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Development of Planting Media for Agricultural Land Prone to Waterlogging

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Abstract: Waterlogging is a serious problem currently being faced in the agricultural sector. Climate change has increased the frequency of extreme rainfall events, which has increased the potential for agricultural land flooding. Therefore, innovations in planting media that can float during waterlogging are required. The purpose of this study was to create a planting medium based on simple automatic water flow and excess water control using a climate-based approach and plant water needs. The study stages were divided into three categories: climate data, planting media design and simulation, and field tests. The results of this study show that the design of planting media that considers plant water needs based on the amount of water lost can save water. The application of a drainage system on the side of the planting media prevented plant death in the planting media due to waterlogging, based on projections of an increase in extreme R-events. The use of plastic bottles in the design of the planting media was effective in providing buoyancy to the planting media during waterlogging. The developed planting medium is suitable for adaptation to agricultural land that is prone to waterlogging amidst the threat of the climate crisis that the world is currently facing.

Keywords: Agricultural land; Climate change; Planting media; Waterlogging

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1. Introduction

The problem of waterlogged agricultural land in Indonesia is often faced by farmers, resulting in decreased yields and crop failures. It is estimated that agricultural land in Indonesia will continue to decrease because of waterlogging. It is estimated that in Java, it will decrease by 146,473 ha and in Sulawesi by 17,069 ha [1], whereas there are no data for Sumatra, Kalimantan, and Papua. Waterlogging has a major impact that can significantly complicate various activities [2,3]. Waterlogging, in addition to drought and agricultural land pollution, is a serious problem currently faced by the agricultural sector [4,5]. Waterlogging is typically caused by extreme rainfall[6]. Waterlogging is estimated to affect approximately 10% of land globally, which has an impact on the reduction or loss of agricultural land, reduced yields, and affects plant growth and death [7-10]. The longer the duration of waterlogging on agricultural land, the greater the impact [6]. In addition, agricultural lands that are not equipped with drainage systems are at greater risk of flooding [11,12].

The threat of climate change, such as extreme rainfall events, will continue to increase because of the influence of increasing air temperatures. It was estimated that for every 10-year period, increasing air temperatures will increases the frequency of extreme rainfall events. An increase of 1 °C will increase the frequency of extreme rainfall events by 1.3, 1.5, 2 °C will increase by 1.7 times, and 4 °C by 2.7 times [13]. The averages air temperature in Indonesia has increased by 1.2 °C over the last 40 years, with an increase rate of 0.03 °C per year [14,15]. It is estimated that the increase in air temperature in Indonesia by 2050 could reach 2 °C, which would cause a 1.3 to increase in extreme rainfall. This estimate is supported by observations from weather stations, which indicate that extreme rainfall tends to increase in Indonesia [13].

Climate change also causes the intensity of annual rainfall per year to tend to change, either increasing or decreasing [13,14]. This condition affects changes in the wet and dry months per year [16]. The potential for flooding agricultural land in Indonesia is increasing because of climate change. Therefore, to address the potential for an increasing incidence of flooded agricultural land, innovation in integrated agricultural systems is required [12]. Innovation can be in the form of making planting media that can float when there is waterlogging; this floating concept can utilize plastic bottles in media design. Automatic water control must be added to the design to prepare for future droughts. The purpose of this study was to develop floating planting media with automatic water control using a climate study approach and to determine plant water needs.

2. Method

2.1. Material

The materials used in this study included material for planting media, software, and computer devices. The climate data studies and data processing were performed using Microsoft Excel, and design creation and simulations were performed using SolidWorks. The materials needed to make planting media are ½″ PVC pipes, pipe connections, plastic bottles, 500 µm geomembranes, ½″ ball valves, PVC glue, cable ties, and a set of drip irrigations.

2.2. Research Procedures

The research stages were grouped into three parts: climate data study, design creation with a simulation approach using SolidWorks software, and field testing to determine the success of the planting media design **(Figure 1)**.

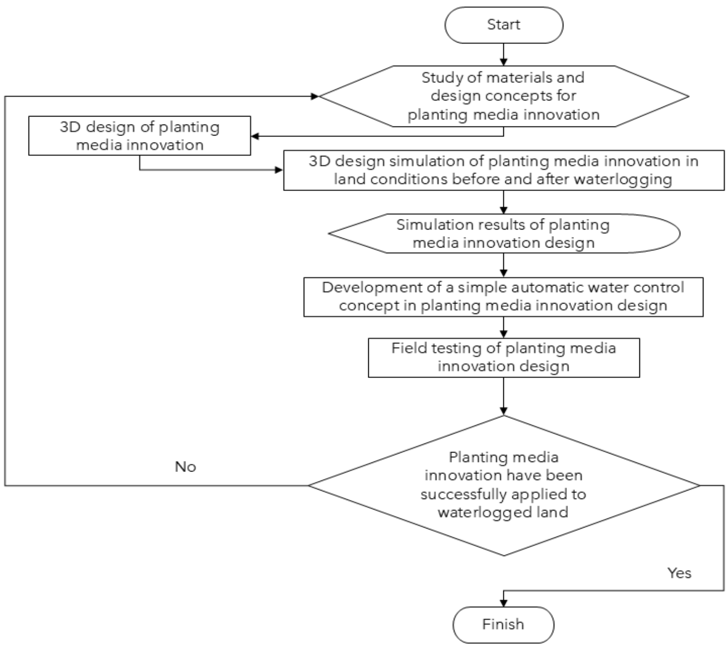

Figure 1. Research flow

2.2.1. Climate data study

The climate data were accessed through The Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG) (https://dataonline.bmkg.go.id/home) and NASA Power (https://power.larc.nasa.gov/data-access-viewer/) [17,18]. Data were accessed over the last decade (2014–2023). The data variables studied included the minimum air temperature (Tmin), maximum air temperature (Tmax), average air temperature (Tavg), relative air humidity (RH), rainfall (R), duration of sunshine (SS), and average wind speed (FFavg). Climate data in South Sumatra from the BMKG were processed using the data processing function in Microsoft Excel (average, max, and min). Climate data were used to estimate the water requirements of the media based on the evapotranspiration rate (ET). The gaps in the air temperature data on certain days were filled with air temperature data from the previous day to ensure completeness of the variable data used in the ET estimation [19]. Changes in the minimum, maximum, and average daily air temperatures from the BMKG data were analyzed using the trend function in Microsoft Excel [14]. NASA Power data were used to estimate the climate details at the location for field testing of the planting media.

2.2.2. Planting media design

a. Estimate plant water requirements

The water balance principle was used to estimate the water requirement of the planting media. The water balance principle describes a comparison between R and ET [20]. The estimation of the ET rate provides information on the water loss that occurs in the planting media. The ET rate was estimated using the FAO Penman-Monteith model [21]:

$$ET = \frac{0{,}408\,\Delta(R_n - G) + \gamma\,\frac{900}{T + 273}\,U_2(e^o - e_a)}{\Delta + \gamma(1 + 0{,}34\,U_2)} \qquad (1)$$

Description:

R_n = Solar radiation on the plant surface (MJ m^{-2} day^{-1})
G = Soil heat flux density (MJ m^{-2} day^{-1})
γ = Psychrometric constant (kPa $°C^{-1}$)
T = Average temperature (^oC) (Tavg)
U_2 = Win speed (m/s)
e^o = Saturation vapor pressure (kPa)
e_a = Actual vapor pressure (kPa)
$e^o - e_a$ = Saturation vapor pressure deficit (kPa)
Δ = Slope of vapor pressure curve (kPa $°C^{-1}$)

b. Design and design simulation

The design and simulation of the planting media were performed using SolidWorks software. The design was based on the results of climate data studies and estimates of the water requirements of the planting media. The design was made by assembling a combination of pipes using plastic bottles with the criteria of having a capacity of 12 L or 15 L, planting media, irrigation systems, and excess water disposal systems. The design was simulated to determine the fluid flow in the planting media when it rains, speed conditions, and water flow patterns in the irrigation system. The stages of the planting media simulation were carried out by conceptualizing a 3D model, input boundary and initial conditions, running model, and simulation results [14].

2.2.3. Field testing

Field testing was used to determine the success of the planting media design, which was made to float from the impact of waterlogging, the water disposal system from the impact of excess water, and the irrigation system. The buoyancy of the planting media against waterlogging was tested using a waterlogging simulation. The planting media were designed to measure 1.90 × 1.65 × 0.28 m and were placed in a test pool (dimensions 3 × 2 × 0.5 m) filled with continuously flowing water to determine the media's ability to float. The planting media was soil without a mixture of other materials.

The working system for removing excess water from the planting media was tested by providing excess water irrigation and observing the operation of the planting media system to remove excess water and avoid waterlogging. The success of the planting media irrigation system was tested by observing the average flow of water for watering the entire planting media.

3. Results and Discussion

3.1. Climate data study

A case study in South Sumatra showed climate conditions in the last decade (2014 to 2023) by reviewing climate data from the BMKG, showing an average Tmin of 24.54 °C, Tmax of 32.99 °C, Tavg of 27.79 °C, Rh of 84.54%, FFavg of 1.68 m/s, and R of 2478.71 mm/year. The projected climate conditions in 2050 are that Tmin will increase by 1.69 °C, Tavg will increase by 2.29 °C, and R of 2,314.76 mm/year, whereas Tmax will decrease by -0.25 °C **(Figure 2)**. Climate data projections from to 1980-2020 to 1980-2050 air temperature increased by 1.87 °C, Tmin 1.65 °C, Tmax 2.35 °C, and Tavg 1.60 °C [14]. It is estimated that extreme R events will increase by 1.5 up to 1.7 times due to an increase in air temperature of 1.87 °C [13]. This projection shows that the R value increases, indicating that the potential for agricultural land to be flooded is increasing, and the air temperature also increases, which causes the need for plant water to also increase.

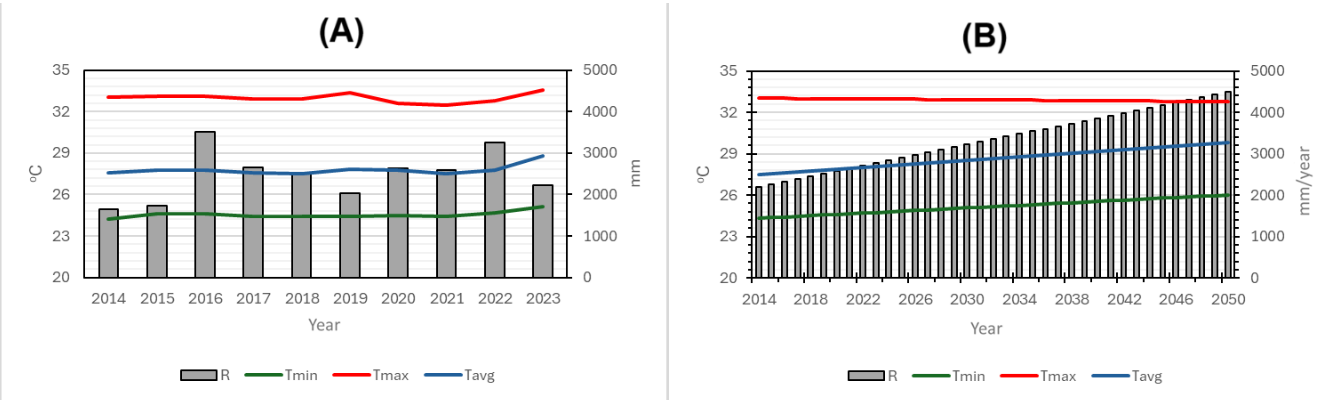

Figure 2. Tmin, Tmax, Tavg, R 2014 - 2023 (A) and projection to 2014 - 2050 (B)

Specific details of field testing were conducted in Prabumulih City with climate conditions in 2023-2024 based on climate data studies from NASA Power showing Tmin 23.97 °C, Tmax 30.76 °C, and Tavg 27.07 °C, Rh 87.06%, R 2567.68 mm/year, and FFavg 2 m/s. The correlation between the NASA Power data and data from the BMKG South Sumatra Climatology Station showed a correlation (R^2) of 0.95. An R^2 value of 0.95 indicates a very strong data correlation [22]. Based on these results, it can be concluded that the climate conditions in Prabumulih City are very similar to those in South Sumatra.

3.2. Planting media design

The ET rate from 2014 - 2023 showed an average of 4.42 mm/day, a maximum of 7.04 mm/day, and a minimum of 2.20 mm/day. With the changes in climate conditions, the ET rate projected to 2050 is expected to decrease by -0.02 mm/day (-0.01 mm/day up to -0.05 mm/day), which means that the the water evaporation will be smaller **(Figure 3)**. The ET rate is closely related to changes in air temperature, such that every change in air temperature will affects the change in the ET rate by 10 up to 30% [20]. Based on the projection of climate conditions in 2050, air temperature conditions tend to increase, but the ET rate value tends to decrease because the Tx and FFavg values show a downward trend, and Rh tends to increase, causing the ET rate estimate to show a downward trend. An increase in air temperature and wind speed increases the ET rate; otherwise, if there is a decrease, the ET rate also decreases [23]. An increase in Rh, which is inversely proportional to the air temperature and wind speed, decreases the ET rate, and vice versa [24]. Further sensitivity analysis is needed to determine which variables most affect the ET rate using the FAO Penman-Monteith model [23]. The results of the sensitivity analysis of the FAO Penman-Monteith model showed that Tx was the most sensitive variable compared to the other variables [25].

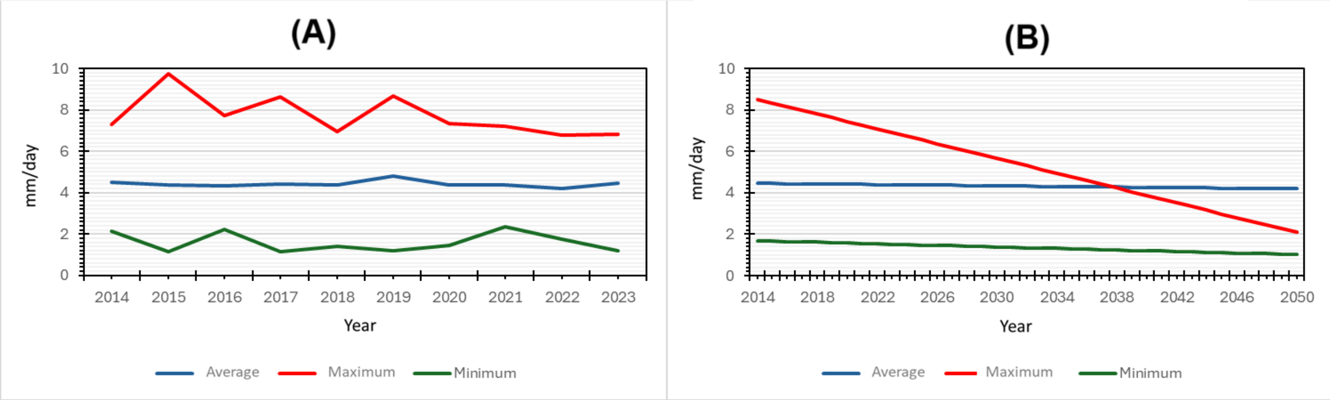

Figure 3. ET rate from 2014 to 2023 (A) and ET rate projection to 2014 to 2050 (B)

The design of the planting media combines PVC pipes, pipe connections, plastic bottles, planting media (soil and geomembranes), irrigation systems using drip irrigation, and excess water disposal systems **(Figure 4)**. Soil functions as a planting medium, and the geomembrane becomes a medium to hold soil and protect water from entering from the outside if the location where the planting media is placed is flooded. The PCV pipe functions as a frame to tie plastic bottles and is assembled into a square shape. A square shape was used to provide the same buoyancy force on each side of the planting media. A square shape was used to provide the same buoyancy force on each side of the planting media. The planting irrigation system was regulated using a drip irrigation system that considered the amount of water required (daily ET rate) in the planting media, with the irrigation source stored in plastic bottles in the middle of the planting media. The excess water system was created by adding a ball valve on the side of the geomembrane so that excess water would not cause the planting media to be flooded with water.

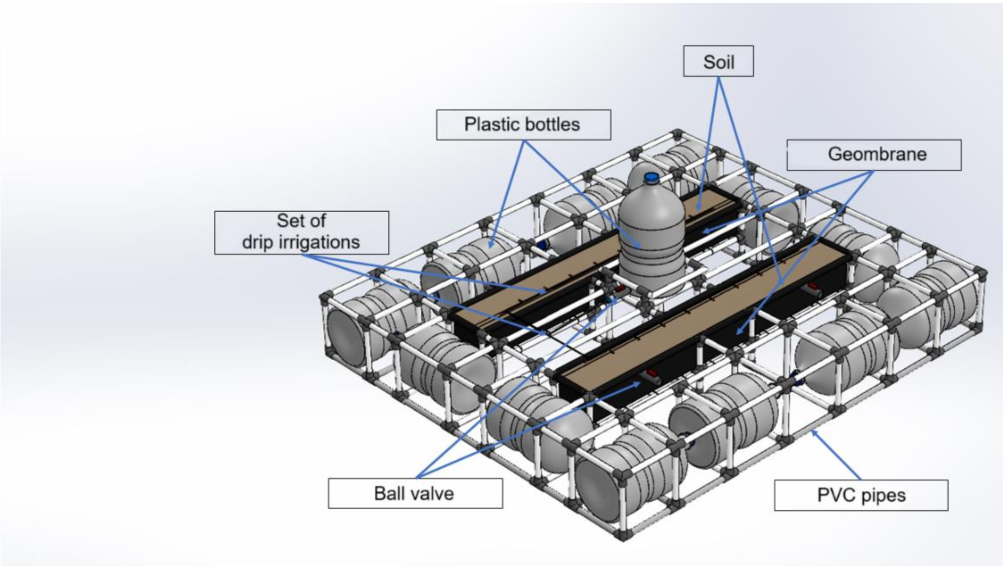

Figure 4. Planting media design for agricultural land prone to waterlogging

Simulation using Solidwork of the flow of R when falling into the planting media design provided information on the flow pattern and changes in water velocity when it hit the planting media **(Figure 5)**. This pattern provides information on the direction of R falling towards the planting media, including the potential for excess water collected in the planting media. The intensity of R determines the amount of water collected in the planting media, thus R causes water to be collected in the planting media because the porosity value of the soil used affects water infiltration before it is discharged through the ball valve.

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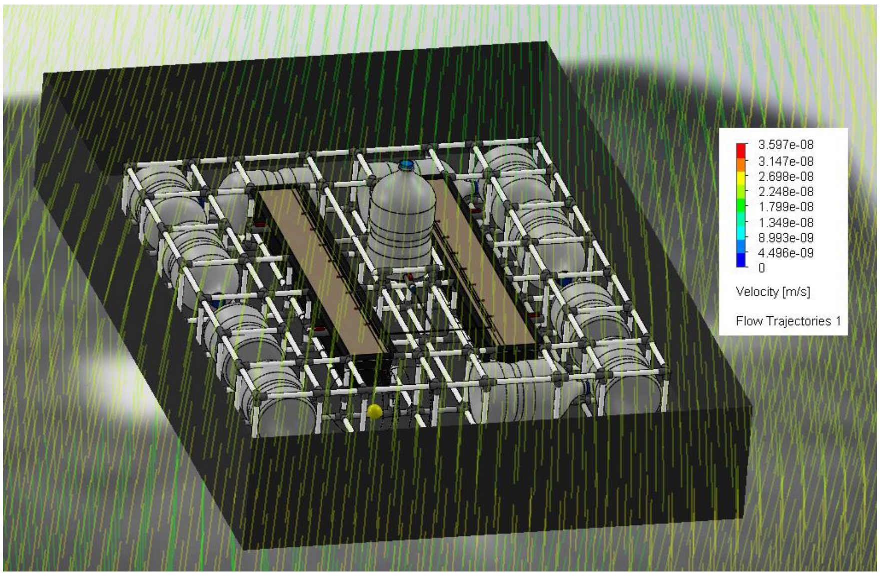

Figure 5. Simulation of R flow in planting media

The water flow in the design of the planting media irrigation system using a drip irrigation system simulated using SolidWorks exhibited an uneven change in the water flow rate at each outlet **(Figure 6)**. These conditions require adjusting the water flow rate at the drip irrigation outlet by providing a water flow density setting that is adjusted to the water speed simulation. The water flow rate at the drip irrigation system inlet was adjusted based on the calculated average ET rate of 4.42 mm/day. If adjusted to the area of the planting medium, the water requirement is 18 x 10^{-3} m^3/day (1.86 L/day) or 21 x 10^{-8} m^3/s. Although the simulation results did not show an even water flow rate at each drip irrigation outlet, the overall water flow rate of 39 x 10^{-8} m/s (18 x 10^{-8} m^3/s) was not significantly different from the amount of water needed for the entire area of the planting media. To adjust the water requirements of the planting medium, the inlet must flow at a speed of 30 x 10^{-8} m/s so that the outlet can meet the water requirements of 21 x 10^{-8} m^3/s. The plastic bottles used in the drip irrigation system can hold 12 L of water, so that the filled water can irrigate the plants for 6.47 days. This irrigation system saves water by adjusting the water requirements of the plants and irrigation.

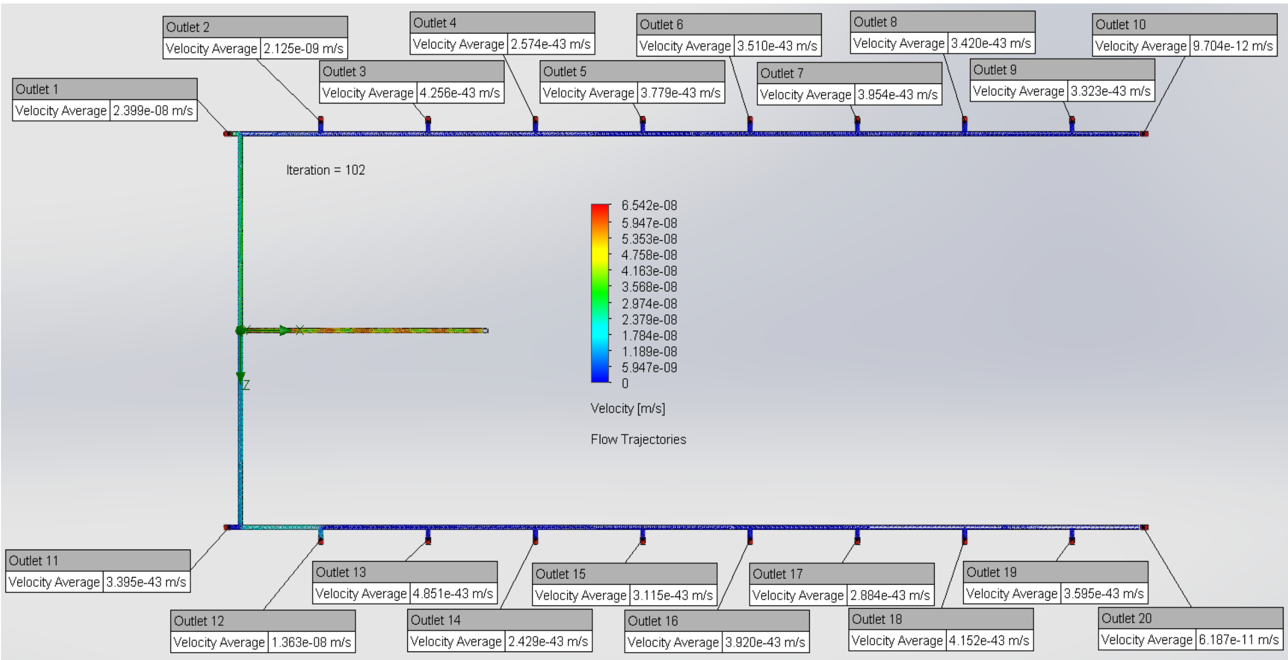

Figure 6. Simulation of water flow rate in planting media with drip irrigation system

3.3. Field testing

The floating ability test of the planting media indicated that the design of the planting media allowed it to float. This planting medium design is only suitable for vegetable plants with a short harvest period. The test results showed that 2/3 of the planting media floated on the water **(Figure 7A)** and 1/3 of the planting media was below the water surface **(Figure 7B)**. However, the field test could not be able to determine the maximum load that could be accommodated by the planting medium. In addition, the movement of the floating planting media is greatly influenced by the wind speed. These results show that this planting medium can adapt to agricultural land prone to waterlogging because of its floating ability.

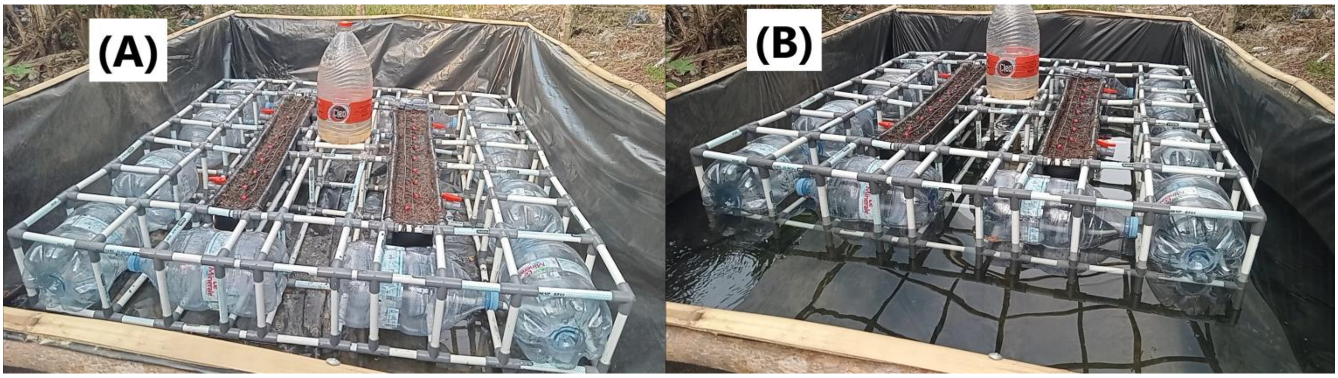

Figure 7. Field testing of the floating ability of planting media, before being submerged in water (A) and after being submerged in water (B)

The application of an excess water disposal system in the planting medium can also prevent the planting medium from being waterlogged, which can cause plant death **(Figure 8B)**. In addition, the amount of water used to irrigate the plants is controlled by adjusting the water needs of the planting medium so that water can be saved from the potential of an irrigation system that exceeds the water needs of the plants **(Figure 8A)**. However, for the long-term durability of water reserves in used plastic bottles connected to a drip irrigation system, it cannot last up to 6.47 d owing to problems with leakage in the flow system, and the very small flow rate settings make it difficult to provide exact figures. Changes in the pressure of the plastic bottles arranged parallel to the top surface of the planting medium also affected the watering system because the pressure produced also decreased as the amount of water decreased.

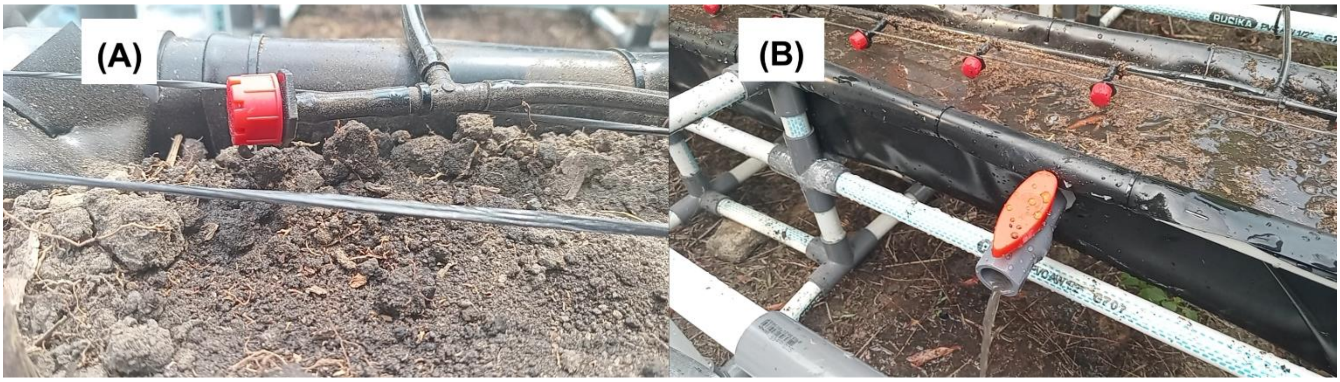

Figure 8. Field testing of planting media, drip irrigation system (A) and testing of excess water disposal system (B)

4. Conclusion

The design of floating planting media, considering the water needs of plants and climate analysis, can save water because the irrigation system in the planting media is in accordance with the needs of the plants, which means that it can prevent excessive water loss. Future climate analysis predicts that extreme R events will increase, and by adding a drainage system on the side of the planting media, plant death in the planting media due to waterlogging can be prevented. The use of geomembranes can prevent water from entering planting media when waterlogging occurs. Application of plastic bottles in the design of planting media. The results of field tests showed effective results in providing buoyancy to the planting media when waterlogging occurs, making it very suitable for adaptation to agricultural land that is prone to waterlogging amidst the threat of the climate crisis that the world is currently facing.

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