed musculoskeletal discomfort (MSD). In contrast to non-farmer working populations in rural areas, farmers consistently report heightened levels of MSD in regions encompassing the hands, forearms, lower back, hips, alongside a slightly elevated, albeit statistically insignificant, incidence of discomfort in the neck, shoulders, and knees (Holmberg et al., 2003). Some other occupational factors linked to MSD prevalence among farmers' entail extended daily work hours, recurrent stooping, kneeling, bending, and crawling, operation of heavy machinery, equipment upkeep and repair, material handling, and repetitive motions, such as milking.

The investigation into the association between MSD and the plucking activity specific to water-chestnut harvesting remains unexplored. Within the context of water-chestnut cultivation, the workforce in this agricultural sector may experience heightened susceptibility to work-related MSD. The engagement in uncomfortable postures and repetitive hand movement stands out as a principal factor contributing to the emergence of MSD, particularly concerning the plucking operation in the context of water-chestnut harvesting.

Agriculture tools and implements are useful to increase the productivity and reduce the drudgery in the cultivation process (Gautam et al., 2023; Rakhra et al., 2022). Various types of tools were developed in the past to assist the cultivation and increase the productivity. These tools can be manual, semi-mechanical, mechanical or robotic. Despite rise in the machinery and robotics in various sector, many farmers still perform the tasks manually without any aid. Sometimes these tasks are very repetitive and stressful and farmers compromise their health.

Aquatic farmers don't have appropriate tools, or equipment for harvesting water chest-nut. The harvesting is mostly done with bare-hands in the traditional way and farmers face many challenges. Farmers have to remain up to six hours daily in the stagnant water during the peak time of harvesting. As the harvesting work requires repetitive hand and finger movement along with force exertion, their hands/ fingers become fatigued very soon. These workers also do not use any personal protective equipment/measures. Thus, the need of the hour is to develop appropriate tools or technique that can

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facilitate in reduction of drudgery along with enhancing their performance. Hence the current r aims to design and develop a plucking aid to pluck/ harvest the water-chestnut fruit.

4.2 Methodology

The study was divided into two phases; the first phase consisted of a survey for detailed information of the harvesting method. In the second phase design and development of the plucking aid was done.

10 farmers were interviewed about the cultivation process. The interview was focused on tools used by the farmers while harvesting and the step involved in the harvesting process. Video, and photography documentation of the data were done after obtaining prior permission from ethical committee and the consents of the farmers.

Farmers described the detailed cultivation method of water-chestnut crops that involved various steps like seedling preparation, cleaning of water bodies, transplanting of seedlings, harvesting, and cleaning of fruit. The harvesting season starts in the month of September and continues till November.

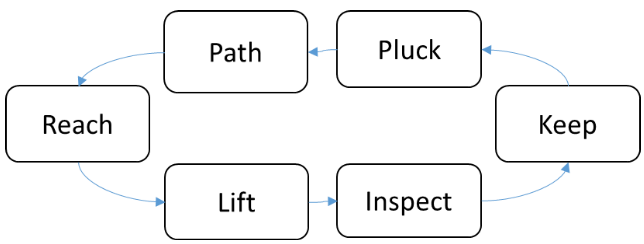

Figure 35. Steps involved in the harvesting of a water-chestnut crop

The harvesting task of the water-chestnut crop is divided into six sub-task, as shown in Figure 35, (a) The waterbody is densely covered with the water-chestnut plant. With the help of hands, farmers move the dense covering of the plant and create a path to move forward. (b) To harvest the fruit the farmer reaches near to every plant. (c) The farmer lifts each plant through the crown portion with the non-dominant hand. (d) The farmer has to inspect each fruit and search for mature fruit. (f) After identifying the mature fruit, they pluck the fruit and keep it in a vessel.

After the identification of the problem, in the second phase different concepts were brainstormed and the most feasible solution was selected through the Pugh chart matrix. Further, its CAD model was developed considering anthropometric data. The prototype was developed using a 3D printer. In

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addition, testing was done with the user for feasibility and modification. Anthropometric measu of the thumb was taken with the help of Vernier calipers.

4.2.1 EMG analysis

Muscular efforts were measured through surface electromyography (sEMG) after identifying the suitable muscles.

4.2.1.1 Participants

Ten (10) male aquatic farmers (age: Mean ± SD) participated voluntarily in the experiment after being informed about the procedure and risks associated with the experiment. The participants were explained about the experiment and the task that they need to perform.

4.2.1.2 Muscle selection

Following literature review (Bhattacharyya, 2011; Koizumi et al., 2021), it was identified that for studying muscular effort in plucking plucking type of activities with thumb and index figure movement, lumbricales and abductor pollicis brevis (APB) would be appropriate muscles. The selected muscles have been shown in Figure 36.

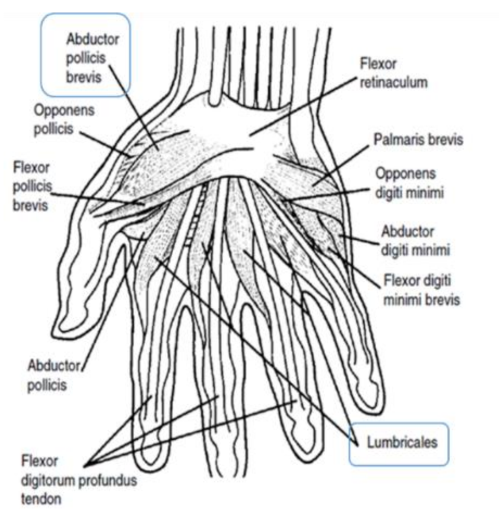

Figure 36. Intrinsic muscles of the hand (Marras, 2006)

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4.2.1.3 Experimental set-up

The experiment was conducted in the lab environment. Delsys surface EMG system was used to record the EMG signal from the targeted two muscles (lumbricales and abductor pollicis brevis) while performing the plucking operation with and without the plucking-aid. EMG of selected muscles were recorded with Trigno wireless EMG system (DAC filter Band width DC – 500 Hz, 160 dB/Dec, baseline noise < 0.5 mV RMS.

4.2.1.4 Experimental process:

Before placing the electrodes or sensors, the skin surface of the subject was cleaned with an alcohol-based spirit to ensure proper contact and minimize interference. Trigno wireless EMG sensors were placed on the respective muscles in the dominant hand of the participants. Participants were asked to pluck the fruits from the plants with and without using the plucking aid. EMG data was recorded for 30 sec time and appropriate 10 sec data during the plucking action was considered for analysis.

4.2.1.5 Analysis of the data

The raw EMG data from the experiment was analyzed by plotting it on graphs to visualize the muscle activity. Additionally, the mean Root Mean Square (RMS) values were calculated to quantify the effect of using the plucking aid. These values were compared to understand how the device influenced muscle exertion.

4.3 Results and Discussion

The farmers pluck the fruits in either of the two ways, in the first way they grab the whole fruit by hand and pluck the fruit by twisting the wrist. This is a repetitive task and cause numbness in the wrist. While grabbing the whole fruit, there is a chance of thorn piercing because the fruit contain thorns in the body (Guo et al., 2017). Another way to harvest the fruit is by use of thumb and fingers, while using this second option they need to put pressure through the thumb tip and support by the other fingers to detach the fruit from the plant as also shown in Figure 37. The steps involved in the harvesting of water-chestnut is a tiresome job. While harvesting dirt accumulates on nails that can enter into the stomach while consuming food and cause various infections (Hurst, 2019; Karan et al.,

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2012). The farmers use a vessel and plastic sack to harvest the water-chestnut crop. They use th to keep the plucked fruit and the sack to transfer the collected fruit when the vessel gets full. The vessel float on the water surface and mostly the shape of the vessel is round, so that it does not get entangled with plant branches.

Figure 37. Plucking of water-chestnut fruit

Due to quick movement and repetitive tasks they develop pain and numbness in the wrist and thumb (Gallagher & Jr, 2017; Koizumi et al., 2021). The repetitive task with awkward posture can lead to musculoskeletal disorders (Andarawis-Puri & Flatow, 2011). To cope with this problem either provide rest between tasks else a job rotation with the other worker/ farmer. However, in this case, both solutions would not be feasible as they have a limited number of workers and harvesting is done in specific time period of a year which restricts them to rest for longer duration. Hence, field observation and survey suggests to innovate single hand operated plucking aid for the plucking of water-chestnut crop. Based on the survey and observation following user requirement were identified.

Table 9. User requirement

Single hand operated	Comfort and Maneuverability
Easy to wear, attach, and detach	Light weight
Suitable for working in a wet environment	Proper fitting with hand or finger
No discomfort in long-term use	Low cost
Easy to manufacture	Long-lasting

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4.3.1 Concept generation

The brainstorming session was done with a group of 5 people having educational background in design. User requirement and design brief were explained to the group before the brainstorming session. Many concepts were developed in the brainstorming session but only five were found feasible in the existing scenario. Figure 38 shows some selected sketches from the brainstorming session.

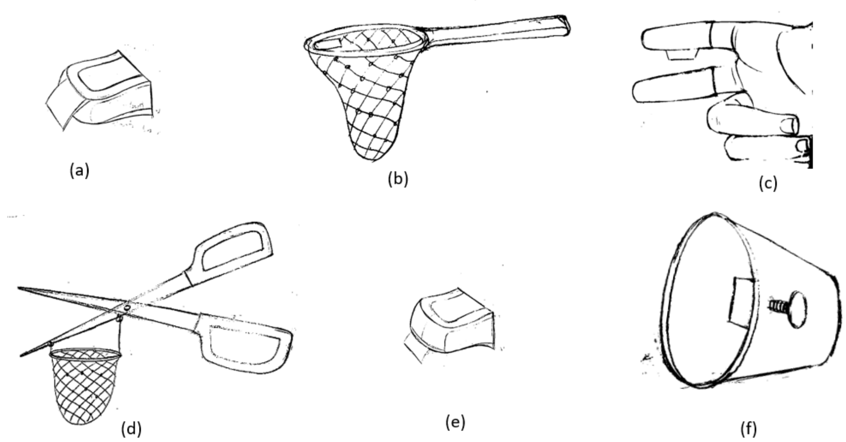

Figure 38. Different concepts generated

4.3.2 Concept Selection

The selection of the most feasible concept was done through the Pugh chart (Pugh, 1991). Table 2 depicts the Pugh Chart Matrix, as shown in the table Concept 2 (b) is selected as DATAM, and rating for other concepts depends upon the comparison with the DATAM.

Table 10 Comparative analysis utilizing Pugh chart matrix

Design criteria	weight	Concepts					
		(a)	(b)	(c)	(d)	(e)	(f)
Easy in use	2	+	D	+	+	+	-
Easy to wear	2	+	A	+	+	+	+
Obstruction free motion	1	+	T	-	-	+	+
Light weight	2	+	U	+	-	+	-
Posture while working	2	-	M	-	+	+	+
Safety	2	+	0	-	-	+	+
Weighted sum of +ve		9	0	6	6	11	8
Weighted sum of -ve		2	0	3	5	0	4
Total		7	0	3	1	11	4

Concept ‘e’ is selected for the final design as it received the highest score, the design is developed in CAD software after considering the anthropometric dimensions of the thumb.

4.3.3 Thumb anthropometric data for deciding plucking aid dimensions

The dimensions of the prototype were based on the anthropometric data of the thumb that was taken with the help of Vernier calipers (Themisto TH-M61 (0-150MM/6")) of agriculture workers in Assam. The dimension of the plucking aid is based on the anthropometry data of the 50 agricultural workers and the dimension is presented in Table 11. The measure of thumb thickness, width, and length of distal the phalanx was also shown in Figure 39. These data were taken because the required data is difficult to find in any anthropometric data repository.

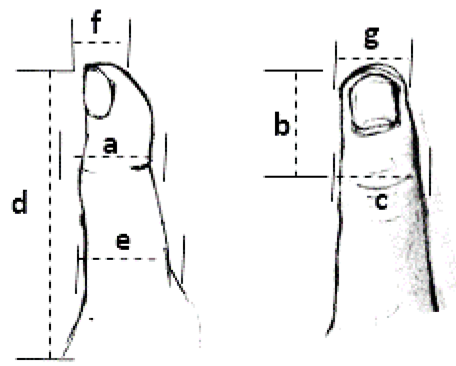

Figure 39. Dimensions of the thumb

Table 11. Anthropometry of thumb finger of agriculture worker (n=50)

Thumb dimension	Description of dimensions	Mean (cm)	SD	Percentile (cm)			Max	Min
				5^{th}	50^{th}	95^{th}		
a	Thickness of the thumb at interphalangeal joint	18.16	1.36	16.51	17.95	20.84	21.32	16.33
b	Length of thumb distal phalanx	29.33	3.68	26.03	29.90	33.49	35.12	17.22
c	Width of the thumb at interphalangeal joint	21.82	1.51	19.62	22.04	24.71	25.61	19.26
d	Length from the tip of distal phalanx to metacarpophalangeal joint	59.66	4.38	53.48	59.69	65.58	67.78	49.35
e	Diameter at the center of proximal phalanx of the thumb	61.78	10.35	38.53	63.02	73.65	76.49	30.83

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f	Thickness of the thumb tip at distal phalanx	10.72	1.52	8.71	10.18	12.45	15.45	8.44
g	Width of the thumb tip at distal phalanx	15.40	1.41	13.64	15.24	17.47	17.70	13.34

The dimension of the plucking aid was based on the anthropometry data of the 50 farmers and the dimension is presented in Table 11. The measure of thumb thickness, width, and length of distal phalanx has been also shown in Figure 39. Dimensions of the thumb. These data were taken because the required data is difficult to find in any anthropometric data repository.

To test the design, we utilized the average dimensions of the thumb to create a CAD model using SOLIDWORKS software. For efficient mass production, it is advisable to create the plucking aid in three distinct sizes: Small, based on the 5th percentile data; Medium, using the 50th percentile data; and Large, incorporating the 95th percentile data. This approach ensures a superior fit and enhanced comfort for users of different sizes.

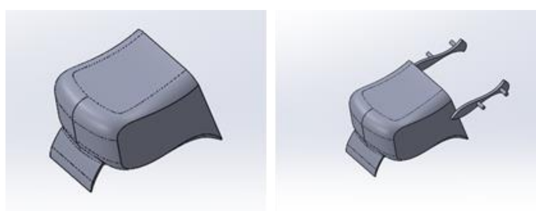

Figure 40. Selected concept and modification to avoid slip

In the final concept, a modification was made to avoid the detachment of the plucking aid during the operation. Both sides of the body were provided with support so that any elastic material or Velcro can tighten it as shown in the second image of Figure 40 and the rendered image also shown in Figure 41. The device is found suitable as it matches with the general practice of plucking activity. The design was prototyped through 3D printing as shown in Figure 42. The design does not obstruct the motion of the thumb as it does not block the interphalangeal joint of the thumb. The design does not obstruct the motion of the thumb as it does not block the interphalangeal joint of the thumb.

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Figure 41. Rendered CAD model of thimble (Top, side and perspective)

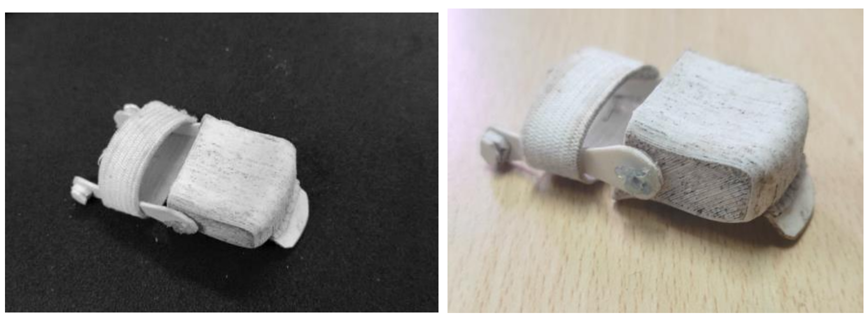

Figure 42 3D printed prototype

Figure 43. Posture of thumb while plucking the fruit without (left) and with plucking aid (right)

The nail-like extrusion at the bottom of the plucking aid is intentionally made thick (about 2 mm) and blunt which does not harm other fingers while working.

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4.3.4 Comparisons of muscular activity of fingers with and without plucking aid

The raw EMG signal data was taken for both muscles, with and without the plucking aid and shown in Figure 44.

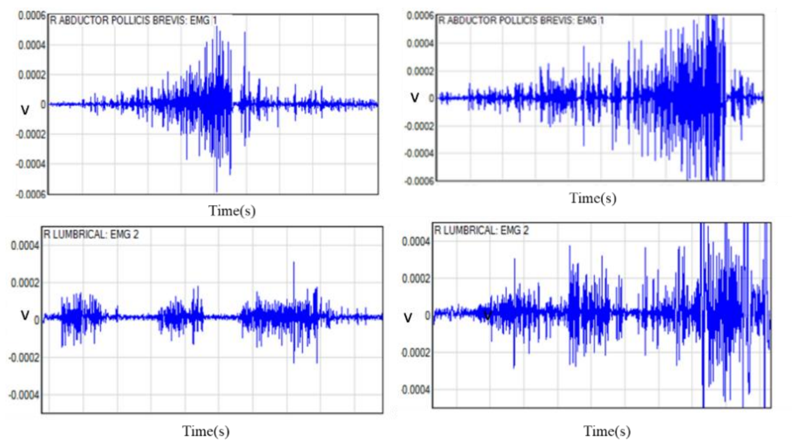

Figure 44. Raw EMG data

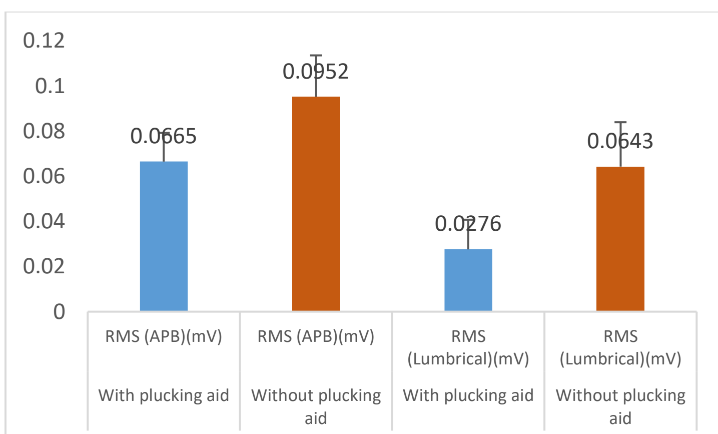

Figure 45. Mean EMG RMS value with and without the plucking aid

From the EMG study it is clear that more muscular activity is found less for the selected muscle. Hence the plucking aid can be beneficial for long-term use.

Figure 45 shows that the mean of RMS for APB muscles with the use of plucking aid is 0.066 $\pm$ 0.013 mV while the value of the same muscle without plucking aid is 0.095 $\pm$ 0.018mV. In the lumbricales muscle, the mean value of RMS is found to be 0.0276 $\pm$ 0.013 mV with the use of the plucking aid and 0.0643 $\pm$ 0.019 mV without the use of plucking aid.

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The result suggests that muscular activity is reduced with the use of a plucking aid as the v
the RMS mean was reduced (Oliveira & Gonçalves, 2009; Renshaw et al., 2010). EMG data shown in Figure 45 proved that the device improved the task of plucking as the thumb posture also improved while working as shown in Figure 43. The device cannot help in reducing the number of repetitions but it has reduced the force required to perform the job successfully and improved the posture of the thumb.

Following the field survey and collecting feedback from the user, it was noticed that farmers were satisfied with the device. The device helped them to harvest for prolong duration. Another benefit of the device is that it protects the nail of the thumb from the dirt as the contact between the nail of thumb and stem is removed. The plucking aid is also working like a personal protective equipment (PPE) in this case to protect the thumb nail (Levesque et al., 2012; Walton et al., 2017). Due to the reduction in the angle of the posture it reduced pressure on the thumb tip. Whole pressure comes to the extruded area and, technically this product works on the principle of a knife as force is concentrated on a small area that increase the pressure and cut the piece into two part.

4.4 Conclusion

The current chapter successfully introduces a novel plucking device designed for water-chestnut harvesting, integrating ergonomic principles into its development process. The developed plucking device is lightweight, easy to use and effective. The extruded nail-like projection at the bottom of the plucking aid was found to be beneficial for the long-term use of the plucking process. It has improved the posture as well as reduced the force required for the plucking of the water-chestnut. The innovative plucking aid developed through systematic research and development has been found beneficial for the farmers for water-chestnut harvesting.

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5 Protecting farmers from water and water insects

Abstract

The cultivation practices of aquatic crops often require farmers to spend prolonged periods in water bodies, which can lead to various health issues such as swelling, itching, and waterborne diseases. Unfortunately, the protective aids available are expensive and not easily accessible in the local market. Farmers are unaware of the existing of protective aids specifically designed to safeguard their skin during such activities. Recognizing this research gap, the study aimed to develop a low-cost Personal Protective Equipment (PPE) suitable for use in water bodies to protect against water and water insects. To achieve this objective, an extensive exploration of various materials available in the market that had the potential to be converted into a waterproof PPE was conducted. Several cutting and sealing methods were explored to determine the most effective approach. Subsequently, a total of eight types of PPE were developed and tested under laboratory and actual field conditions. To evaluate the effectiveness of the developed PPE, feedback from the farmers were taken and based on their valuable input, it was determined that the PPE made from 120 GSM Polytrap and HDPE materials exhibited superior performance in terms of manoeuvrability, comfort, and durability. These findings highlight the application of polymer-based material for successful development of a PPE that addresses the specific needs of farmers working in water bodies.

5.1 Introduction

The safety and health of farmers are of paramount importance and remain a significant concern as the farmers face various occupational hazards and risks while working in the agricultural sector. These hazards can range from physical injuries due to machinery accidents, falls, handling of heavy equipment, as well as to exposure to harmful chemicals and pesticides that can pose long-term health risks (Batoa et al., 2019; Damalas & Eleftherohorinos, 2011; Key & Wheat, 2021). Additionally, working in extreme weather conditions, such as excessive heat or cold, can also have adverse effects on the well-being of farmers (McMichael & Lindgren, 2011; Nilsson & Kjellstrom, 2010).

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Furthermore, the repetitive nature of many farming tasks can lead to musculoskeletal disord chronic pain.

Farmers cultivating water-chestnut crops are required to spend prolonged periods submerged in water bodies, with half of their bodies immersed also shown in Figure 46. This practice often leads to swelling and itching in various body parts. Moreover, farmers have to struggle with the presence of waterborne insects in the water bodies. Currently, they use old clothes that offer protection against insects but fail to shield them from direct water contact. While in some countries, farmers utilize waders to safeguard their bodies from water, these protective gears are not readily available in India. Furthermore, the unaffordable cost of waders makes them unaffordable for small-scale farmers.

Occupational health hazards are expensive for individual workers, their families, their businesses, and the country as a whole from a financial, physical, and emotional standpoint. If workers choose and wear the right personal protective equipment, these hazards can be reduced (Alemu et al., 2020). As a result, everyone at work must prioritize occupational health and safety in order to create a safe and healthy workplace. PPEs are essential for ensuring the general health and safety of workers. PPEs include clothing that provides weather protection and is designed to be worn or held up against a person while they are at work to protect them from threats to their health or safety.

The hierarchy of controls are listed from most effective to least effective in the following order: elimination, substitution, engineering controls, administrative controls, and PPE. PPE is required by employers when elimination, substitution, and engineering controls do not work and when administrative controls are not feasible or do not provide adequate protection (Goldman et al., 2021; Yokel & MacPhail, 2011). When administrative and engineering support is ineffective for the worker in the working environment and there are no other options available for the worker's safety, PPE is necessary. PPE development is an interdisciplinary field that combines materials science, textile engineering, ergonomics, and medical science, among other fields. Its goal is to provide individuals with the greatest level of protection from potential risks (Shi et al., 2021).

Laboratory coats, scrubs, uniforms, and disposable body coverings provide a level of protection from splash hazards. Special hazards and material qualities such as flame resistance, specific chemical resistance, physical strength (e.g., leather) and visibility should be considered when selecting PPE for skin and body protection. Any additional piece of clothing or protection worn for a purpose, aside from gloves, serves to protect the skin. For example, lab coats are worn to guard against potential chemical

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splashes. Face shields protect the wearer from potential impact dangers, chemical splash potentially contagious fluid.

Several studies have examined barriers to wearing other forms of personal protective equipment (PPE) among different types of workers. Common reasons cited for non-use were discomfort, misperceptions of risk, and negative attitudes about the efficacy of PPE (Akbar-Khanzadeh, 1998; Forst et al., 2006). Among fishing industry workers, there may be similar perceptions and attitudes; they may feel that a PPE will be uncomfortable and encumber them in their work.

The farmers involved in the harvesting of these water-chestnut and other aquatic crops are economically deprived and not able to use costly intervention or high cost of wader in the cultivation, which range from rupees 5000 ($60) to rupees 10,000 ($120) moreover the use of these type of PPE was found problematic as the cost of these material are high and the material are relatively heavy and can create problem in the cultivation process. Given the challenges faced by workers in water bodies and the high cost associated with available Personal Protective Equipment (PPE), our objective was to develop an affordable PPE solution utilizing materials readily available in the local market.

Figure 46. Farmers performing cultivation activity (left- Cleaning of water bodies, right harvesting of the fruit) inside the water bodies.

5.2 Material and Methods

The fabrication approach for the development of protective aid for the farmers involved the following method.

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5.2.1 Interaction with the farmer

A survey was conducted to understand the current protective measure adopted by the farmers in the cultivation of water-chestnut crop. The farmers were also interviewed to know their awareness and level of understanding about the available PPEs.

5.2.2 Exploration of different solution

A thorough exploration of various solutions was undertaken to identify effective measures for protecting farmers from water and waterborne insects. The objective was to identify a comprehensive range of options that would address the specific challenges and risks associated with working in water bodies, considering factors such as durability, affordability, ease of use, and the ability to provide adequate protection against water and potential insect-related hazards.

5.2.3 Development of PPE

The steps for developing the PPE involved a systematic approach to explore and fabricate effective solutions. Initially, an extensive exploration phase was conducted to gather information on existing PPE designs and materials used in similar context. Following this, a thorough search for various materials suitable for the aquatic farming environment was conducted at the market, considering factors such as waterproofing, durability, and comfort. Various materials were evaluated and selected based on their suitability for the intended purpose. The fabrication process included several stages, including mockup making, cutting, stitching, and sealing. Special attention was given for ensuring proper sealing and reinforcement in critical areas to enhance the PPE's water resistance and longevity.

5.2.4 Cost analysis

In the next step, a comprehensive analysis of the cost was conducted to ensure the suitability of the developed PPE for the farmers. This analysis aimed to strike a balance between the effectiveness of the protective gear and its affordability for the target users. The cost analysis involved evaluating the expenses associated with the materials, manufacturing processes, and any additional features or components incorporated into the PPE design. Factors such as the availability and accessibility of the materials in the local market, scalability of production, and the overall economic feasibility were considered.

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5.2.5 Testing

Lab testing – To ensure the efficacy and reliability of the Personal Protective Equipment (PPE) developed for aquatic farmers, rigorous testing procedures were conducted. One test involved air testing using a blower, followed by the application of pressure by hand to detect any potential leakage. This step was essential to verify the PPE and ensure that it provided a secure and airtight barrier against water.

Field testing and feedback from the farmers - To assess the performance and acceptability of the developed (PPE) for aquatic farmers, field evaluations were conducted under actual working conditions. The farmers who utilized the PPE were actively engaged in providing feedback regarding their experience with the equipment. A 5-point rating scale was used to gather their feedback, with specific focus on three key aspects: maneuverability, comfort, and durability.

5.3 Result

5.3.1 Interaction with the farmers

The interaction with the farmers included discussions on various subjects, including the protective measures employed by the farmers, intercultural activity challenges, and awareness regarding the usage of PPE.

5.3.1.1 Protective measures used by the farmers

Currently, farmers tie the bottom end of the pants/ trousers using a small rope. This tying protects farmers by preventing insects from getting inside the pants (shown in Figure 47). They use jute or a plastic rope for tying, which also sometimes becomes loose and obstructs the farmer from working, and they have to come out from the waterbodies and tie the knot again to enter. Moreover, this method protects (to some extent) the farmer from water insects but does not provide protection from continuous water contact.

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Figure 47. Protective measure by the farmers

5.3.1.2 Challenges in intercultural activity

In intercultural activity farmers use to clean the water bodies along with it they spray insecticide and pesticide. The farmer carries the pesticide along in a container and spray the chemical in the water bodies either with the water syringe or with small mug as shown in Figure 48. The chemical directly mixes with the waterbodies and causes several types of side effect because of direct contact of chemical and with body through water. In this condition, it become particularly important to use the PPE for the protection of the farmer that would be helpful for the farmers.

Figure 48. Application of fertilizers in the waterbodies

5.3.1.3 Awareness about the PPE

The farmers exhibited a lack of awareness regarding PPE. Many expressed that they had not encountered or heard of PPE before. However, few farmers were aware of the term PPE. Their limited knowledge of PPE was primarily influenced by their exposure to the term during the COVID-19 pandemic, where they had observed doctors and healthcare professionals using disposable PPE. As a result, their perception of PPE was associated with unaffordable costs, considering the pricing of medical-grade PPE during the pandemic.

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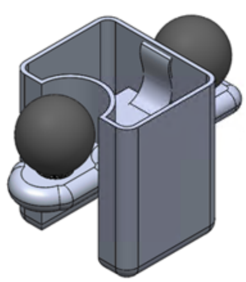
It became evident that the concept of PPE designed specifically for agricultural activities, water chestnut cultivation, was unknown to the farmers. Their lack of awareness regarding the availability and functionality of agricultural PPE indicated a potential gap in the dissemination of information and access to suitable protective gear for their occupation.

5.3.2 Exploration of different solution

Figure 49 shows two types of protection, but option 1 would not be feasible for the farmer's protection in the water bodies that are densely covered with the web of the water-chestnut plants.

The online market offers several types of PPE, including waders, which are suitable for use in water bodies. However, the cost of these commercially available waders is prohibitively high, making them an impractical choice for farmers belonging to the low-income group. The high price point renders these alternatives inaccessible and financially burdensome for those seeking affordable and effective protection during their agricultural activities.

Option 1



Advantages
- Protection against water insects
- Protection from water

Disadvantages
- It cannot be used at shallow water level
- **Difficulty in navigation** - Plants that are spread on the surface and their stems under the water will obstruct the motion of the device
- Balancing will be difficult
- Picking of the plant will be restricted

Option 2

Chest height PPE including shoe will be made using silicone-rubber/ PVC fabric /Neoprene.

Advantages
It will protect the farmer from leeches and other water-based insects.
Farmer can use it in shallow water height too.

Figure 49. Concepts for protecting farmers from water contact

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5.3.3 Description of all the materials

It was decided to make a wader-type PPE that can be used by the farmers in the cultivation method, the wader should be low cost, easy to maintain and fulfill two major purpose of water contact and insect. For this purpose, all the available (in the local market) materials that have the potential for making such type of product were explored. The search was started on Google Maps using keywords such as waterproof fabric, textile, etc., to find out the available shops in the local market. Following are the materials that were found in the market as well the online retailer website.

Types of material found in the market that have the potential to convert into wader type are – 90 GSM, 120 GSM, 150 GSM Polytrap, PVC coated fabric, rubber coated fabric and SRF.

5.3.4 Fabrication process

The development of the PPE involved two major steps: material cutting and material sealing/joining. In the first step, the materials were carefully cut according to the predetermined patterns and specifications. This process ensured precise sizing and shape consistency for the different components of the PPE. Following the cutting stage, the next step involved the sealing or joining of the materials. Special attention was given to this process to ensure a secure and watertight bond between the various parts of the PPE.

There were two major steps involved for development of PPE. The first one is the cutting of the material and the next one is the sealing or joining of the material. The fabrication process is one of the challenging tasks as it involves folding and cutting the material with correct shape. Sealing the unit with the heat sealer, the plastic type of material is sealed using heat sealer while the fabric type material is sealed using the sewing machine.

5.3.4.1 Challenges in the joining of the shoe part

Joining the shoe was the most challenging aspect of the PPE development process in the case of polymer type of material, which uses heat sealer for the sealing/joining. To overcome this challenge, various methods were explored to find an effective solution. One approach involved the use of a thick paper inserted between the material sheets during the joining process. This innovative technique ensured that no two materials would stick together, allowing for easier assembly and preventing any unwanted adhesion.

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5.3.4.2 Working of heat sealer

A machine that uses heat to seal materials is known as a heat sealer shown in Figure 50. It operates by sending a strong impulse of current to the heater ribbon that is located on the device's surface. As a result, a surge of heat is created that is powerful enough to melt and seal the bag or sheet that is sandwiched between the sealing bars. If they have a thermoplastic layer, heat sealers can be utilized to attach or seal together both distinct and similar materials. When the sealing bar is sufficiently heated, the material melts and fuses together like a zip-liner bag. This is frequently used to seal bags and even cover other objects in plastic to protect them from the effects of deterioration.

Figure 50. Heat sealer (left), sealing process (right)

5.3.5 Different manufactured PPEs

Figure 51 shows various waders that have been developed using a range of varied materials. Each wader design represents a unique combination of materials chosen for their specific properties and suitability for the intended purpose. The diverse selection of materials used in the construction of these waders demonstrates the flexibility and adaptability in addressing the challenges posed by aquatic environments.

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90 GSM Tarpaulin | 120GSM Tarpaulin | 0.3 mm PVC | PVC coated fabric

LLDP | 150 GSM Tarpaulin | Rubber coated fabric | HDPE

Figure 51. PPE developed with different materials

5.3.6 Testing

The lab testing of the PPE was done for leakage test with the help of air blower and water, as shown in the Figure 52. If any leakage was identified, then sealed with the heat sealer or with the help of soldering iron and a Teflon cloth.

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Figure 52. Leakage test of wader

5.3.7 Field testing

The developed PPE was taken to the farmers as shown in Figure 53, and explained how to use it. Then they were asked to rate about the product

The developed PPE was introduced to the farmers, and a comprehensive explanation was provided on how to properly use and utilize the protective gear. The farmers were actively engaged in the demonstration and were encouraged to ask questions to ensure a clear understanding of the PPE's functionalities and benefits.

Figure 53. Testing of PPE along with the floating device

5.3.8 Feedback from farmers

The feedback from the farmers were taken and shown in the Table 12.

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Table 12 Feedback from the farmers

	Observation of farmers					Fabrication analysis		
	Materials	Comfort	Maneuverability	Durability	Total	Cost per sq.m (Rs)	Material cost of 2 sqm (Rs)	Tools used for development
1	90 GSM	4.0	3.8	2.2	10.0	57	115.	Heat sealer
2	120 GSM	4.0	3.3	3.7	11.0	92.	184.	Heat sealer
3	150 GSM	3.3	2.2	4.5	10.0	104.	209.	Heat sealer
4	0.3 mm PVC	2.2	3.7	2.5	8.3	136.	273.	Heat sealer
5	PVC coated fabric	3.7	4.5	2.2	10.3	130	260	Sewing machine and waterproof tape
6	LLDP	4.2	2.5	3.5	10.2	140	280	Heat sealer
7	Rubber coated fabric	2.5	2.2	2.2	6.8	120	240	Sewing machine
8	HDPE	3.3	3.3	3.8	**10.5**	160	320	Heat sealer
9	SRF	-				616	1232	Adhesives

From the feedback from the farmers, it was found they have given the highest score to the PPE made from 120 GSM material and HDPE material.

5.3.9 Repair and maintenance of the wader (PPE)

The repair and maintenance of Waders are crucial for long-term use. Since these are constructed using locally available materials, it is preferable for repairs to be done locally or by the farmers themselves. This approach saves both time and money for farmers, considering that time is a crucial factor during the cultivation process. An innovative method has been developed to repair these waders (PPE) using a soldering unit. This device enables the repair of the PPE effectively.

Repairing Method:

- Identify the damaged part of the PPE.
- Acquire the necessary cost of the same material used in the PPE.
- Place a Teflon cloth over the punctured area and gently apply heat using the soldering device.

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- Take caution to ensure that no two parts encounter come into contact with the sc device, as it may cause them to stick together and further damage the PPE, making it difficult to use.

By following the methodology, farmers can efficiently repair their PPE, promoting longer use and reducing the need for additional expenses or professional assistance.

5.4 Discussion

In this chapter, the objective was to design and develop an affordable PPE/wader that effectively protects farmers from direct contact with water and harmful insects present in water bodies. Our focus was on creating a lightweight product that would enable farmers to wear it comfortably for extended periods and maneuver easily within the water body. By emphasizing low cost and practicality, we aimed to address the challenges faced by farmers in terms of accessibility, functionality, and overall usability of the protective aid.

The traditional cultivation practices employed by the farmers for water-chestnut crops are characterized as primitive and lack adequate protection against water insects and chemical exposure. The absence of protective measures leaves the farmers vulnerable to potential health risks and discomfort during various activities, particularly during intercultural activities involving the application of chemicals in the water bodies to promote plant growth. Direct contact with chemicals poses a significant concern as it can lead to adverse health effects (Wely, 2017). Therefore, the development of suitable PPE becomes crucial in ensuring the safety and well-being of the farmers.

The observation from the field study and interaction with the farmers highlights the importance of creating awareness and education programs regarding PPE tailored to the needs of aquatic farmers (Bondori et al., 2018; Sharifzadeh et al., 2019). It is crucial to address their concerns regarding cost and demonstrate the availability of affordable and effective PPE options designed explicitly for their work environment. Through awareness generation and sensitization, farmers can make informed decisions about adopting and utilizing appropriate protective equipment during water chestnut cultivation activities.

Skin illness, which is extremely expensive and includes contact dermatitis, skin cancer, and numerous skin injuries and infections, is the second-most common type of occupational disease(Arora

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& Attwood, 2009; Donham & Thelin, 2016). The classification of skin dangers into those th in occupational skin sickness falls into four categories. Chemicals can enter the skin by aerosols, immersion, splashes, close contact with contaminated surfaces, and aerosol deposition. Biological agents including parasites, germs, plants, and animals can cause a range of problems when they come into contact with the skin (Dutkiewicz et al., 2011; Rim & Lim, 2014).

Locally available material is used for the development of the product a poly sealer has been used for the sealing for the PPE

For farmers that cultivate water chestnuts, the available personal protective equipment (PPE) in the form of waders can be quite expensive. These can range between rupees 10,000 to 20,000, excluding their maintenance. The income that farmers earn helps them meet the most basic necessities of their daily lives; however, they are unable to afford the more expensive items (Seepaul et al., 2015; Sigauke, 2020). The farmers have been growing these crops for more than ten years, but they have not been able to come up with the best answer on their own; all they can do is produce a cheap design, which only satisfies their most fundamental requirements; however, they face a great deal of difficult challenges.

The developed PPE can be used with the floating device/aid, which will help the farmers to go in the high-water level (above 3-4 feet). The PPE will protect the farmer from water contact and insect while the floating device will help the farmers to do the cultivation activities in the high water level area.

The manufacturing process of the PPE involved the use of readily available materials sourced from local markets and e-commerce websites. These materials were selected for their waterproof and durable properties, although they were not traditionally used as PPE by farmers. The cutting of the material was carried out using a scissor, while a poly sealer equipment was utilized for sealing the PPE, ensuring proper protection against water and other elements. The dimensions of the PPE were determined based on anthropometric data, allowing for the development of three different sizes: small, medium, and large. The feedback received from the farmers indicated that the PPE was effective in terms of comfort, durability, and maneuverability, further validating its suitability for use in the challenging conditions of water chestnut cultivation.

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The utilization of locally available materials in the construction of the wader significantly r the material cost, making it affordable for farmers. This approach not only addresses the financial constraints faced by farmers but also ensures that the protective aid remains accessible to a larger number of individuals. Additionally, the method employed to rectify any damage or wear and tear of the product proves to be highly beneficial for its long-term use.

India has numerous waterlogged area and these area has potential to generate employment and a source of income for the various farmers with the cultivation of aquatic crops. Previous research shows that there is a need for the intervention for safety and reducing the challenges of the farmers in the cultivation of the crops (Chauhan et al., 2022; Chauhan & Karmakar, 2021). With the advance in the cultivation methods, it will empower and motivate other farmers who have water-bodies and do not use for any purpose. Hence with the small innovation considering the economic status and working condition of the farmers.

5.5 Conclusion

The developed PPE offers farmers protection against both water contact and waterborne insects. Designed to be lightweight, the PPE ensures that farmers can comfortably wear it for extended periods while navigating through water bodies. This innovation not only safeguards them from unhygienic water conditions but also provides a barrier against potential insect-related hazards. Through its thoughtful design, the PPE aims to contribute to the farmers' occupational health and safety, enabling them to work efficiently in their aquatic cultivation activities.

By providing an affordable and accessible protective aid, our research endeavors to enhance the safety and well-being of farmers engaged in aquatic crop cultivation. The identified PPE design offers a practical solution to mitigate the health risks associated with prolonged water exposure, ultimately improving the farmers' working conditions and overall productivity. These outcomes contribute to the broader objective of promoting sustainable and inclusive agricultural practices in the context of aquatic crop cultivation.

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6 Discussion

The main conclusions of the current study are outlined in this chapter, together with an explanation of how the technique used and the findings/observations made it possible to achieve the pre-set objectives. This chapter also covers the testing of the hypothesis, a list of characteristics that explain why the newly designed floating device is superior to the one currently in use, new contributions to the thesis, limitations of the current research, as well as the potential for future research, and conclusions from the reported research.

Insights from field studies and interviews with farmers shed light on the need for intervention in the harvesting process. Farmers involved in the harvesting of these crops often use primitive tools, are not literate enough, and come from under income groups. Consequently, high-tech and costly interventions may not be appropriate for supporting farmers in harvesting water chestnut fruit.

The cultivation of aquatic crops is a challenging task and a deeper understanding was required to dispel any preconceived notions about the associated issues. With the help of detailed field studies, like plant properties and growing environments, we were able to identify what could be feasible solutions. Interviews with the farmers about each step involved in the harvesting helped bring out the challenges faced by the farmers during the task. In the study, we have also used the Borg CR 10 scale to identify body part discomfort (Vimal et al., 2022) which is considered an effective measure for the prediction of associated risks and problems in the future (Waongenngarm et al., 2022).

In the research, several challenges were identified through field observations and interactions with farmers. These challenges include difficulties in accessing high water levels for the harvesting activities, repetitive plucking tasks, and prolonged exposure to unhygienic water bodies. Recognising the limitations of traditional floating devices made from bamboo, tin, or earthen pots – devices that lack durability, comfort, and pose maneuverability challenges in water bodies – three new products were developed and tested. The objective of these products is to assist farmers in the cultivation process by addressing the aforementioned issues. Farmers encountered various difficulties with traditional methods of cultivation, specifically harvesting, primarily due to their poor design, lack of research in the domain, and financial constraint of the farmers, thereby leading to musculoskeletal problems.

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Previous literature also highlighted the importance of redesigning harvesting tools to assist and reduce muscle fatigue and strain (Młotek et al., 2015; Mohamaddan et al., 2021; Nourani et al., 2017).

One of the solutions developed is a durable floating device made with FRP material. This device aims to aid farmers involved in aquatic crop cultivation by providing better maneuverability in water bodies. Another innovation involved the design and development of a plucking aid using 3D printing technology. The plucking aid features an extruded portion at the bottom, which effectively reduces the bending angle of the thumb during plucking, compared to the normal technique.

Furthermore, the research also focused on fabricating low-cost waders (PPE) using locally available materials. These waders serve to protect farmers from water insects and prolonged exposure to unhygienic water. The context-specific waders are suitable for use with the developed floating device, providing comprehensive protection and convenience to the farmers involved in aquatic crop cultivation.

6.1 Key findings/ observations

The following are salient findings of the research regarding the cultivation of water-chestnut crop.

- The cultivation of the water-chestnut crop is difficult in terms of human efforts. The cultivation process involves different steps i.e. seedling preparation, cleaning of the field, transplanting, inter-culture to harvesting that are performed in stagnant water bodies.
- Among the steps involved in the cultivation of the water-chestnut crop, cleaning of the water bodies and the harvesting of fruits are the most time-consuming and full of drudgery.
- The tools used by the farmers for assistance in farming activities are primitive and need intervention. They are poorly designed, scare identified literatures addressing intervention in the cultivation process.
- Water-chestnut plants are completely different from terrestrial crops. Hence, the required design, materials, and working mechanisms of tools are different for these crops. In this regard, the physical properties of plants are an important factor to consider while developing agricultural field tools.
- The water level in the water bodies varies from bank to center; it also exhibits seasonal variation, like higher and lower levels during monsoon and summer, respectively. The

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farmers have to perform the activities in these varying conditions and they have to inside the water bodies, remaining partially submerged which causes various skin diseases. Different upper-half and lower-half body temperatures also cause discomfort during work.

- In the research, three major challenges were identified during field study and interaction with farmers; accessing higher water levels for harvesting activities, repetitive plucking tasks and prolonged partial submersion in the unhygienic water bodies. Considering the drawbacks of the traditional floating devices made from bamboo, tin, or earthen pots, which are neither durable nor comfortable and pose navigation challenges in water bodies, three new products were developed and tested. These products aim to assist farmers in the cultivation process, addressing the issues discussed before.
- A durable floating device was developed with FRP material, aimed at helping the aquatic farmers in maneuvering in the water bodies.
- A plucking aid was designed and developed using 3D printing technology. The researcher also confirmed a reduction in the thumb bending due to the extruded portion at the bottom of the plucking aid.
- Fabrication of the low-cost wader (PPE) from locally available materials for the protection of farmers from water insects and continuous unhygienic water contact was done. The context specific wader is suitable for use along with the floating device.

6.2 Testing of hypothesis

***Hypothesis* 1:** *Harvesting of aquatic food-crops can be facilitated by developing requirement specific assistive products (which help in reduction of manual effort and enhance occupational health and safety) in activities that are not only directly but also indirectly associated with the harvesting process.*

In the present research, the hypothesis has been verified through the design, development and testing of the innovative products that facilitate harvesting. It is important to notice that facilitating the harvesting process does not only refer to product development directly associated with the harvesting process; it is also essential to note that the harvesting can be facilitated by many other designs and development of assistive products which are not directly associated with harvesting of aquatic crop. For example, the plucking-aid, which has been developed for manual plucking activities i.e. directly helping in harvesting but the other two products; floating device and low-cost wader (PPE) are indirectly helping in harvesting process. The innovative floating device is reducing manual efforts by

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easy maneuverability of the floating device through the mess of water chestnut plant. Wader-ty is useful in avoiding direct contact of the submerged body parts with unhygienic water bodies.

- Manual efforts have been reduced as there is no requirement for the removal of entangled floating plant branches with the novel floating device. In the case of the traditional floating device, farmers used to put a lot of efforts for removal of plant branches entangled with the floater during maneuvering through the water bodies filled with floating branches of water-chestnut plants.
- There is less chance of toppling as the newly developed floating device provides better balance.
- Allowing comfortable working posture through back support provision by reducing the abduction angle for both thighs. Field trials showed a significant ($p<0.01$) increase in the harvesting rate with the developed floating device shown in Figure 32 in Chapter 3.
- A low-cost wader-type PPE is useful in avoiding direct contact of the submerged body parts with unhygienic water bodies during harvesting. Moreover, it protects the farmers from insects, snakes, etc. present in the water bodies. Thereby, the PPE minimises potential health hazards associated with prolonged exposure.
- The developed design interventions help in reduction of drudgery of the aquatic farmers as and enhance the productivity during harvesting activities.

6.3 Fulfilment of the objectives

Objective 1: To study the various steps involved in the cultivation of water chestnut crop with special emphasis on harvesting.

To fulfil the objective, an explorative research methodology was adopted. The detailed description of the method has been mentioned in Chapter 2. Fulfilling the objective, the study described a step-wise cultivation method and addressed the challenges involved in the cultivation of the crop.

Objective 2: To identify the problem associated with harvesting of water chestnut.

Through field observation, interviews with the farmers were conducted to gauge their discomfort for fulfilling the objective. Discomfort levels were assessed using the Borg CR-10 scale, a widely used subjective rating scale. Participants were asked to rate their discomfort levels on a scale from 0 (no discomfort) to 10 (extreme discomfort) during product usage. Following the field study, it was found

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that the challenges included the disadvantages associated with locally made floating devi potential ill effects of staying in water bodies, the discomfort of boat harvesting, and bare-hand plucking. Detailed descriptions for the same have been provided in Chapter 2 of the thesis.

Objective 3: To identify most appropriate/ feasible solution to address the various problems associated with harvesting process of water chestnut

During the study, challenges related to the harvesting of water-chestnut were identified. To address these challenges, three assistive products were developed. The products include a floating device, a plucking aid, and a low-cost Wader (PPE). The design and development description of each prototype are included in Chapter 3, 4 and 5 respectively.

A floating device was designed and developed to aid in the harvesting process of water-chestnut. The device intends to provide support and stability to the farmers while working in water bodies. It helps enhance their balance, mobility, and overall efficiency during the harvesting process. Another assistive product, a plucking aid has been designed to facilitate efficient and effective plucking of water-chestnuts fruit from the plants. The aim is to reduce the physical strain on the harvesters. The study recognized the importance of safety from contact with water and water-insects during the harvesting process, the study also focused on developing appropriate low cost wader (PPE).

Objective 4: To design and develop the targeted solution and field testing for studying effectiveness

In the research three prototypes have been developed and the description of the design and development of each prototype is given in Chapters 3, 4 and 5 respectively.

Prototypes were tested using suitable methodologies. Each testing method and its corresponding results have been presented in their respective chapters. Productivity measurements were employed to evaluate how the product affected users' efficiency and output. These involved tasks completed, time taken, or other relevant productivity metrics.

Heart rate monitoring was also used to assess the physiological response of users during product use. A comprehensive evaluation of the products was validated through different testing methods.

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6.4 Novelties of the research

- Product design strategies concerning aquatic agriculture is a prominent contribution in the knowledge domain. The product design strategies for water chestnut harvesting may easily be adopted for any other aquatic food-crops (lotus stem, foxnut, water mimosa, nori, gim etc.) across different geographic locations. Innovativeness of the developed floating device, and plucking aid is evident from the corresponding patents and design registration. The current thesis has demonstrated that facilitating the harvesting process not only happens (or is possible) through product development directly associated with the harvesting process but it can also be facilitated by developing assistive products that are indirectly associated with the harvesting. This is a unique observation of the current thesis.
- The design and development of a durable and easily fabricable floating device is a novel contribution of the research. The device's development highlighted the design criteria and methodology for fabricating an assistive floating device for aquatic crop cultivation. The application of FRP has been explored for developing a new floating device and for increasing farmers' productivity with the use of the new floating device compared with the traditional floating device.
- Development of innovative plucking aid with 3D printing technology for plucking the water-chestnut fruit. The design of the plucking aid is unique and the extruded portion at the bottom of the aid helps to maintain the thumb's neutral position during plucking activities.
- Different water-proof materials have been explored and tested for developing a low-cost wader (PPE) as an alternative to the costly waders available in the market. The strategy followed for local fabrication of such PPE will be beneficial for the farmers in a resource-constrained scenario. The feasibility of local fabrication and its effectiveness in a real aquatic cultivation environment have been tested to obtain satisfactory results.
- The application of Design-thinking for interventions in the domain of aquatic agriculture is the first of its kind. In the study, user-centric design and participatory approach methods were used for the understanding the challenges of the farmers as well as for the development of different assistive products to enhance the ease of working condition. The methods found useful for product development in the case of low-income groups in the developing countries.

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6.5 Key contributions of the present research

The findings of the research constitute a substantial addition to the knowledge base and the design-development process for aquatic crop cultivation. The original contributions made by this research have been discussed below.

6.5.1 Contribution to the knowledge-base

The research reported in the present thesis is the first of its kind study that explores the cultivation of water chestnut and the various challenges faced by the cultivators. As the reported research related to the use of design thinking method, and the application of ergonomic principles in the design and development of tools and techniques for aquatic agricultural practices is scarce, the current research is a novel approach to highlighting and addressing the prominent research gap in this domain. The research has demonstrated systematic design research and the process of developing and field testing various accessories and agricultural aids (a floating device, a plucking aid, and a low-cost wader-PPE), which have proven to be very helpful for productivity improvement and drudgery reduction of the aquatic farmers. The novel knowledge regarding aquatic cultivation of water-chestnut in north-east India reported in the current thesis would help and motivate budding researchers, agriculture scientists, agriculture engineers/ designers to focus more on the unexplored areas. This would ultimately lead to betterment of socio-economic conditions of the aquatic farmers.

It has been observed from field visits that farmers involved in the cultivation of the water-chestnut crop (an aquatic food crop) use primitive methods and tools for the cultivation of the water-chestnut crop. The tools lack functionality and have many disadvantages. The literature review suggests a huge gap between the research and development for terrestrial crop cultivation and aquatic crop cultivation.

6.5.2 Methodological perspective

The current research provides a systematic design and research methodology to develop aquatic agricultural tools and techniques. The methodology deals with research gap identification following literature review; understanding the aquatic cultivation process by field observation and interacting with the farmers; identifying various challenges faced by the farmers during field surveys (using questionnaire); exploring various product concepts to address the identified problems; developing prototypes and thereafter conducting field trials to get feedback from the aquatic farmers and finally design modification towards final deliverables. The reported methodology would help other

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researchers follow a similar approach as they plan to execute their research in design and devel of agricultural aids with due consideration of ergonomic principles and participatory design methods.

6.5.3 Contribution to society

The research is directly linked to the grassroots workers and people coming under the 'Base of the Pyramid'. The study observations such as cultivation methods and interventions in the current setting, can be demonstrated to the farmers of other areas, allowing the utilization of unused water bodies and easy cultivation of the aquatic food crops. The current research has addressed very prominent issues regarding physical labor and the occupational health and safety of the aquatic farmers. It has displayed how drudgery can be reduced and productivity and work efficiency can be enhanced through appropriate design interventions.

It is interesting to note that all the developed design solutions are low cost, possible for local fabrication, and easily adaptable. Thus, there is a fair chance of acceptance of the solutions among the aquatic farmers. It is expected that the reported research will motivate other researchers, designers, and engineers to conduct similar research to address the real life needs of aquatic agricultural workers. It is believed that systematic research and, thereby, implemented design intervention will aid their socio-economic upliftment.

Aligned with the global agenda for sustainable development, this thesis contributes to several Sustainable Development Goals (SDGs) outlined by the United Nations. SDG 2: Zero Hunger - By improving the efficiency of harvesting water-chestnuts, these tools can contribute to ensuring food security. Increased productivity can lead to higher crop yields and the availability of nutritious food, thereby helping combat hunger and malnutrition. SDG 3: Ensure healthy lives and promote well-being for all at all ages. The thesis addresses this goal by focusing on the development of assistive tools that reduce drudgery and increase crop productivity. By minimizing physical strain and fatigue among agricultural workers, these tools promote the well-being and health of the individuals involved in the harvesting process.

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6.6 Limitations and scope for future research

Although the researcher took sufficient care to perform the experiments in the best way possible, numerous shortcomings still exist. The limitations and future scope have been mentioned in the following section.

- The study was conducted only in the Assam state of India, which that has a large portion under waterlogged conditions. The developed product can be tested with farmers from other parts of the country.
- Due to COVID induced access restrictions, fewer farmers were identified for testing and data collection, but online resources were explored for the validity of the research.
- Only male farmers were involved in the cultivation of the crop hence, the female group is not considered in the study.
- The solution or prototype proposed as a research outcome to assist the farmers are manual tools. IOT and robotics-based interventions have not been considered because of the design complexity, inadequate electric-power supply in the remote areas and the lack of cost feasibility for the farmers.
- Prototype testing has been done with only one aquatic food crop, while it can also be tested with other aquatic crop cultivation like lotus stem, and foxnut.
- The proposed prototype of a floating device was tested in stagnant water bodies and should be used in the same conditions, the use of the device in rivers or any water streams is not recommended.

6.7 Conclusion

The research aimed to explore the cultivation method, challenges involved, need identification, and assistive-aids development to facilitate harvesting of water-chestnut cultivated by aquatic farmers in north-east India. The design and development of three assistive tools i.e., a floating device, a plucking-aid and a low cost wader were found effective in terms of productivity, safety and reducing the drudgery of the farmers engaged in aquatic cultivation.

An ergonomically designed floating device, which is one of the outcomes of the present research, demonstrated salient design characteristics in terms of maneuverability ease through webbed water-chestnut plant branches floated on and within water bodies, comfortable posture during harvesting

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activities, and ease of maintaining balance. Developed lightweight, water resistant, and compatible plucking-aid was found easy to use and effective for harvesting. The extruded nail-like projection at the bottom of the plucking-aid was helpful in reducing muscular activity and maintaining the thumb neutral position for long-term usage during plucking. Additionally, the use of a low-cost wader (PPE) was noticed beneficial for protecting the farmers from unhygienic water contact as well as water insects.

The research methodology used in the present research may be reproduced by emulating similar exploration in various occupational sectors to recognize occupation specific ergonomic stressors and suggest suitable solutions, specifically for workers in unorganized sectors. The current user-centred research is novel in the domain of aquatic agriculture by addressing challenges faced by the farmers from the perspective of productivity and OSH through the design and development of context specific design solutions.

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Appendix

Appendix I - Question used for data collection

1. Serial number	
2. Village/ Block	
3. District	
4. State	
5. Age	
6. Gender	1. Male 2. Female
7. Native place (block, district and state)	
8. Marital status	
9. Education Level	1. No education 2. Primary 3. Secondary 4. above
10. Hand domination	1. Left 2. Right
11. Operational land holdings	
12. Experience in the cultivation of water chestnut	<5 years 5-10 years 10-15 years >15 years
13. Total working hours in a day?	
14. Total working days in a week ?	
15. How many times you take rest during working hour ?	
16. how long you take rest between the work ?	
17. Reason for taking break	1. Lunch 2. Due to tiredness 3. Smoking 4. Other………..
18. Weight	
19. Work related accident, slip, trip and fall	Yes No
20. Smoking	Yes No
21. Alcohol Intake	Yes No
22. Job satisfaction	1. Low, 2. Moderate, 3. High

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Appendix II Pond Related information

1. Area of the pond		
2. Depth of the pond (minimum and maximum)		
3. Which variety of water chestnut you use for the cultivation?		
4. What way/ways you use for harvesting water chestnut?	Tools	When it is used
	1. Boat	
	2. Locally made floating device	
	3. Wearing PPE	
	4. without any aid	
5. While working in the field, have you met with any accident in past?	A. Cuts on the body with any sharp object B. Any insect bite C. Got unbalanced while working D. Others please specify………	
6. In which month you start the cleaning ?		
7. In which month you start the harvesting ?		
8. In which month harvesting end?		
9. Harvesting rate (Kg of water chestnut harvested per person per day)		
10. Animal harm the crop	1. Strongly disagree 2. Disagree 3. Unsure 4. Agree 5. Strongly Agree	
11. productivity reduces due to attack of insect	1. Strongly disagree 2. Disagree 3. Unsure 4. Agree 5. Strongly Agree	

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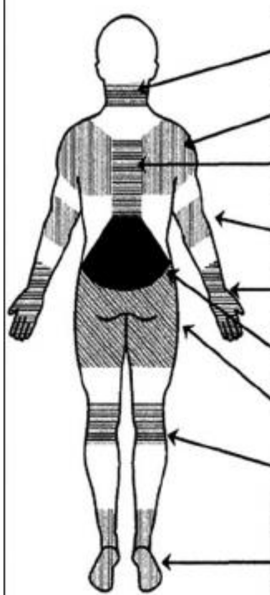
Appendix III - Nordic Questionnaire



	Have you at any time during the last 12 months had trouble (such as ache, pain, discomfort, numbness) in:	During the last 12 months have you been prevented from carrying out normal activities (e.g. job, housework, hobbies) because of this trouble in:	During the last 12 months have you seen a physician for this condition:	During the last 7 days have you had trouble in:
NECK	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes
SHOULDERS	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes
UPPER BACK	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes
ELBOWS	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes
WRISTS/ HANDS	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes
LOWER BACK	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes
HIPS/ THIGHS	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes
KNEES	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes
ANKLES/ FEET	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes

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Appendix IV System Usability Scale

Sr.no.	System Usability Scale questions	Ratings				
		Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
1.	I think that I would like to use this product frequently.					
2.	I found the product unnecessarily complex.					
3.	I thought the product was easy to use.					
4.	I think that I would need the support of a technical person to be able to use this product.					
5.	I found the various functions in the Product very well integrated.					
6.	I thought there was too much inconsistency in the Product.					
7.	I would imagine that most people would learn to use the Product very quickly.					
8.	I found the Product very cumbersome to use.					
9.	I felt very confident using the Product.					
10.	I need to learn many things before I could get going with this Product.					

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Appendix V Polar Heart rate monitor

Particular	**Specification**
Manufacturer	Polar Electro Oy Finland
Model	RS800CX
Battery type	CR2032
Maximum files	99
Maximum time	99 h 59 min 59 s
Operating Temperature	-10° C to + 50°
Recording interval	1s, 2s, 5s, 15s or 60s
R-R Recording	Yes, accuracy of 1ms
Heart rate measurement	bpm, %, and % HRR
Heart rate measuring range	15-240 bpm
Accuracy of heart rate	±1% or 1 bpm, whichever larger
Data transfer	Compatible with Polar Pro Trainer 5 software Via IrDA USB Adapter
System Requirements	Windows® 2000/XP/Vista 32/64-bit or Windows 7 32/64-bit IrDA compatible port (an external IrDA device or an internal IR port

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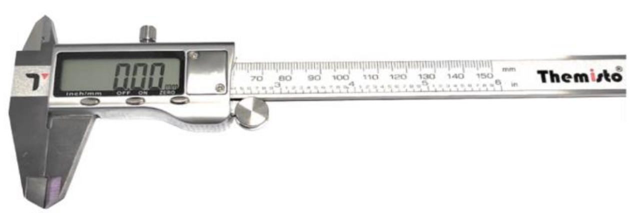
Appendix VI Delsys Trigno Wireless EMG Sensors

Particular	**Specification**
Typical Operating Range	40m
RF Frequency Band	240-2483 MHz(ISM)
Power Consumption	<6W (operation)<14W (during recharge)
Sensor Recharge Time	<2.5 Hours
USB Type	USB 2.0 complaint, high speed
Temperature Range	5-50 degree Celsius
Maximum number of Sensors	16
Signal group delay	48ms
EMG Signal Range	±5V
Effective EMG Signal Gain	909 V/V ±5%
Channel Offset(r.t.o)	±157mV (max)
Baseline Noise	<0.5 mV RMS
DAC Filter Bandwidth	DC-500 Hz, 160 dB/Dec.
Passband Ripple	<2% with Sin(X)/X correction
Connector Type	Scsi-68, Type II

Appendix VII Digital Vernier Calliper



Particular	**Specification**
Measuring range	0 -6" / 0-150mm; Accuracy: ± 0.001"/ 0.02mm; Resolution: 0. 0005"/0. 01mm
Measurement modes	The digital caliper has 4 measurement modes, inside and outside diameter, depth, and step with two sets of jaws and a probe
LCD DISPLAY	6" digital

Publications

Chauhan, J. S., Singh, H. J., & Karmakar, S. 2022. Promoting OSH of aquatic agricultural workers through ergonomic design of a floating device. (Abstract), Safety and Health at Work. 13, S255

Chauhan, J.S., Karmakar, S. 2021. Urge for Human-Centered Design Intervention for Harvesting Aquatic Food Crops. In: Chakrabarti A., Poovaiah R., Bokil P., Kant V. (eds) Design for Tomorrow Volume 1. ICoRD 2021. Smart Innovation, Systems and Technologies, vol 221, pp 59-69. Springer, Singapore (2021).

Chauhan, J.S. Singh, H. J., and Karmakar, S. 2021. Traditional cultivation practices of water chestnut in Northeast India (Assam): A field survey. Full paper accepted as a book chapter in proceedings book volume (Advances in Intelligent Systems and Computing) of 19th International Conference of Indian Society of Ergonomics (HWWE2021).

Context-specific considerations for the selection of appropriate crop harvester: Current state of the knowledge (Communicated)

Design and development of plucking aid for water-chestnut harvesting following design thinking process. (Communicated)

Ergonomic Design and development of a Floating Device for Aquatic Agriculture Workers of Northeast India: A systematic design process (communicated)

- **Patents**

Utility patent:

1. Ergonomic floating device. [**Granted**],
   Indian patent Application No.: 202231058384; IP Kolkata
   Date of Filing: 12/10/2022

Design patent:

1. Floating aid for aquatic agriculture. [**Granted**]
   Indian Design Registration Number: 350248-001, Class: 08-08; IP India
   Filed on 27/09/2021.
2. Floating device for aquatic crop. [**Granted**]
   Indian Design Registration Number: 350209-001, Class: 08-08; IP India
   Filed on 27/09/2021.
3. Ergonomic thimble (plucking aid). [**Granted**]
   Indian Design Registration Number: 350283 -004, Class: 08-08; IP India
   Filed on 18/08/2022

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