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Research Article

Rainwater harvesting and water-saving irrigation for enhancing land productivity in upland rice cultivation

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ABSTRACT

The development of dry land requires precise planning due to its climate-sensitive nature. It is essential to ensure water availability to meet crop water requirements. Rainwater harvesting remains underutilized in upland rice cultivation. The field experiment was conducted in Tulungagung Regency, East Java province, Indonesia from August to December 2017. The research aimed to develop water harvesting technology and irrigation management for upland rice. The nested design was the experimental design with irrigation levels and varieties of upland rice treatments. Four irrigation levels were farmer's customs, 70%, 85%, and 100% of the crop water requirement, while the varieties were Situ Patenggang, Inpago-9, and Inpago-11. Our findings revealed that 70% of the crop water requirement was sufficient for upland rice cultivation in dryland. Crop yields were unaffected by the irrigation level. Differences among upland rice varieties were only significant on plant height character. There was an increased cropping index due to additional water sources in the last months of the dry season until the early rainy season. Rainwater harvesting can be adapted to climate change, especially in areas that often experience water shortages.

Keywords: *dry land, channel reservoir, irrigation level, crop water requirement*

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INTRODUCTION

Research and development on climate and water resources must help accelerate agricultural growth. In dry lands, water is the primary determinant of production sustainability. Uncertain water availability constrains crop production on dry land due to spatial and temporal variations in rainfall.

In Tulungagung Regency, the cropping index has increased due to additional water sources in the dry season. The dry land area in Tulungagung Regency is approximately 18.32% (Tulungagung Regency Government, 2022). Dryland development in East Java province targets areas not served by irrigation networks. The research was conducted on the direction and focus of dry land research and development, namely optimizing the use of existing dry land, mainly land based on smallholder agriculture. Rice farming is a form of subsistence farming typically used to meet daily needs. This aligns with Oonyu (2011) finding that upland rice is the preferred commodity for maintaining income, especially in drought-prone areas.

The agricultural sector faces various challenges when it comes to using dry land as a new source of growth, namely the rapid degradation of land resulting from soil erosion, loss of soil organic matter, soil compaction, and water supply scarcity (Rachman, 2017). The scarcity of water supply hampers dry land agriculture in dry climates. Upland rice has been able to increase production with the development of technological innovations such as superior varieties and cultivation technology (Toha et al., 2008). Excellent upland rice varieties have been developed to overcome various physical and biological problems in dry land (Hairmansis et al., 2016). Nevertheless, the adoption rate by farmers is low despite the potential productivity increase of upland rice by superior varieties. Upland rice cultivation is usually carried out during the rainy season, which has hindered technological innovations in water management for dry land upland rice.

Water sources can be obtained from natural sources such as springs or water harvesting technology. The techniques developed are tailored to the location and do not burden farmers with their farming activities. According to Rachman (2017) and Heryani et al. (2013a), to improve soil quality and crop yields, conservation agriculture can apply techniques without tillage (TOT) and the use of mulch. TOT can increase the percolation rate, while mulch can protect the soil surface and increase crop yields.

Water harvesting techniques have been applied worldwide to meet crop water requirements and increase dry land productivity (Bafdal & Dwiratna, 2018; Aznar-Sánchez et al., 2017; and Qadir et al., 2007). This study employed channel reservoirs as a water harvesting system in addition to small farm reservoirs and long storage. The construction of channel reservoirs involves damming small rivers or natural channels. Soil and water productivity can be increased by having additional water sources from water harvesting (Heryani et al., 2013b; 2014). Using rainwater harvesting for irrigation in dry land is needed and should be expanded for the sustainability of agricultural production. Water resources should be used more efficiently, supported by water-saving irrigation techniques (Ertop et al., 2023).

In addition to increasing the cropping index, water harvesting also has other advantages: 1) farmers have access to water in dams, so they do not depend too much on rainfall; 2) in certain countries, water harvesting can reduce the fee for paying household water use by 50-60%; 3) water harvested for any purpose will prevent groundwater degradation; 4) the costs of a water harvesting system are affordable, and it can reduce dependence on springs; groundwater can be recharged by using excess harvested water; 5) can reduce the likelihood of flooding in urban areas and reduce soil erosion in sloping agricultural areas (Morey et al., 2016). The research aimed to develop water management designs and irrigation techniques for cultivating upland rice plants on dry land.

MATERIALS AND METHODS

Location and materials

The field experiment was conducted on the farmer's dry land with a wet climate in Kedoyo Village, Sendang subdistrict, Tulungagung Regency of East Java province, Indonesia from August 9th to December 7^{th,} 2017. Three rice varieties were used: Situ Patenggang, Inpago-9, and Inpago-11.

The fertilizers used 250 kg Urea ha^{-1}, 150 kg SP-36 ha^{-1}, and 100 kg KCl ha^{-1}. Urea was given half the dose at planting and the remainder 45 days after planting. SP-36 was given at planting, while KCl was given three weeks after planting. The fertilizer was placed at 5-10 cm from the plant row.

Cyperin 250 EC insecticide was used to control pests with a dosage of 2mL L^{-1}. Fungicide of Dithane M-45 (2g L^{-1}) was mixed with seeds at planting time to prevent and eradicate fungal-borne disease and repeated in ten days. Herbicide (Roundup Biosorb 486 SL0) was applied 14 mL Roundup L^{-1} of water, and applied before tillage. Straw mulch thickness of 2 tons ha^{-1} was used about ten days after planting.

Channel reservoir infrastructure design

Channel reservoirs, small dams in natural channels or small rivers, are a source of irrigation water that can increase the water level to be channeled as irrigation water. The channel reservoir was constructed using stone, sand, and cement materials. Table 1 presents the design of the channel reservoir infrastructure.

Table 1. Preconditions and characteristics of water channel reservoirs.

No.	Parameters	Preconditions	Infrastructure characteristics
1	River characteristics		
	Wide (L)	< 15 m	Weir height (H) <2 m If L = 20 - 25 m, H <1.5 m If L = 30 - 40 m, H< 1 m
	Depth (D)	< 2 m	
	The difference in elevation between the water surface of the river and the land surface	The land surface elevation is lower than the water level.	Constructing a primary canal made of masonry between the weir and inlet is necessary, with a maximum distance of less than 1 km.
	Soil or rock properties of river body	Not easy to slide	We need to make a weir wing.
2	Flow characteristics		
	Water levels increase during floods	< 1 m	-
	Minimum discharge during the dry season	25 $l.s^{-1}$	Minimum target land area of 25 ha
	Flow Quality	Do not bring materials (sand, stone) during the flood.	The weir needs to be equipped with a drain door.

Experimental design

The experiment used a nested design with three replications. The treatment consisted of two components: irrigation levels and rice varieties. Irrigation levels consisted of four levels: 1) irrigation level according to farmers' habits without calculating the volume of water used; irrigation was stopped when the soil conditions got moist; 2) irrigation level of 70%, 3) 85%, and 4) 100% of the plant's water requirement based on FAO method of crop water balance analysis (Doorenbos & Pruitt, 1975). The Rice variety consisted of Situ Patenggang, Inpago-9, and Inpago-11. The mathematical model is as follows: $Y_{ijk} = \mu + V_i + K_{j/i} + P_k + VP_{ik} + \varepsilon_{ijk}$; i = 1, 2, 3, 4; j = 1, 2, 3, and k = 1, 2, 3; Y_{ijk}: observation of the irrigation factors at *i* level, *j* replication, and *k* variety; μ: General average; *V*: The effect of irrigation techniques; *K*: The effect of replication nested in irrigation; *P*: The effect of variety; *VP*: The effect of interaction between irrigation and variety; ε: experimental error. Differences between treatment means were studied by Duncan's Multiple Range Test (DMRT) is at the 5% level.

The parameters observed were: 1) Plant height of 10 clumps per plot randomly measured before harvest, 2) Number of productive tillers calculated per clump, 3) Number and length of panicles per clump for ten clumps per plot, calculated at harvest time, 4) Number of filled and empty grain calculated per panicle of one main panicle in the samples, 5) Weight of 1,000 filled grain grains was measured with moisture content of 14%, 6) Yield of dry grain harvested on each plot.

Determination of irrigation interval

The optimization of irrigation intervals was determined by comparing net irrigation needs or net irrigation depth (NID) in each plant growth phase with cumulative crop evapotranspiration. Crop evapotranspiration was calculated based on the following equation: Etc = Kc x ETo; Etc: crop evapotranspiration; ETo: reference evapotranspiration; Kc: crop coefficient.

Crop evapotranspiration was determined by 1) identifying the stages of plant growth, determining the length of each growth period, and selecting the Kc that corresponds to the growth period, 2) calculating the Kc during the middle of the growth period based on daily climatic conditions, using the following equation:

$$K_{cmid} = K_{cmid(Tab)} + [0.04(U_2 - 2) - 0.004(RH_{\min} - 45)]\left(\frac{h}{3}\right)^{0.3}$$

Kc mid (Tab): Kc at mid-plant growth period; u_2: daily average wind speed at mid-plant growth period (ms^{-1}); RHmin: average daytime minimum relative humidity; h: Plant height at mid-plant growth period (m).

RESULTS AND DISCUSSION

Soil and climate characteristics

The study was conducted on Inceptisol soil with a 15-30% slope, low to moderate soil fertility, and low soil organic matter content. Increasing the amount of soil organic matter was an effort to enhance the soil's capacity to hold water. According to the laboratory analysis, the top layer 0-20 cm of 1.01-1.07 g cc^{-1} had a reasonably dense bulk density; moderate total pore space (52.2-56.3 % vol); moderate aeration pore (10.3-15.5% vol; moderate available pore water (9.9-13.0% vol); fast soil permeability of 3.30-4.90 cm $hour^{-1}$; and clay texture. The density of the soil in the study site was high. Such conditions could be improved through minimum tillage and the application of organic matter, along with a fertilization system that was balanced according to plant requirements in the location.

Sendang sub-district was classified as a dry land area with a wet climate, with an average annual rainfall of 2,333 mm. Rice plants on dry land require optimum rainfall of > 1,600 mm per year and consecutive wet months of at least four months with rainfall >200 mm (BPTP 2009 in Aisyah et al., 2023). The Sendang sub-district monthly rainfall distribution indicates that the wet month period (rainfall exceeding 200 mm per month) occurs for six consecutive months, from November to April, suggesting that Sendang district was suitable for cultivating upland rice. The dry month period (rainfall < 200 mm per month) lasts six months, starting in May and ending in October. According to Oldeman (1975), the study area's climate type D3 means that rice and other crops can only be planted once a year, and irrigation is necessary during the dry season. Irrigation is essential, especially in the early growth phase. According to Ray et al. (2016), the emergence of seedlings will be hampered if there is a lack of water at an initial stage.

Figure 1 presents the daily rainfall, temperature, and humidity. During August 2017, there was no rain, but on September 28, 2017, the rain reached 40.5 mm. Rain began to occur frequently in October-December, gradually reaching 81.5, 398, and 244.5 mm per month. The average air temperatures in August, September, October, November, and December 2017 were 26.9, 27.3, 28.5, 28.1, and 28.4 °C, respectively.

Water management design through channel reservoir

Water management for the development of upland rice cultivation during the dry season was carried out by constructing a channel reservoir in the Duren Podang rivers with potential target irrigation of 32 ha and discharge in the dry season at 26 L sec^{-1} (Figure 2).

This study showed that rainwater harvesting through channel reservoirs can be used as a source of irrigation in the dry season (in August and September 2017). This is in line with Rejekiningrum et al. (2022a, b), Pauline et al. (2020), Velasco-Muñoz et al. (2019), and Qi et al. (2019) that channel reservoirs as well as other rainwater harvesting technologies like small reservoirs have the irrigation potential.

Usually, in the research area, upland rice cultivation is only carried out once in the rainy season. The recent study was carried out at the end of the dry season (early August) and continues to the rainy season (until early December). The farmers continued to the second rice planting season at the end of December until April. Correspondingly, the channel reservoir increased the cropping index of upland rice from 100 to 200%. This result aligns with Hamdani et al. (2016) and Heryani et al. (2002; 2001) that the channel reservoir increases the cropping index in South Sulawesi and the Special District of Yogyakarta, respectively.

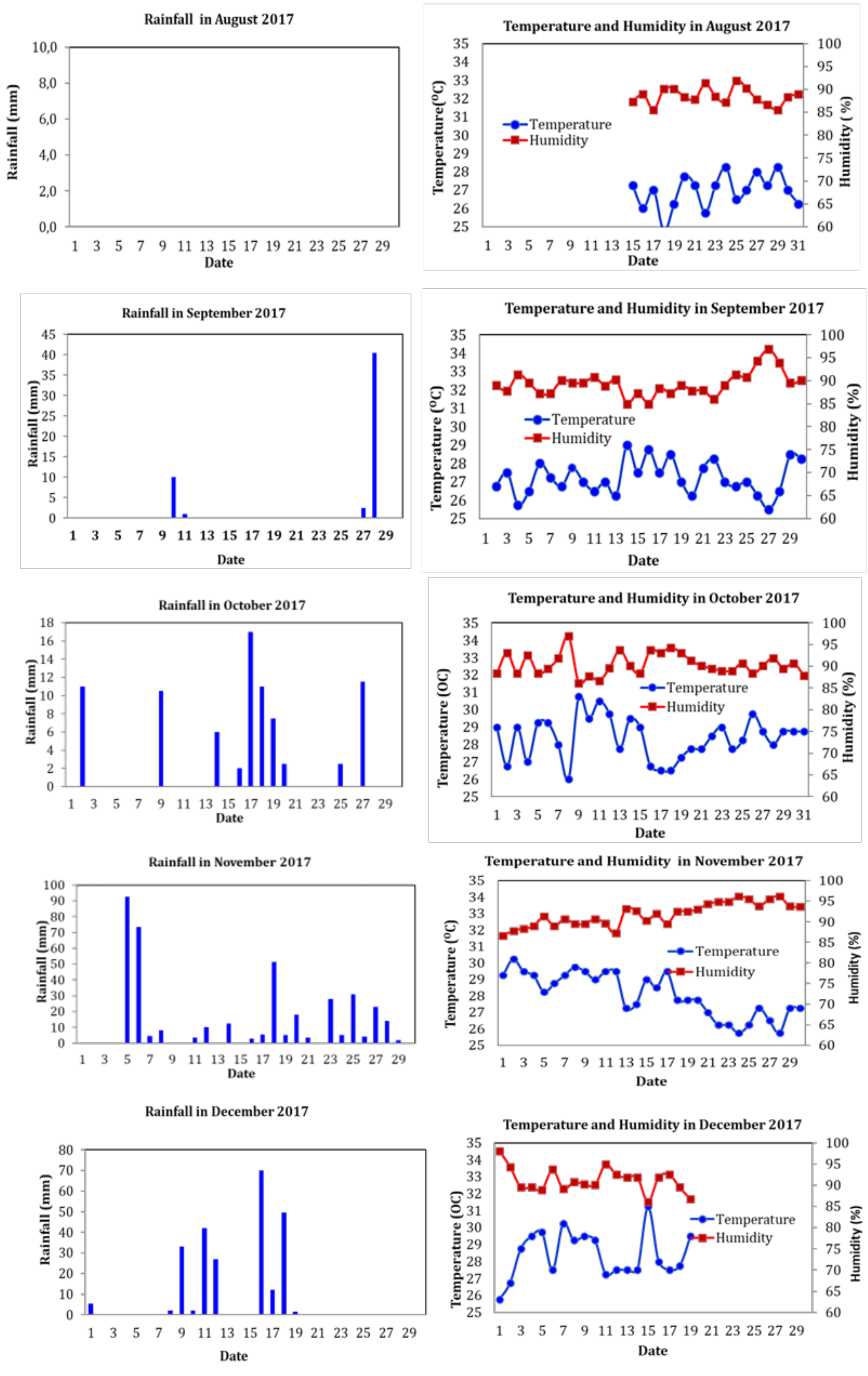

Figure 1. The daily rainfall, temperature, and humidity from August to December 2017.

Figure 2. Channel reservoir as a source of irrigation in upland rice cultivation.

Water distribution system for upland rice cultivation

The distribution of water from the channel reservoir to the upland rice fields was done in the following manner: (a) Open channels were used to channel water to the weir, (b) A weir was a location where water was drained before it was distributed to the land, (c) Water flow to the land using a tarpaulin hose, and (d) Farmers irrigated their land according to their habits, by flooded irrigation. Conditions of canals and weirs and irrigation application activities are presented in Figure 3.

Crop water requirements

Upland rice is generally planted during the rainy season, but upland rice cultivation can be done in the dry season with irrigation water. Initially, the land was only produced once, but now it has been planted twice using the planting pattern of rice-rice-fallow. Tables 2 and 3 present an analysis of water balance to determine 100% crop water requirements. Irrigation in the vegetative stage required 24 mm of water each time with a 9-day interval. As much as 37 mm of irrigation was necessary during the generative phase with a 9-day interval, while in the ripening stage, it was necessary to irrigate 49 mm with a 16-day interval. The irrigation was halted one week to 10 days before harvest. The duration of watering was determined by the volume of water required for each irrigation treatment, which was 70, 85, and 100% of the crop water requirement and the water level in the weir.

Figure 3. Water distribution through channels and the water level setting in the weir.

Table 2. The analysis of evapotranspiration and water available.

Planting date: Aug. 9, 2017										
GP	LGP	Periods		ETo	Kc	Etc	Water content		Density	WA
							FC	PWP		
	days			mm. day^{-1}		mm. day^{-1}	0.3 Bar	15 Bar	g.cm^{-3}	%
Vegetative	60	Aug 10,17	Oct 8,17	2.8	1.01	2.83				
Generative	30	Oct 9,17	Nov 7,17	3.5	1.20	4.20	38.1	26.4	1.04	12.2
Ripening	30	Nov 8, 17	Dec 7,17	3.6	0.90	3.24				

Note: GP: Growing Periods, LGP: Length of GP, FC: Field Capacity, PWP: Permanent Wilting Point, WA: Water Availability

Table 3. Irrigation water requirement for upland rice.

GP	LGP	Periods		ETo	WA	MRD	TWA	GWRF	NWR	Ii
	day			mm day^{-1}	mm m^{-1}	m	mm	p	mm	day
Vegetative	60	Aug10,17	Oct 8, 17	2.8		0.50	61		24	9
Generative	30	Oct 9,17	Nov 7,17	3.5	122.0	0.75	91	0.4	37	9
Ripening	30	Nov 8,17	Dec 7,17	3.6		1.00	122		49	16

Note: GP: Growing Periods, LGP: Length of GP, MRD: Maximal Root Depth, TWA: Total Water Availability, GWRF: Groundwater Reduction Fraction, NWR: Netto Water Requirement, Ii: Interval irrigation.

Plant growth and yield

Plant growth is represented by plant height parameters, the number of tillers in the vegetative phase, and the number and length of panicles (Table 4). Plant height, number of tillers, number of panicles per clump, and panicle length were not affected by irrigation levels. The number of tillers, panicles per clump, and length of the panicles of the Situ Patenggang, Inpago 9, and 11 varieties were not significantly different. The Inpago 9 and Inpago 11 varieties' plant heights significantly differed from those of the Situ Patenggang variety. Situ Patenggang plant height, Inpago 9 and 11 were 102.6, 118.5, and 120.8 cm, respectively, still within the range according to the description of each variety. According to Malik (2017), the plant heights of the three varieties are 100-110 cm, 115 cm, and 124 cm, respectively. The number of panicles is most sensitive to temperature stress, solar radiation, and water deficit (Sridevi & Chellamuthu (2015).

Table 4. Plant height, number of tillers, number, and length of panicles of 3 varieties of upland rice on four irrigation levels

Treatments	Parameters			
	Plant height (cm)	Tillers number	Panicles	
			Number	Length (cm)
Irrigation				
Farmer customs	108.2a	10.8a	9.6a	27.2a
70% of crop requirement	116.7a	12.9a	10.2a	26.5a
85% of crop requirement	116.8a	12.5a	10.0a	27.0a
100% of crop requirement	114.1a	11.7a	9.4a	26.0a
Varieties				
Situ Patenggang	102.6a	12.1a	9.2a	24.4a
Inpago 9	118.5b	11.9a	10.4a	26.4a
Inpago 11	120.8b	11.9a	9.9a	29.3a

Note: Means values followed by the same letter in the same column are not significantly different ($p > 0.05$) according to DMRT.

Differences in irrigation levels did not significantly impact rice yields and plant yield components (Table 5). Thus, the crops' water requirements were met with an irrigation level of 70% of the overall condition, which has a positive impact on conserving irrigation water. Almost during the plant growing periods (August-November), the crops' water requirement was met from the channel reservoir except in November. It did not rain in August (Figure 1), so the crops' water requirement was satisfied from the channel reservoir. On September 10 and 20, and on October 10 and 20, crops' water requirement of as much as 24 mm and 37 mm, respectively (Table 3) was fulfilled from the channel reservoir.

On September 29, irrigation was not provided because rainfall of 40.5 mm was sufficient for the crops' water requirement, while on October 20, crops' water requirement was met by rain that occurred for four consecutive days on October 16-19, as much as 37.5 mm. Only in November, all crops' water requirements were met by rainfall that occurred on November 5-7 and 16-29, respectively, as much as 170.5 and 119.5 mm.

The productivity of Situ Patenggang, Inpago 9, and Inpago 11 varieties were 2.5, 3.4, and 3.2 tons ha^{-1}, respectively (Table 5). These yields were still inferior to the average yield usually achieved by the three varieties, which were 4.6, 4.6, and 4.1 tons ha^{-1} (Hairmansis et al., 2016). The productivity level is still low compared to the average productivity of national rice in Indonesia, which is 4.89 to 5.11 tons ha^{-1} (The Central Bureau of Statistics, 2020). However, the productivity of the superior varieties Inpago 9 and 11, which reached 3.4 and 3.2 tons ha^{-1}, was still on par with the productivity of upland rice in 2013, with an average yield of 3.3 tons ha^{-1} (Ministry of Agriculture, 2014).

Table 5. Weight of grain, stover, 1,000 grains, filled and empty grains of 3 upland rice varieties at several irrigation levels.

Treatments	Weight of GDG (tons ha^{-1})	Weight of DB (tons ha^{-1})	Weight of 1,000 grain (g)	Number of grains	
				Filled	Empty
Irrigation					
Farmer's customs	2.93a	7.55a	25.0a	100.3a	62.6a
70% of crop requirement	3.36a	7.26a	24.7a	110.5a	65.5a
85% of crop requirement	3.36a	5.77a	24.5a	95.7a	78.9a
100% of crop requirement	2.49a	7.11a	22.8a	99.0a	77.8a
Varieties					
Situ Patenggang	2.50a	6.24a	23.6a	94.3a	65.6a
Inpago 9	3.40a	6.86a	25.4a	100.5a	67.7a
Inpago 11	3.20a	7.67a	23.7a	104.7a	80.3a

Note: Means values followed by the same letter in the same column are not significantly different (p > 0.05) according to DMRT. GDG: Ground Dry Grains, DB: Dry Biomass

The weight of 1,000 grains of Situ Patenggang variety was about 23.6 g (Table 5) less than its potential production of around 26.5-27.5 g. Rice cultivation requires intensive maintenance, especially against pests and diseases. At the time of the research, despite the effort to install plant cover nets, the bird attacks were due to the area around being fallow. During the grain-filling phase, planthopper pests attacked the crops, causing a decrease in yields and resulting in a high percentage of empty grain.

In Indonesia, the productivity of upland rice ranges from 1.93 tons ha^{-1} in West Kalimantan to the highest of 4.48 tons ha^{-1} in West Java. Abiotic, biotic, and socioeconomic problems cause the low productivity of upland rice in dry land. The main abiotic problems in dry land include soil acidity and aluminum poisoning, low soil fertility, drought, shade, and temperatures, while the main biotic problem is blast disease (Hairmansis et al., 2016). Drought contributed to the growth, development, and yield of upland rice (Langangmeilu et al., 2023), leaf area, panicle length, total grain per panicle (Sinton et al., 2023), low number of filled grains, high number of empty grains (Lanna et al., 2021). Matsumoto et al. (2014) state that the upland rice components of grain filling, number of panicles, and 1,000-grain weight are greatly influenced by water availability. From the socioeconomic aspect, the results of research by Sahara et al. (2021) in Boyolali district showed that the profitability of upland rice farming was influenced by seed prices, planting area, farmer's age, and time allocation for working on the land. Farmers can increase profits by decreasing the number of seeds and expanding the planting area. According to Kankwatsa et al. (2019), superior upland rice varieties used on dry land in Uganda are known for their early maturity, disease resistance, drought tolerance, high yield potential, and increased grain quality. The advantage of cultivating crops in the dry season is that drying is easier and more cost-effective, and pest attacks are relatively reduced. Sunlight is adequate for photosynthesis and supports superior grain quality production.

CONCLUSION

During the dry season, the channel reservoir was the source of supplemental irrigation. Water spread to the fields through open canals and to crops through flooding irrigation techniques, with irrigation levels of 70, 85, and 100% of the crop water requirement. The canals discharged 2-4 L sec^{-1}, sufficient to meet the water requirement for upland rice during the dry season. Crop yields were not affected by the provision of water with irrigation levels of 70, 85, and 100% of plant water requirements. Therefore, it was sufficient to use an irrigation level of 70% of the crop water requirement for cultivating upland rice during the dry season. The plant growth represented by plant height significantly differs between Inpago 9 and Inpago 11 with the Situ Patenggang variety. Supplementary irrigation using rainwater harvesting increased the land productivity through cropping index from one to two growing seasons.

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Authors Nani Heryani, Budi Kartiwa, Popi Rejekiningrum, Aris Pramudia, and Hendri Sosiawan contributed equally in the research conception, data acquisition, data analysis, manuscript preparation and writing.

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