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Yield gap analysis between irrigated and rainfed rice agroecosystem

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Abstract

Rice is an essential crop for worldwide food security, providing the primary feeding for nearly half of the people on earth. In order to meet the increasing demand for rice, it is necessary to reduce the yield gap between irrigated and rainfed rice agroecosystem; therefore, a descriptive approach is used to estimate the yield gap (Yg) between irrigated (Yp) and rainfed rice agroecosystems (Yw) and identify its key factors. This research aimed to identify the causes of the yield gap between irrigated and rainfed rice agroecosystems and evaluate the causes of the yield gap so as to minimize the yield gap. This research had been conducted from December 2021 to April 2022 in two different locations, an irrigated and a rainfed rice agroecosystem (planted between *M. cajuputi* stands). Fourteen genotypes were grown in a complete randomized block design consisting of three blocks in each location (irrigated and rainfed rice fields). The experimental unit at each research location was 20 m² (4 m × 5 m), and the harvest area was 12 m² (3 m × 4 m), consisting of 192 populations of rice plants. The results showed that soil fertility limiting factors, including total nitrogen, phosphorus and available potassium caused the yield gap. The maximum yield recorded was in G2 (8.83 ton.ha^{-1}) in the irrigated agroecosystem, while the minimum yield was in G8 (0.64 ton.ha^{-1}) in the rainfed agroecosystem. Yield gap analysis revealed a gap of 5.27 ton.ha^{-1} between the irrigated and rainfed systems. The most significant yield gap was observed in G3 at (6.92 ton.ha^{-1}), whereas the least was in G10 (3.17 ton.ha^{-1}). The genotype G2, exhibiting the highest yield in the irrigated agroecosystem, is recommended for planting, while G4, with a potential yield of 4.14 ton.ha^{-1}, is suggested for rainfed agroecosystems.

INTRODUCTION

Rice (*Oryza sativa* L.) is an important crop for global food security that serves as the main food source for almost half of the human population (Wan et al., 2020). The growing global population demands an increase in agricultural production to meet ever-increasing food needs. In Indonesia, rice is the most widely cultivated food crop that plays a strategic role in the economy. The demand for rice continues to increase along with the increase in population because rice is the main staple food in Indonesia. Rice production in Indonesia in 2024 is estimated to reach 52.7 million tons (FAO, 2024). This result is below the previous five-year average, due to reduced output of the main crop which was affected by dry weather conditions linked to El Nino. In an effort to ensure food security and meet the increasing demand for rice, rice production must be increased. However, the agricultural sector is facing difficult challenges, including climate change, water shortages, land degradation, and reduced land availability (Nhamo et al., 2014; Lampayan et al., 2015). With increasing population and decreasing

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availability of resources, food production must be increased on available land.

Irrigated agroecosystem is where water supply is assured from both surface sources of rivers and dams or wells and where drainage can be controlled (Zeigler & Barclay 2008). The intensity and distribution of water in rice fields serve the primary function of increasing rice productivity (Phengphaengsy and Okudaira 2008; Li et al., 2018). Most rice is cultivated in rice fields under flooded conditions during its life cycle. Rice agroecosystems are known for their good soil fertility quality and sufficient water availability for plants. Soil quality is the capacity of soil to function in ecosystem, maintaining productivity and promoting plant growth (Karlen et al., 2001). Good soil fertility of rice field agroecosystems can affect the productivity of cultivated rice. Aristya et al. (2021) reported the potential yield of genotypes cultivated in irrigated rice fields, where GM 28 (7.67 $ton.ha^{-1}$), Mutan Lampung Kuning (7.97 $ton.ha^{-1}$), and Mutan Rojolele 30 Pendek (7.92 $ton.ha^{-1}$) are rice genotypes that have high yields and other morphological properties that can overcome flood stress.

In rainfed agroecosystems, drought stress can occur at any stage of growth and can cause a significant reduction in yield (Swain et al., 2017). Drought in rainfed agroecosystems occurs due to the need for water that is only sourced from rainwater. Drought that occurs during the life cycle of rice can cause disrupted growth and yield. Drought can reduce stomatal conductance, transpiration rate, water use efficiency, relative water content, and photosynthesis rate (Yang et al., 2014). Under drought conditions, leaf expansion, root growth, plant height, and tillering are severely inhibited (Ji et al., 2012). All these morphological and physiological changes affect the reduction of rice yield under drought conditions. Besides drought, there are other limiting factors in rainfed agroecosystems, such as low soil fertility and climate (Tuong et al., 2000). Rice productivity in rainfed agroecosystems is low on average, which is caused by various limiting factors. According to Jaramillo et al. (2020), rainfed crop yields are about 50% lower than irrigated rice yields. Yields of rainfed agroecosystems in South Asia, parts of Southeast Asia, and parts of Africa are found to be very low, which is 1–2 $ton.ha^{-1}$ (Zeigler & Barclay 2008). Nadif et al. (2021) reported the use of several rice genotypes known to be more adaptive to rainfed areas, namely Situ Patenggang (3.03 $ton.ha^{-1}$), GM 2 (2.92 $ton.ha^{-1}$), GM 28 (2.86 $ton.ha^{-1}$), and GM 8 (2.42 $ton.ha^{-1}$).

One of the main strategies to meet the increasing demand for rice in the future is by reducing the yield gap and increasing resource efficiency (Foley et al., 2011). The yield gap is used to indicate the difference between potential yields and the actual average yield obtained by farmers (Lobell et al., 2009). In general, crop yield gaps can be caused by the biophysical environment of plant growth that is not adequately addressed by agricultural management practices (Mueller et al., 2012). Ran et al. (2018) reported factors that could influence yield gaps including variety, fertilization, climate, as well as topography and soil properties. In various countries, the yield gap between potential and farmer yields is still very high due to various obstacles, such as poor farm management, farmers' economic conditions, lack of knowledge resources, and lack of government involvement (Mondal, 2011). This research aimed to identify the causes of the yield gap between irrigated and rainfed agroecosystems and evaluate the causes of the yield gap so as to minimize the yield gap.

MATERIALS AND METHODS

Study area

This research was conducted from December 2021 to April 2022 in two different locations. The first location is an irrigated agroecosystem, and the second location is a rainfed agroecosystem, where in rainfed agroecosystem rice is planted between M. cajuputi stands (Taryono et al., 2023). The irrigated agroecosystem research location was at the Agrotechnology Innovation Center (PIAT), Berbah District, Sleman Regency, Yogyakarta Special Region Province, Indonesia. The rainfed agroecosystem is located in Menggoran Tourism Forest, Playen District, Gunungkidul Regency, Yogyakarta Special Region Province, Indonesia (Figure 1). For each agroecosystem, initial soil samples were taken before treatment at several different points at a depth of 0 – 20 cm and then composited. The average temperature and relative air humidity in irrigated agroecosystem were 30.50°C and 69.10%, respectively. Meanwhile, the mean temperature and relative humidity in the agroecosystem rainfed site were 24.58°C and 87.25%, consecutively (Taryono et al., 2022).

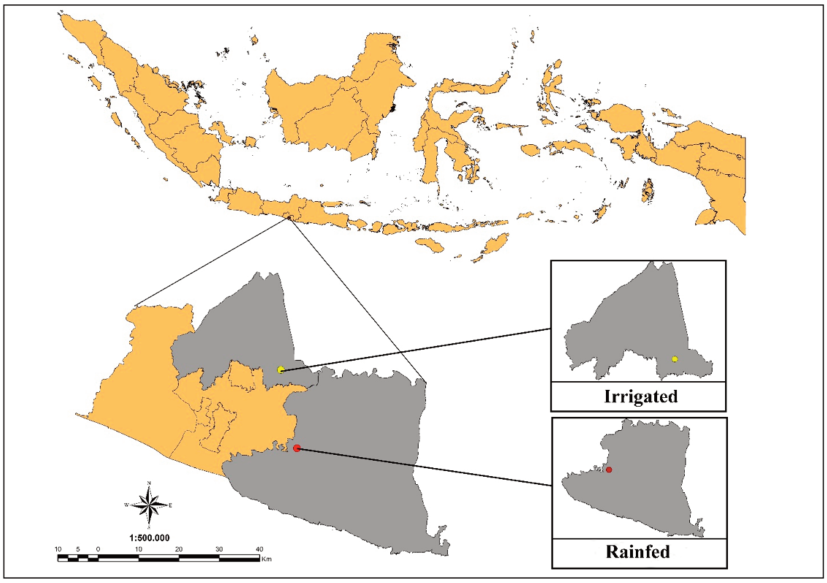

Figure 1. Geographical location of the research locations: irrigated agroecosystem (7°47'21.7 "S 110°27'43.8 'E), and rainfed agroecosystem (7°57'49.2 'S 110°29'52.5 "E).

Experiment design

The experiment carried out was a multi-location test consisting of irrigated and rainfed agroecosystems (Figure 2). The experiment was arranged in a factorial complete randomized block design consisting of three blocks as replications in each location (irrigated and rainfed rice fields). There were fourteen genotypes used, including G1 (V11), G2 (GM 28), G3 (GM 2), G4 (GM 8), G5 (Mutan Lampung Kuning), G6 (Mutan Rojolele 30 Pendek), G7 (Mutan Rojolele 30 Tinggi), G8 (Mutan V12T), G9 (Mutan Mayangsari), G10 (Mutan Lakatesan), G11 (Inpari 30 Sub Ciherang), G12 (Inpari 42), G13 (Inpago 12), and G14 (Situ Bagendit).

The experimental plot at each research location was 20 m² (4 m x 5 m), and the harvest area of 12 m² (3 m × 4 m), consisting of 192 populations of rice plants. The planting space for both locations was 25 cm × 25 cm. The addition of 10 ton.ha^{-1} organic matter per hectare was incorporated into the soil layer during tillage at a depth of 0-20 cm. Urea fertilizer of 300 kg/ha was given three times, namely at 14, 28, and 42 days after transplanting. A total of 100 kg ZA fertilizer per hectare was given twice, namely at the age of 14 and 42 days after transplanting. SP-36 fertilizer and KCL fertilizer were given at the time of transplanting as much as 150 kg/ha. The necessity and utilization of fertilizer in both irrigated and rainfed agroecosystems are analogous, assuming that soil fertility and crop management are similar (Dobermann et al., 2013), thereby enabling the calculation of the yield gap. The water requirement in irrigated agroecosystems was derived from irrigation canals and rainwater, while water sources in rainfed locations were only from rainwater.

Data collection and analysis

The observed research variables included initial soil physical and chemical properties. The particle size distribution of soil in the study area was determined using the hydrometer technique (Bouyoucos, 1962). Soils are separated into sand, silt and clay based on their particle size, where sand has the largest particle size, silt has medium particle size, and clay has the smallest particle size. Furthermore, these soils are classified according to the USDA (United States Department of Agriculture) system, which categorizes soils based on their texture (USDA 2012). Soil organic carbon was measured using the Walkley and Black method (1934), which is one of the most widely used methods for measuring soil organic carbon content. The process involves oxidation of soil organic carbon using potassium dichromate under acidic conditions, followed by a titration to calculate the amount of oxidized carbon. The result of this titration was used to determine the amount of organic carbon present in the soil sample. Cation exchange capacity (CEC) was determined using the distillation method referring

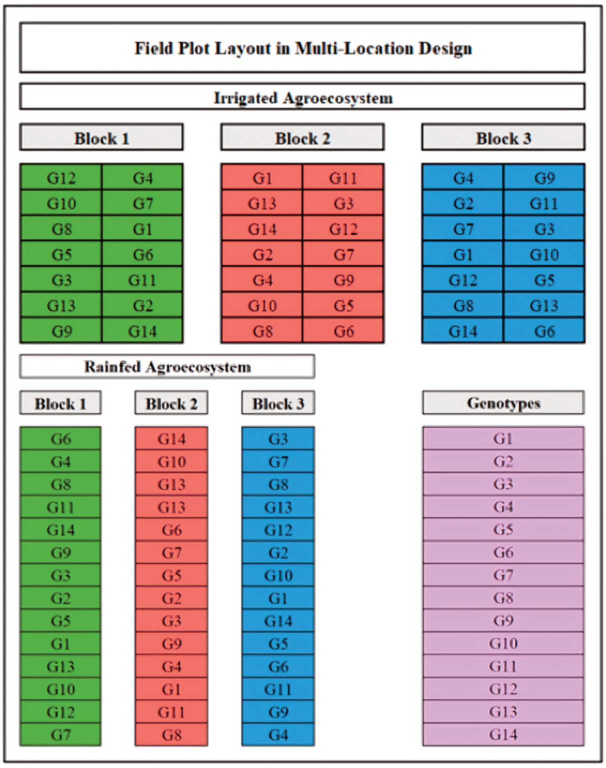

Figure 2. Multi-location design layout of the experiment

to a technique used to measure the number of exchangeable cations in soil. Measurement of total nitrogen in soil was carried out using the Kjeldahl method, which is used to measure total nitrogen in soil samples by converting organic nitrogen in the soil into ammonia (NH_3) through acid digestion, which is then measured through distillation and titration (Bremner and Mulvaney, 1982). Furthermore, Olsen method was applied to measure the availability of phosphorus that can be absorbed by plants in the soil. The observation of available potassium was carried out using the Morgan-Wolf method to measure the amount of available potassium that can be absorbed by plants from the soil. Extraction using ammonium acetic acid solution is able to release potassium that is not strongly bound in the soil, which is useful to determine the potassium nutrient status of the soil.

Yield components (the number of grains per panicle, the number of filled grains per panicle, 1000-grain weight, and productivity) and harvest index (HI) were also observed. The number grains of per panicle, the number of filled grains per panicle, and the weight of 1000 were determined by systematically selecting using five samples, which were taken from the planting plot positioned inside the edge of the plant outside the harvest area. To obtain grain yields, all panicles from a harvest area of 12 m^2 (3 m × 4 m) were harvested using a sickle. Harvested panicles were threshed and dried in the sun, and the empty grains were removed. Grain weight and water content were determined using a manual scale, and water content was measured using a digital scale (Moisture Meter Version AR991).

The data collected were analyzed using Analysis of Variance (ANOVA Significant differences were tested using post hoc test of Tukey's Honest Significant Difference (HSD) α = 0.05. The data analysis was performed using SAS® On Demand for Academics via a web browser (https://welcome.oda.sas.com/login)

Yield gap analysis

Yield gap (Yg) is the yield difference between potential yields of irrigated crops (Yp) or rainfed crops (Yw) and actual yields (Ya) (Affholder et al., 2013; Ittersum et al., 2013). In regions that do not have major soil fertility constraints, Yp is the most relevant benchmark for irrigated land systems with sufficient water supply. For crops cultivated on rainfed land, yield limited by inadequate water availability (Yw) is a relevant benchmark. The definition of Yw is similar to that of Yp, but the biggest difference is that plant growth is limited by water availability, soil type, and land topography (Ittersum et al., 2013). In this study, yield components were observed at research locations on irrigated and rainfed land. Harvest yields were measured in tiled plots at each research location. Yield in the irrigated (Yp) and rainfed agroecosystem (Yw), were then used to determine yield gap as the difference between Yp and Yw (Yg = Yp – Yw) (Lobell et al., 2009).

RESULTS AND DISCUSSION

Overview of soil properties in irrigated and rainfed agroecosystems

The soil in the irrigated agroecosystems is regosol soil (Table 1). Regosols are weakly developed mineral soils that are neither very thin nor rich in coarse fragments (like Leptosols), not sandy (like Arenosols), and do not contain fluvic materials (like Fluvisols) (FAO, 2014). The results of soil analysis are characterized by a sandy texture with 33% sand, 47% dust, and 20% clay, which is included in the class of loamy soil texture (USDA, 2012). The bulk density was 1.31 g cm^{-3} classified as high, the permeability was 0.42 cm h^{-1} classified as slow, soil pH was 5.5 classified as moderately acidic, soil organic carbon content was 1.92% classified as medium, soil organic matter content was 3.31% classified as low, and cation exchange capacity was 23.09 cmol(+) kg^{-1} classified as high. The total N in the soil (0.20 %) was classified as medium low, total Ca (0.94%) and Mg (0.10%) were classified as very low, while total Na (0.22%) was classified as low. The available P in the soil amounted to 0.99% and available K 0.13%, each of which was classified as very low. This is in accordance with the results of research by Peniwiratri et al. (2020), reporting that the characteristics of regosol soil are low total N content 0.15% and sandy texture with sand content of 44.96%.

The soil in the rainfed agroecosystems are Lithic Haplusterts (Table 1) (Suryanto et al., 2020; Taryono et al., 2022). Lithic Haplusterts are part of the vertisol soil type, which has shallow solum and rock (Alam et al., 2019). Vertisol soils have the ability to expand and contract, causing cracks in the topsoil and soil structure throughout the soil. It has cracks more than 5 mm wide and up to 100 cm or more deep that contain slickensides or lenticular peds at some depth within the solum (Kishné et al., 2009; Kovda, 2020). The floating and shrinking ability of vertisol soils is caused by wetting and drying of the soil mass (Dengiz et al., 2012). The results of soil analysis on rainfed land have a content of 27% sand, 38% dust, and 35% clay, which is included in the clayey loam texture class (USDA, 2012). The bulk density was 1.17 g cm^{-3} classified as medium, permeability was 1.80 cm h^{-1} classified as rather slow, and soil pH was 7.2

Table 1. Soil properties in irrigated and rainfed agroecosystems

Soil characteristics	Agroecosystem		
	Unit	Irrigated	Rainfed
Soil physical properties			
Bulk density	g cm^{-3}	1.31	1.17
Permeability	cm h^{-1}	0.42	1.80
Soil texture			
Sand	%	33	27
Silt	%	47	38
Clay	%	20	35
Soil chemical properties			
pH H_2O	-	5.5	7.2
Soil organic carbon	%	1.92	2.22
Soil organic matter	%	3.31	3.82
Cation exchange capacity	cmol(+) kg^{-1}	23.09	31.07
Total nitrogen	%	0.20	0.08
Total calcium	%	0.94	2.94
Total magnesium	%	0.10	0.22
Total sodium	%	0.22	0.05
Availability phosphor	%	0.99	0.67
Availability potassium	%	0.13	0.12

classified as neutral.

Soil organic carbon (SOC) and soil organic matter (SOM) in the rainfed agroecosystem, showing values of 2.22% and 3.83%, respectively, were significantly different from those in the irrigated agroecosystem. High SOC accumulation is caused by partial degradation products, microbial products, and fire residues (Lorenz & Lal 2014). In addition, according to Voltr et al. (2021), manure application can maintain or even increase the content of soil organic carbon. Meanwhile, high SOM content can be caused by particulate organic matter (Nyabami et al., 2024). SOM plays an important role in maintaining and improving soil physical, biochemical and biological properties, which are crucial for ensuring agroecosystem productivity (soil quality and health) and for future food security (Voltr et al., 2021). The cation exchange capacity in the rainfed agroecosystem of 31.07 cmol(+) kg^{-1} was significantly different when compared to the irrigated agroecosystem. Cation exchange capacity values are influenced by clay minerals and organic matter (Olorunfemi et al., 2016). Organic matter in soil is the main source of negative electrostatic sites; therefore, there is a strong correlation between cation exchange capacity values and the amount of organic matter present in the soil. This research is also in line with the research of Vogelmann et al. (2010) who reported that soil samples with higher cation exchange capacity values were found to have high levels of organic matter and pH. The total N in the soil was 0.08% classified as low, total Ca was 2.94% classified as low, and total Mg and Na was 0.22% and 0.05% each classified as very low. The content of available P and K in the soil amounted to 0.67% and 0.12% each classified very low criteria.

There are factors that cause yield gaps, referred to as yield-limiting factors, including soil quality, genetic factors, and cultivation management (irrigation, fertilization, pest management, and planting factors) (Licker et al., 2010). Plant growth and development are inseparable from the availability of water and nutrients. Generally, the higher the level of inputs, the higher the yield. Among the many inputs used in agricultural production, nitrogen, phosphorus, potassium, and water are the most important. Poor soil fertility in rainfed soils is often considered as one of the major constraints for rice production (Dossou-Yovo et al., 2020). Among soil properties, available nitrogen plays a major role in the variation of rice yield gap, indicating that rice yield gap is sensitive to available nitrogen (Ran et al., 2018). The results of soil observations show that low levels of total nitrogen and available phosphorus and potassium in the soil can lead to low yields in rainfed agroecosystems, as evidenced by the low yields in rainfed agroecosystems when compared to irrigated agroecosystem (Table 4). Low nutrients, including nitrogen, phosphorus, potassium, and others can limit yields (Hajjarpoor et al., 2018)

Other factors that cause yield gap include the growing environment such as climate, temperature, humidity, and light. Debnath et al. (2021) reported that future climate conditions (2030 and 2040) could increase the yield gap by 20.9 and 22.2%. Low light can have an impact on changes in morphology, physiology, biomass, plant quality, plant development, and yield (Yang et al., 2019). The observation of light intensity in the irrigated agroecosystems showed light intensity during the day between 52,900– 92,300 lux, while in the rainfed agroecosystems, the light intensity during the day was between 34,500–41,400 lux. The low light intensity in the rainfed agroecosystems was caused by *M. cajuputi* stand, which shaded the rice plants. Low light intensity conditions in rainfed agroecosystems leads to the decrease in the rate of plant photosynthesis and respiration. Liu et al. (2014) reported that low light significantly affects the agronomic and physiological traits of rice plants, inhibiting physiological metabolism, including photosynthesis, respiration, antioxidant characteristics, and carbon and nitrogen conversion and distribution. Low light conditions can cause depletion of starch content in the grain, inhibiting grain filling and rice yield (Panda et al., 2023). Nutrient limitations (Haefele et al., 2009) and water stress (Tuong and Bouman (2003) are a major contributor to yield gaps in rainfed rice systems. Lobell et al. (2009) emphasize that socioeconomic factors and infrastructure explain a significant portion of yield gaps.

Nutrient uptake of 14 genotypes in irrigated and rainfed agroecosystems

Table 2 provides information that there is an interaction effect of rice genotypes and agroecosystems on the uptake of phosphorus (P) and potassium (K). Phosphorus absorption is frequently constrained in dry soils because of diminished root development and decreased P diffusion rates, resulting in shorter root length (Lynch, 2011). In this result, the P nutrient uptake of plants on the irrigated agroecosystem

Table 2. Nutrient uptake of 14 genotypes in irrigated and rainfed agroecosystems

Genotype	Uptake P (mg⁻¹)		Uptake K (mg⁻¹)	
	Irrigated	Rainfed	Irrigated	Rainfed
G1	57.75 a-d	39.22 cde	331.13 a	244.91 a-g
G2	50.85 a-e	47.34 a-e	301.71 a-d	227.70 c-g
G3	56.39 a-e	36.79 e	271.57 a-f	204.96 efg
G4	52.21 a-e	42.38 b-e	266.71 a-f	212.33 d-g
G5	54.60 a-e	40.67 b-e	304.06 a-d	230.55 b-g
G6	51.82 a-e	40.28 b-e	290.87 a-e	232.46 b-g
G7	50.51 a-e	38.31 de	248.06 a-g	225.82 c-g
G8	58.74 abc	36.79 e	315.41 abc	78.93 h
G9	55.60 a-e	48.94 a-e	297.83 a-d	311.60 abc
G10	59.53 ab	40.17 b-e	319.99 ab	165.75 gh
G11	63.43 a	42.90 b-e	299.15 a-d	218.50 d-g
G12	56.45 a-e	38.25 de	294.57 a-e	173.03 g
G13	52.25 a-e	39.74 b-e	270.01 a-f	188.63 fg
G14	49.81 a-e	41.77 b-e	243.83 a-g	186.81 fg
Mean	54.99	40.96	289.64	207.28
Interaction	+	+	+	+

Remarks: Means followed by the same letters in the same column and factor are not significantly different on Tukey's HSD distance test at α=5% level; (+) significant interaction; G1 (V11), G2 (GM 28), G3 (GM 2), G4 (GM 8), G5 (Mutan Lampung Kuning), G6 (Mutan Rojolele 30 Pendek), G7 (Mutan Rojolele 30 Tinggi), G8 (Mutan V12T), G9 (Mutan Mayangsari), G10 (Mutan Lakatesan), G11 (Inpari 30 Sub Ciherang), G12 (Inpari 42), G13 (Inpago 12), and G14 (Situ Bagendit).

showed the highest value of 54.99 mg⁻¹, higher than P uptake in the rainfed agroecosystem of 40.96 mg⁻¹. G11 obtained the highest P uptake value of 63.43 mg⁻¹ in the irrigated agroecosystem, while the lowest P nutrient uptake was in G8 44.41 mg⁻¹ in the rainfed agroecosystem. The higher P uptake in G11 in the irrigated agroecosystem was due to the efficient root system and availability of phosphorus in the soil, while the low P uptake in G8 was due to the poor root system of the plant. Vanlauwe et al. (2010) showed the integrated soil fertility management (ISFM) improves P use efficiency in low-input systems. According to Balemi & Negisho (2012), higher P uptake is caused by root system, development of large root system, exudation of low molecular weight organic acids, protons and enzymes such as phosphatases and phytases, and association with mycorrhiza all of which contribute to increased P use efficiency. Rice genotype with higher P uptake, acquisition efficiency, and use efficiency is P efficient genotype (Irfan et al., 2020). According to Dissanayaka et al. (2018), grain yield and yield components are determined together with biomass and P accumulation in various vegetative and reproductive organs. Nutrient absorption is significantly influenced by soil moisture availability, particularly in dry areas where nutrient distribution is limited. Drought reduces root length density and root activity, resulting in decreased nutrient absorption, especially immobile nutrients such as phosphorus (Lynch, 2011). Rainfed agroecosystems are more susceptible to nutrient losses through runoff and demonstrate decreased nutrient use efficiency due to unpredictable precipitation (Kumira et al., 2010). Inadequate and delayed fertilizer application in rainfed agroecosystems restrict nutrients absorption and agricultural yield (Vanlauwe et al., 2010). Nutrient absorption correlates with production potential; hence, more productive systems assimilate greater quantities of nutrients (Fageria et al., 2010).

Potassium nutrient uptake of plants in the irrigated agroecosystems obtained the highest value of 289.64 mg⁻¹ compared to that in the rainfed agroecosystems (207.28 mg⁻¹). G1 obtained the highest K uptake value of 331.13 mg⁻¹ in the irrigated agroecosystem when compared to G8, resulting K uptake of 78.93 mg⁻¹ in the rainfed agroecosystem, which was obviously the lowest value. The higher K uptake in the rice irrigated agroecosystem compared to that

Table 3. Yield components of 14 rice genotype in irrigated and rainfed agroecosystems

Genotype	Filled grain per panicle		Number grains per panicle	
	Irrigated	Rainfed	Irrigated	Rainfed
G1	153.13 a-f	100.80 g-j	173.73 abc	114.60 d-g
G2	158.27 a-e	73.67 ij	184.33 ab	110.53 e-h
G3	182.87 a	121.73 c-h	202.60 a	145.13 b-g
G4	129.07 c-h	116.47 d-i	160.80 a-e	158.93 a-e
G5	168.40 abc	154.07 a-f	187.53 ab	161.47 a-d
G6	135.73 b-g	104.47 ghi	158.53 a-e	119.73 d-g
G7	114.73 e-i	91.20 g-j	131.53 c-g	103.87 fgh
G8	178.13 ab	55.67 j	205.20 a	60.87 h
G9	154.87 a-e	107.60 f-i	186.00 ab	121.80 d-g
G10	103.27 ghi	85.67 hij	122.07 d-g	98.47 gh
G11	127.60 c-h	104.60 ghi	150.27 b-f	117.73 d-g
G12	168.20 abc	88.73 g-j	205.07 a	105.00 fgh
G13	163.47 a-d	102.13 g-j	186.73 ab	129.13 c-g
G14	104.00 ghi	104.73 ghi	125.40 c-g	128.00 c-g
Mean	145.84	100.82	169.99	119.66
Interaction	+	+	+	+

Remarks: Means followed by the same letters in the same column and factor are not significantly different on Tukey's HSD distance test at α=5% level; (+) significant interaction; G1 (V11), G2 (GM 28), G3 (GM 2), G4 (GM 8), G5 (Mutan Lampung Kuning), G6 (Mutan Rojolele 30 Pendek), G7 (Mutan Rojolele 30 Tinggi), G8 (Mutan V12T), G9 (Mutan Mayangsari), G10 (Mutan Lakatesan), G11 (Inpari 30 Sub Ciherang), G12 (Inpari 42), G13 (Inpago 12), and G14 (Situ Bagendit).

in the rainfed agroecosystem is due to soil type and plant root system. According to Klinsawang et al. (2018), correlation analysis results showed that good root system and long root hairs were associated with increased plant biomass and increased tissue potassium content. Soil type can affect potassium uptake rate in rice, in which higher potassium uptake leads to higher chlorophyll content, higher net photosynthetic rate, and higher dry matter accumulation in rice tissue (Zhang et al., 2021).

Yield and yield components

Yield components were affected by the interaction between rice genotypes and agroecosystem ($p<0.05$) (Table 3). The interaction between rice genotypes with agroecosystem had a significant effect on the number of grains per panicle and the number of grains per panicle. The yield of filled grains per panicle was higher in the irrigated agroecosystem (145.84) than in the rainfed agroecosystem (100.82). GM 2 in the irrigated agroecosystem showed the highest grain yield per panicle (182.87), and G8 in the rainfed agroecosystem (55.67) showed the lowest value. The number of grains per panicle was higher in the irrigated agroecosystem (169.99) than the number of grains per panicle in the rainfed agroecosystem (119.66). G8 in the irrigated agroecosystem showed the highest number of grains per panicle (205.20), and G8 in the rainfed agroecosystem showed the lowest value (60.87). Optimal conditions and management in irrigated agroecosystem enable rice plants to reach their genetic potential for spikelet quantity. Enhanced biomass accumulation and effective source-sink partitioning in irrigated agroecosystem may lead to an increased number of grains per panicle. Enhanced nutrient absorption under ideal soil moisture levels in irrigated agroecosystem promotes more spikelet growth and reduces spikelet abortion (Fageria et al., 2010). Spikelet sterility due to drought and extreme temperature significantly contributes to the reduced grain count per panicle in the rainfed rice (Jagadish et al., 2007).

The interaction between rice genotype and agroecosystems had a significant effect on 1,000 seed weight and yield (Table 4). The 1,000-grain weight yield was higher in the irrigated agroecosystem

Table 4. Yield and yield components of 14 genotypes in irrigated and rainfed agroecosystems

Genotype	1000-grain weight (g)		Yield (ton.ha^{-1})		Harvest index	
	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed
G1	18.40 h-k	16.40 kl	6.81 cd	1.58 ijk	0.34 a-e	0.10 ghi
G2	25.67 b-f	24.60 b-h	8.83 a	2.06 h-k	0.49 a	0.11 f-i
G3	25.37 b-g	22.40 d-k	8.50 ab	1.58 ijk	0.47 ab	0.10 ghi
G4	32.47 a	29.77 ab	8.17 abc	4.14 fg	0.44 ab	0.25 c-g
G5	22.63 d-k	22.83 c-j	7.03 bcd	3.39 gh	0.36 a-d	0.23 d-h
G6	18.97 g-k	18.33 h-k	8.03 abc	3.00 ghi	0.42 ab	0.19 e-i
G7	27.90 a-e	16.60 jkl	6.39 de	2.61 g-j	0.33 b-e	0.15 f-i
G8	18.07 ijk	10.57 l	7.31 a-d	0.64 k	0.36 a-d	0.05 i
G9	28.10 a-e	25.20 b-g	7.78 a-d	2.64 g-j	0.38 a-d	0.15 f-i
G10	29.23 abc	22.87 c-j	5.17 ef	2.00 h-k	0.26 c-f	0.13 f-i
G11	27.80 a-e	22.73 d-k	7.53 a-d	1.31 jk	0.37 a-d	0.08 hi
G12	24.17 b-i	20.73 f-k	7.56 a-d	1.39 jk	0.38 abc	0.12 f-i
G13	24.93 b-g	21.97 e-k	7.36 a-d	1.61 ijk	0.36 a-d	0.11 ghi
G14	28.77 a-d	25.03 b-g	8.06 abc	2.83 g-j	0.42 ab	0.19 e-i
Mean	25.18	21.43	7.47	2.20	0.38	0.14
Interaction	+	+	+	+	+	+

Remarks: Means followed by the same letters in the same column and factor are not significantly different on Tukey's HSD distance test at α=5% level; (+) significant interaction; G1 (V11), G2 (GM 28), G3 (GM 2), G4 (GM 8), G5 (Mutan Lampung Kuning), G6 (Mutan Rojolele 30 Pendek), G7 (Mutan Rojolele 30 Tinggi), G8 (Mutan V12T), G9 (Mutan Mayangsari), G10 (Mutan Lakatesan), G11 (Inpari 30 Sub Ciherang), G12 (Inpari 42), G13 (Inpago 12), and G14 (Situ Bagendit).

(25.18 g) than in the rainfed agroecosystem (21.43 g). G4 in the irrigated agroecosystem showed the highest 1,000-grain weight yield (32.47 g), and G8 in the rainfed agroecosystem showed the lowest value (10.57 g). The interaction between rice genotype and agroecosystems significantly affected the harvest index. Harvest index in the irrigated agroecosystem was higher (0.38) than in rainfed agroecosystem (0.14). G2 in the irrigated agroecosystem showed the highest harvest index value (0.49), and G8 in the rainfed agroecosystem showed the lowest value (0.05).

The yield components differed between agroecosystems and between genotypes. Yields can be correlated to yield components, including grain fill per panicle, number of grains per panicle, 1,000-grain weight, and harvest index (Table 3 and Table 4). Filled grains per panicle and the number of grains per panicle are positively correlated to yield (Li et al., 2014; Zhao et al., 2020). Similarly, 1,000-grain weight also has a positive relationship with yield (Saketh et al., 2023; Xu et al., 2015) and harvest index (Kujur et al., 2023). The results of this study indicate that high yields can be achieved by increasing the number of filled grains per panicle, the number of grains per panicle, 1,000-grain weight, and harvest index. The increase in yield components can be influenced by soil fertility and nutrient uptake. According to Dissanayaka et al. (2018), grain yield and yield components are determined by biomass and P accumulation in various vegetative and reproductive organs of the plant. In addition, rice growth and yield are affected by climatic and ecological variations (Gupta and Mishra, 2019; Tan et al., 2021). Thus, crop varieties and cultivation methods must be selected appropriately to achieve optimal yields under specific conditions.

Genotype yield in irrigated and rainfed agroecosystems

This study showed that the combination of agroecosystems and genotypes showed diverse results. Table 5 shows that agroecosystem, genotype, and genotype × agroecosystem significantly affect grain yield. The irrigated agroecosystem resulted better grain yield compared to the rainfed agroecosystem (Table 4). Rice yield was higher in the irrigated agroecosystem (7.47 ton.ha^{-1}) than in

Table 5. Actual yields and yield gaps of 14 genotypes in irrigated and rainfed agroecosystems

Genotype	Productivity (ton.ha⁻¹)		
	Irrigated	Rainfed	Yield gap
G1	6.81 a	1.58 b	5.22
G2	8.83 a	2.06 b	6.78
G3	8.50 a	1.58 b	6.92
G4	8.17 a	4.14 b	4.03
G5	7.03 a	3.39 b	3.64
G6	8.03 a	3.00 b	5.03
G7	6.39 a	2.61 b	3.78
G8	7.31 a	0.64 b	6.67
G9	7.78 a	2.64 b	5.14
G10	5.17 a	2.00 b	3.17
G11	7.53 a	1.31 b	6.22
G12	7.56 a	1.39 b	6.17
G13	7.36 a	1.61 b	5.75
G14	8.06 a	2.83 b	5.22
Mean	7.47 a	2.20 b	5.27

Remarks: G1 (V11), G2 (GM 28), G3 (GM 2), G4 (GM 8), G5 (Mutan Lampung Kuning), G6 (Mutan Rojolele 30 Pendek), G7 (Mutan Rojolele 30 Tinggi), G8 (Mutan V12T), G9 (Mutan Mayangsari), G10 (Mutan Lakatesan), G11 (Inpari 30 Sub Ciherang), G12 (Inpari 42), G13 (Inpago 12), and G14 (Situ Bagendit).

Table 6. Analysis of variance (ANOVA) grain yield

Source	Grain yield (ton.ha⁻¹)				
	DF	SS	MS	F Value	Pr > F
Location	1	582317325.2	582317325.2	2585.51	<.0001 **
Repeat (agroecosystem)	4	2154098.8	538524.7	2.39	0.0625 ns
Genotype	13	39140841.7	3010834.0	13.37	<.0001 **
Agroecosystem × genotype	13	29716907.4	2285916.0	10.15	<.0001 **

Remarks: ns = not significant; ** = significant at 0.001 probability level; DF = degrees of freedom; SS = sum of squares; MS = mean square.

the rainfed agroecosystem (2.20 ton.ha⁻¹). Meanwhile, all genotypes in the irrigated agroecosystem showed better yield compared to in the rainfed agroecosystem. G2 showed in the irrigated agroecosystem the highest yield of 8.83 ton.ha⁻¹ and G8 in the rainfed agroecosystem showed the lowest value (0.64 ton.ha⁻¹).

Yield gaps between 14 rice genotypes in irrigated and rainfed agroecosystems

Among 14 rice genotypes, the average yields in the irrigated and rainfed agroecosystems were 7.47 ton.ha⁻¹ and 2.20 ton.ha⁻¹, respectively. The yield gap obtained between the irrigated and rainfed agroecosystems was 5.27 ha⁻¹ (Table 5). The highest yield gap was in G3 (6.92 ha⁻¹), and the lowest yield gap was in G10 (3.17 ha⁻¹). The yield gaps obtained in 14 genotypes are presented in Table 5.

Yield gap is an important indicator in formulating measures aimed at improving crop yields (Deng et al., 2019). This study showed the factors contributing to yield components, yield, and yield gap in irrigated and rainfed agroecosystems. The yield gap between the irrigated and rainfed agroecosystems was 5.27 ton.ha⁻¹ (Table 5). The average yield gap between genotypes used in this study was 5.27 ton.ha⁻¹, in which genotype G10 showed the lowest yield gap of 3.17 ton.ha⁻¹, and G3 showed the highest yield gap of 6.92 ton.ha⁻¹ (Table 5). These values are within the range of yield gap values of Asian rice farmers reported by Lobell et al. (2009). This finding indicates a high yield gap between the irrigated and rainfed agroecosystems. Yield gaps between locations are largely due to the combined effects of agronomic traits that are strongly influenced by different environmental conditions (Zhao et al., 2020).

CONCLUSIONS

The highest yield was obtained in G2 (8.83 ton.ha^{-1}) in the irrigated agroecosystem, and the lowest yield was in G8 (0.64 ton.ha^{-1}) in the rainfed agroecosystem. According to the yield gap analysis, it was found that the yield gap between the irrigated and rainfed agroecosystems was 5.27 ton.ha^{-1}. It was also found that the highest yield gap was found in G3 (6.92 ton.ha^{-1}), and the lowest yield gap was in G10 (3.17 ton.ha^{-1}). The genotype with the highest yield in the irrigated agroecosystem, which is G2 (8.83 ton.ha^{-1}) can be used as a planting recommendation. Meanwhile, the genotype that can be recommended in rainfed agroecosystems is G4 with a potential yield of 4.14 ton.ha^{-1}.

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