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Water management and irrigation for bulb onion (*Allium cepa* L.) growth and development in the Papua New Guinea Highlands: A review

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Abstract— *Water is crucial for nutrient intake, transportation, temperature regulation, and photosynthesis in bulb onion (*Allium cepa *L.) growth and development. Water scarcity, caused by climate variability and particularly during prolonged dry periods, has proved to be an obstacle to cultivating bulb onions in the Papua New Guinea (PNG) Highlands. Farmers have a limited grasp of the interdependence of soil, water, and plants. They have traditionally depended on precipitation, and water from streams and rivers, to irrigate their bulb onion crops. The main method for providing irrigation support is manual irrigation, with agricultural organisations assisting with basic irrigation technologies. Despite farmers and organisations efforts to improve irrigation practices, the prolonged dry season still raises labour demands for bulb onion farms. Farmers' lack of knowledge about irrigation technology and soil water conservation contributes to this issue. Moreover, the lack of irrigation suppliers worsens the issue of limited soil water in onion farms. This paper gives an overview of onion production in PNG, focusing on irrigation practices and constraints in the Highlands region. It aims to stress irrigation's importance in crop growth and explore PNG's irrigation methods and soil moisture conservation practices. There is a need for a sustainable irrigation and soil water conservation system that is easy to use and incorporates crop water requirements, while offering farmers an improvement in crop profitability. This system is vital for watering onions and conserving soil moisture, promoting their growth and yield. In this context, the use of mulch and irrigation systems can preserve and enhance soil moisture during prolonged dry phases.*

Keywords— *water requirements, rainfall, drought, sprinklers, mulch, agronomic constraints.*

INTRODUCTION

Bulb onion (*Allium cepa* L.) is a globally significant crop due to its substantial economic and nutritional value (Galmarini, 2018; Ochar & Kim, 2023). The crop provides a vital and reliable source of income for smallholder farmers in many developing countries (Khan et al., 2021; Kassu, 2022; Bello & Yakubu, 2023) including in Papua New Guinea (PNG) and provides opportunities for farmers to establish a business (FPDA, 2022b). While bulb onion is well-suited for cultivation in the lowland areas of PNG, with production focused on the Central (Wiles, 1994), East New Britain (ENB), and Madang provinces (FPDA, 2017). In the PNG Highlands, bulb onion has emerged as a horticultural crop of considerable commercial importance, illustrated by its cultivation by an increasing number of households and underpinned by increasing regional demand (Okrupa et al., 2017).

However, various constraints limit the development of bulb onion production in the PNG Highlands including the absence of locally adapted cultivars, pest and disease infestations, suboptimal soil fertility management, inadequate agronomic knowledge, and post-harvest losses (Okrupa et al., 2017). These constraints have contributed to decreased production and output quality (Okrupa et al., 2017; Pamphilon et al., 2019; Kosec et al., 2022). In addition to these constraints, water scarcity poses a particular challenge to cultivating onions in tropical environments (Singh, 2021). Despite the tropical climate and adequate precipitation experienced in the PNG Highlands, climate variability, including the persistence of prolonged dry seasons and drought due to limited soil water availability, persistently impedes the successful cultivation of bulb onions in this region (FPDA, 2016; Bourke et al., 2016; Bourke, 2018). Water plays a vital role in plant physiological processes such as photosynthesis, nutrient intake and translocation, as well as temperature regulation during the growth and development of bulb onions (Brewster, 1990). Insufficient water therefore impedes bulb growth, leading to smaller bulbs and potential root damage (Godspeed et al., 1989) as well as discolouration and acrid flavours in onions (Narayan et al., 2022). Consequently, bulb onions grown in insufficient moisture environments tend to suffer more significant yield and income losses (Pejić et al., 2011).

Irrigation is therefore crucial to address water shortages in onion production in PNG. Farmers require simple, easy-to-set-up and affordable irrigation technologies to regulate the water supply to their crops (FPDA, 2018). Effective management and maintenance of irrigation systems is essential to ensure the long-term viability of onion farming in the PNG Highlands. Excessive on-farm irrigation can cause waterlogging, salinisation, and reduce crop productivity (Kifle et al., 2017; Gebremeskel et al., 2018; Wang et al., 2022). Inefficient irrigation also increases costs and can contribute to soil degradation and water contamination (Gebremeskel et al., 2018).

Farmers often lack knowledge of the complex relationships between soil, water, and plants (Lehmann et al, 2020). Growers may irrigate crops without considering the specific needs of the plant, basing their decision instead on generic guidelines or past experience (Mandal et al., 2022). The amount of water that crops need can differ depending on their location, soil type, how they are cultivated, the amount of rainfall they receive and the local climate (Ewaid et al., 2019). Therefore, identifying the right timing, irrigation quantity, and stress levels during growth stages is vital for effective irrigation (Gu et al., 2020), and optimising crop production per unit of water used.

In this review paper, we provide some background information on the bulb onion industry in PNG as well as the agronomy of the crop, before summarising the primary constraints on production in PNG. In this latter regard, particular attention has been given to current irrigation practices and constraints in the Highlands region. The paper seeks to emphasise the importance of irrigation to crop growth, and to explore irrigation methods and soil moisture conservation practices that may be most relevant to bulb onion producers in the PNG Highlands of to optimise use of scarce irrigation resources.

The information provided in this paper will help research and development organisations in PNG to promote the sustainable development of irrigated bulb onion production in the Highlands, helping farmers to maximise yield and crop quality while optimising water use and moisture retention. Authorities seeking to promote sustainable development of this crop will need to work with local farmers as well as irrigation suppliers to trial and implement new approaches, while also helping farmers to focus on improving crop quality and ensuring a consistent supply to meet market demand.

BULB ONION PRODUCTION OVERVIEW

Crop production in the Papua New Guinea Highlands

Situated within a predominantly rainforest environment, the extensive grassland area found at the time of writing in the PNG Highlands is presumed to have developed as a consequence of human-caused forest clearance for food production (Bayliss-Smith, 1991; Bourke, 2003). The annual rainfall ranges from 2,000 to 9,000 mm, and the mountain areas are cooler than the plains (Bourke, 2017). Henganofi, in Eastern Highlands Province (EHP), features the lowest humidity in the region, with a 5-month dry season and 1,800 mm of annual rainfall (Bourke, 2017). The economy of the PNG highlands is heavily dependent on agriculture, with around 80% of its population relying on subsistence farming and local trade for their livelihood (Bourke & Harwood, 2009).

Most agricultural activities occur between 1,000-2,400 metres above sea level, primarily on the grassland plains (Bayliss-Smith, 1991; Bourke & Harwood, 2009). The mountainous and fertile valleys of the PNG Highlands (comprised of seven provinces; Figure 1) are known as a hub for high-value vegetable crop production in PNG (Okrupa et al., 2017; Brown et al., 2019; Curry et al., 2019). The predominant soil type of the Highlands is humic yellow-brown clay. The region consists of seven provinces. Recent data suggested that sweet potato was the main food crop, with two thirds used for family consumption, and almost one third sold commercially, with the latter sector growing in importance over time (Curry et al., 2019; FPDA, 2020; Culas & Pombre, 2023), supplemented by potatoes and vegetables such as cabbage, carrot, onion, and broccoli. Coffee production also supports farmers' income, especially in the Central Highlands. Onion production compromised 3% of the total value of agricultural production of the PNG Highlands (FPDA, 2020).

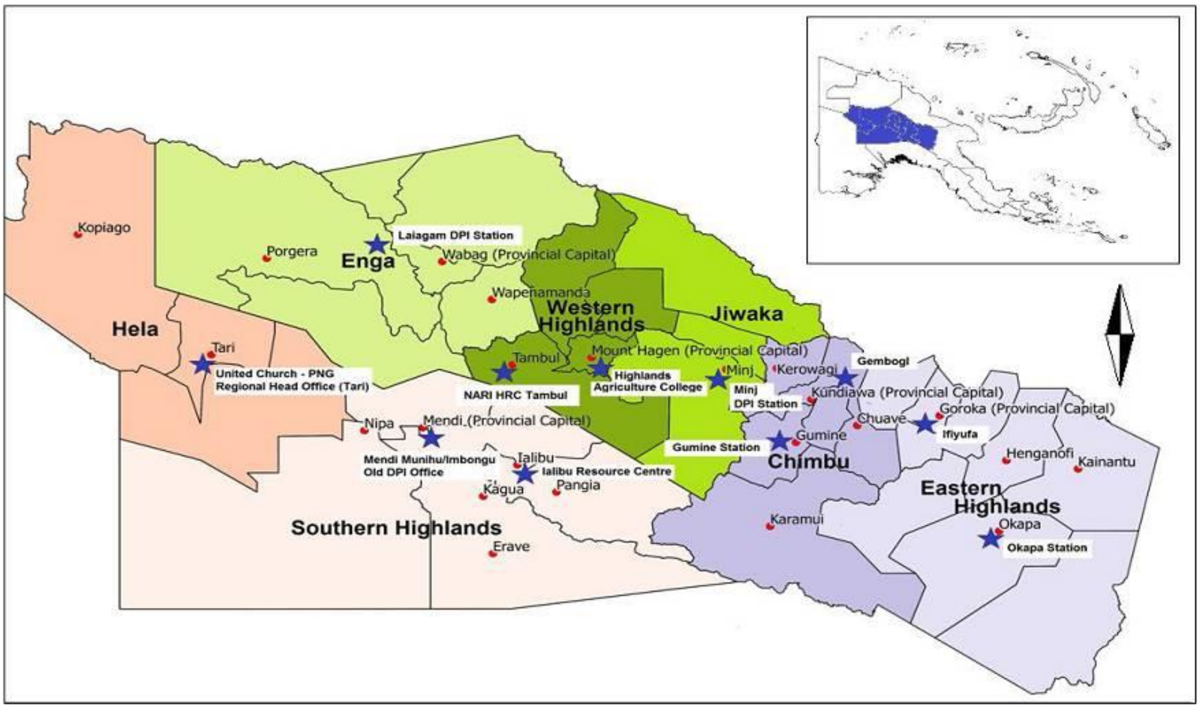

Fig.1 Map showing locations (★) of Farmer Resource Centres established throughout the PNG Highlands where bulb onion demonstration plots were established (Okrupa et al., 2017).

Onion production in Papua New Guinea

Production history

The initial introduction of bulb onions to PNG has been attributed to European settlers, who began cultivating them in the country in early 1930s (Bourke, 1993; Wiles, 1994). Research indicates that onion production in PNG was initially focused on dry lowland areas (Bull & Bourke, 1983) and on Highland regions with a distinct dry season (Kavanamur, nd Pitt, nd). This area of production was supported by a recommendation to avoid cultivating bulb onions in regions of PNG that experience high annual rainfall, particularly in the lowland areas.

In the 1980s, a small group of farmers residing in the PNG Highlands began to cultivate bulb onions to add a viable alternative to their existing repertoire of vegetable crops (Bull & Bourke, 1983; Pitt, nd). During the 1990s, there was some further limited development of commercial cultivation of bulb onions (Wiles, 1994), with the Department of Agriculture aiming to promote increased domestic production of bulb onions. To this end, the Department provided farmers with specialised training on various cultivation and post-harvest techniques. The primary objective behind this initiative was to decrease PNG's dependence on imported onions (Wiles, 2001).

Bulb onion production has become increasingly prominent as a valuable and lucrative agricultural crop alongside sweet potato and potato for farmers in the Highlands region (Okrupa et al., 2017). The primary locations for bulb onion cultivation include Simbu (Chimbu), EHP, Jiwaka and Western Highlands (WHP; Figure 1). Bulb onions are also cultivated in certain parts of Enga, Southern Highlands (SHP), and Hela provinces.

The cultivation of onions on a small scale has increased in diverse agro-ecologies, particularly in the PNG Highlands, providing an emerging income-generating crop. According to the Fresh Produce Development Agency (FPDA) Annual Reports for the years 2016, 2017 and 2020, bulb onion cultivation expanded to WHP, SHP, Enga, and Hela provinces over the next few years. New production collaborations were also established in lowland provinces in PNG, including Central, ENB, and Madang (FPDA, 2021). Despite the need for more specificity about the total area coverage, production spread to other districts within Simbu province and other Highland provinces (FPDA, 2020). Extension staff estimated the volume of bulb onion production to be 27 and 24 tonnes in 1991 and 1992, respectively (Wiles, 1994). By 2016, annual production of bulb onions had increased to 2,329 tonnes year (FPDA, 2016). The imposition of an import embargo in 2015 was a direct contributor to this high level of output (FPDA, 2016; 2017). However, the 2019 FPDA Annual Report (2020) noted that local production had experienced continuous but variable growth from 2010 to 2020.

Economic significance of onion production in Papua New Guinea

Annual production in 2016 exceeded the average import volume of 1,400 tonnes, with a total of 2, 329 tonnes of onions produced (FPDA, 2016). This marked the highest quantity of onions harvested since the inception of the National Bulb Onion Program in 2005. In addition, there was a considerable rise in the value of the crop, exceeding by 50% the 1,021 tonnes imported in 2015 (FPDA, 2016). In 2021, an estimated total amount of K3 million was earned by farmers from their sales of produce (FPDA, 2022a). However, the actual earnings may have exceeded the officially documented figure due to lack of farmer capacity to maintain precise records (FPDA, 2020; 2022). This increase in production was attributed to larger numbers of farmers cultivating onions, as well as more widespread use of improved production technologies (FPDA, 2020; 2021; 2022).

Supporting industry development

The Department of Agriculture also conducted a comprehensive study on bulb onions across various locations in both the highlands and lowlands of PNG (Wiles, 2001). Field trials were conducted in EHP, encompassing Okapa, Aiyura, Raipinga, and Barola. These locations were selected since their elevation exceeded 1,600 metres, with a climate suited to bulb onion production (Wiles, 2001). The research programs focused on six core production domains: variety assessment; timing of planting; cultivation practices (either dependent on rainfall or irrigation; or based on direct sowing or transplanting of seedlings); mitigation of diseases (primarily purple blotch, caused by the fungus *Alternaria porri*; Dar et al., 2020); assessment of fertilisers; and post-harvest practice assessments (including the identification of cultivars most suited to storage). A significant increase in small-scale farm production of bulb onion across multiple provinces in Highland regions occurred in the early 1990s after the establishment of demonstration farms at the Highlands Agriculture Training Institute and in SHP (Wiles, 2001).

The FPDA initiated a PNG Government-funded project in 2015 to improve the farming and marketing of bulb onions in the Gembogl District of Simbu Province (FPDA, 2016). The Gembogl bulb onion endeavour underwent a geographical expansion into additional locations of the Highland provinces, specifically Jiwaka and EHP, under the auspices of The National Bulb Onion Expansion initiative, implemented by the FPDA between the years 2014 and 2015, further sought to expand production in the Highland provinces of Jiwaka and EHP (FPDA, 2016). In 2016, FPDA established a comprehensive program to provide sustained assistance for developing and expanding bulb onion cultivation in PNG (FPDA, 2017; 2020; 2021).

The FPDA sought to boost productivity among farmers focusing on fresh produce by implementing innovative technologies and improved crop varieties to meet market demand (FPDA, 2017; 2020). These innovations were intended to contribute to enhanced competitiveness and greater profitability for farmers. Amongst the various technologies introduced to farmers, implementing a contemporary irrigation system across 12 farms was incorporated as a key component of Climate SMART farming practices (FPDA, 2018; 2020). The primary purpose of irrigation technology development was to support pathogen-tested sweet potato farmers in increasing their crop production. The implementation of new irrigation systems has brought about positive changes in the livelihoods of sweet potato farmers in PNG, resulting in enhanced productivity (ACIAR, 2020). These innovations are just as relevant to bulb onion producers. Furthermore, the establishment of model farms under the auspices of the National Bulb Onion Project, led by FPDA, provided valuable support to over 10,000 farmers and village extension workers across successive years (FPDA, 2016; 2018).

Farmer Resource Centres have been established throughout the PNG Highlands region, with bulb onion demonstration plots planted at each Centre (Figure 1). These Centres serve as a means to facilitate the extension of agricultural information, best practices for crop production and climate-smart technologies, helping to bridge the gap between farmers and the resources necessary to optimise crop production (NARI, 2020). Various training programs on production, post-harvest techniques, and financial management were implemented to underpin expansion in bulb onion production.

AGRONOMY OF BULB ONION PRODUCTION

Farming practices

In the PNG Highlands, bulb onions are cultivated on open fields with ample direct and intense sunlight. Most crops and bulb onion farms are in regions characterised by cliffs, dry foothill slopes, stony or rocky open spaces, grassland areas, and highland plains (Bourke, 2017; FPDA, 2016; 2018). These pose a distinctive challenge for farmers, who must devise strategies to address water scarcity and impeded soil conditions. Methods employed to manage soil moisture deficits include mounding the crop row (as utilised for sweet potato production), drainage infrastructure and irrigation (Bourke, 2017).

In PNG, most bulb onion producers are heavily dependent on rainwater as a primary irrigation source for the crop. Farmers use surface irrigation to manage crop water shortages during dry parts of the season, when sufficient quantities of good quality water are available to allow irrigation (Cobon et al., 2016; FPDA, 2021). The main planting activities are carried out during the rainy season, while the start of the dry season marks the commencement of harvest (Michael, 2019; Crimp et al., 2020; Friedman et al., 2022). Bulb onion seedlings are cultivated within nursery settings through nursery trays, raised beds, or firm seedbeds. After eight weeks, the seedlings are transplanted to the open field. Crop management includes fertiliser application, pest and disease control measures, weed management techniques, and irrigation. The harvested bulbs undergo a curing and storage process before being marketed (FPDA, 2020).

Growing environment

Wiles (2001) stated that bulb onions can be cultivated in both dry lowlands and highlands in PNG; however, for year-round production, careful management is required due to high moisture during the rainy season and the crop’s photoperiodic responsiveness. Generally, sunny and dry weather conditions are suitable for short-day varieties bulb onion production, although some varieties tolerate wet climates (Kiani & Mashayekhi, 2023).

Onions will grow on various soil textures ranging from well-drained sandy to clay loams. However, onions should ideally be grown in silt loamy soil with moisture retention or well-drained soil with irrigation (Tamiru, 2020). Soils must be structured and fertile to maximise growth and yield. Adding organic matter boosts onion bulb production. Nikus and Mulungeta (2010) have noted that pH 6.0-8.0 is ideal. Onions are sensitive to salinity, so saline soils and over-irrigation are ideally avoided (Bikila, 2020; Nurga et al., 2020).

Onions will grow in various climates but are affected by light and temperature, influencing bulb formation. According to Brewster (2008) and Jones & Mann (1963), production thrives in cool temperatures with adequate moisture in the early development stages of growth and warm and dry conditions during maturity and curing stages. Short-day varieties (with a crucial day length of 7 to 8 hours; Cheng et al., 2021) are well adapted to warm to cool temperatures (16°C to 27°C) between 800 and 2500 metres above sea level (Wiles, 1993; FPDA, 2016) including tropical areas in PNG which feature distinctive wet (December-March) and dry seasons (May-October). Short-day bulb onion varieties are. Day length regulates bulb formation, and onion crops thrive in moderate climates that lack both temperature and precipitation extremes (Atif et al., 2020; Cheng et al., 2021). Temperature has a more substantial influence on bulb formation than photoperiod. Higher temperatures (above 20-25°C) increase bulb yields, but extremely high temperatures (25-31°C) or below 0°C decrease yields (Khokhar, 2017). Hot, humid weather adversely affects onions, promoting fungus and diseases. Warm, dry conditions are best for crop development (Ortola & Knox, 2015). From planting to harvest, the growing season typically lasts 130 to 175 days, depending on the local climate (FAO, 2002).

Crop water requirements

The need for appropriate irrigation systems has been identified as the most important constraint for bulb onion producers in the PNG Highlands (FPDA, 2018). It has therefore been noted as a critical to extend suitable irrigation technologies to onion-producing agricultural communities. Most farmers encounter significant challenges regarding water scarcity for crop irrigation (Michael, 2019; FPDA, 2020; 2021).

The water needed for onions can differ significantly, depending on the climate, geographical area, and time of year (Ortola & Knox, 2014). In places with high humidity, additional watering may be required. Similarly, onions require increased water amounts in hotter regions than colder ones (Kumar et al., 2007). In dry areas and seasons, onion growth and bulb development will rely on a consistent irrigation water source (Al-Jamal et al., 2000). Overwatering can contribute to diseases such as root rot (Piccinni et al., 2009; Tripathi & Lawande, 2019). Hence, it is crucial to closely monitor soil moisture content to help ensure optimal crop growth (Blanco et al., 2021; Wakchaure et al., 2021). Onion farmers must therefore be mindful of weather forecasts and adjust their irrigation methods accordingly. To prevent evaporation and achieve optimal efficiency, irrigation is recommended during the early morning or evening hours (Terán-Chaves et al., 2023). The irrigation schedule should also be adapted to match crop growth stage, to avoid contributing to pests and disease incidence, and to minimise water wastage (Blanco et al., 2021; Geries et al., 2021; Belo, 2022).

According to Shock et al. (2004) and FAO (2013), the shallow root structure of onion crops means that they require substantial quantities of water. Several factors, including soil properties, stages of development, species, and weather conditions, and irrigation system, determine the amount of water onion crops require over the growing season (Jiménez et al., 2010; Shaibu et al., 2015). Thus, water needs for onion crops are not evenly distributed throughout the growing season.

Haifa (2022) suggests that an onion crop can require a water supply ranging from 350 to 550mm during its growth cycle. Maintaining plant-available water levels at a minimum of 75% has been suggested to ensure a steady absorption rate (FAO, 2013). It is crucial to ensure irrigation is provided whenever soil moisture levels drop below a specific threshold to secure a successful onion harvest. Regular irrigation may therefore be required to maintain optimal moisture levels and maximise crop yields (Al-Jamal et al., 2000). Moreover, precise water application management is essential to prevent any loss of nutrients through leaching (Ashrafi et al., 2020; Geries et al., 2021; Gnanasundari et al., 2022).

Onion plants are highly responsive to variations in soil moisture levels (Khokhar, 2017). Water shortages are the most significant risk to crop yield during the early crop development stages, particularly in the first ~60 days post-transplant when the bulb undergoes rapid expansion (Brewster, 2008; Ortola & Knox, 2014; Khokhar, 2019). However, water stress does not significantly influence crop growth and development during the vegetative and maturity periods (Kadayifci et al., 2004; Kumar et al., 2007). Therefore, irrigation needs to be reduced gradually. Watering at the right time and in the right amount is essential for the successful growth of onions (Blanco et al., 2021; Geries et al., 2021; Terán-Chaves et al., 2023).

The crop needs optimum water at the bulb enlargement stage to increase bulb size and enhance bulb weight (Kadayifci et al., 2005; Kumar et al., 2007). A deficit of 50-75% of water during the bulb formation period significantly reduces crop yield (Kadayifci et al., 2005). On the other hand, over-frequent irrigation and excessively high water levels during the vegetative and crop maturity stages can lead to bulb splitting, premature ripening, and a delay in onion bulb maturation (Brewster, 1990), and contribute to a higher proportion of unmarketable bulbs (Metwally, 2011). Therefore, the vegetative and maturation crop stages are the best time to reduce irrigation rates and optimise water use across the crop growth period as a whole, especially under limited water supply conditions (Kumar et al., 2007; Metwally, 2011).

Onion production in humid, dry environments can suffer as a result of soil water scarcity (Ortola & Knox, 2014). Farmers use local streams and creeks for irrigation; however these water sources dry up and water shortages become acute during prolonged dry seasons. Often, small-scale farmers need to manually transport irrigation water from the nearest natural source to their farm using small containers (Crimp et al., 2020). Farmers are able to identify the positive impact of irrigation on crop production, highlighting its importance (Hainzer et al., 2021). Therefore, irrigation infrastructure is required to facilitate easier transporting of water from natural sources to fields.

Onions are highly vulnerable to disease attacks in the PNG Highlands and in other areas that experience high levels of humidity. Wiles (2001) demonstrated that prolonged wet weather contributed to crop-damaging diseases, including purple blotch (*Alternaria porri*). Similarly, soft rot (*Pectobacterium carotovorum*), which affects onions grown in moist conditions, can degrade the quality of the crop after harvest (Wiles, 2001). Onion crops are also affected by downy mildew (*Peronospora destructor*) at higher elevations (i.e. in a damp or highly moist environment; Syobu & Watanabe, 2022). Onions are prone to pests and diseases, or post-harvest loss, where prolonged heavy rainfall occurs or when irrigation is used excessively (Kavanamur, nd; Biswas, 2010). In addition to management of soil moisture where possible, crop diseases in onion may be managed by crop rotation, selection of suitable varieties, and routine fungicide treatment (Degani et al., 2022: Prajapati & Srivastava, 2022).

WATER SUPPLY AND QUALITY PROBLEMS IN PAPUA NEW GUINEA

PNG has been identified as one of 37 hotspots in the world with a high level of vulnerability to water scarcity as well as inadequate water services (WHO, 2022). Communities residing in these vulnerable areas rely heavily on surface water, on undeveloped sources, or on distant locations where collecting water might take longer than 30 minutes (WHO, 2022). Additionally, there are water shortages and environmental problems due to the growth in agricultural production in the plains of the PNG Highlands (Bourke et al., 2016; Michael, 2019; Friedman et al., 2022). Water is the most significant limiting factor for increasing crop output in dry, drought-prone locations where rainfall is inadequate (Cobon et al., 2016; Michael, 2019; Hainzer et al., 2021).

Climate change impacts

Most of the PNG Highlands are susceptible to drought (Ghodake, 2002). In a 2015–2016 drought, 35% of people in the Central Highlands and 53% of those residing at elevations of between 2,200 and 2,800 metres were found to have experienced food shortages (Bourke et al., 2016). Drought has been found to restrict the feasibility of irrigation and reduce both irrigated and rain-fed crop yields in various regions of the Highlands by up to 80%, having severe consequences such as food and water shortages, the spread of human illnesses, financial difficulties, and environmental deterioration (Ghodake, 2002). In contrast, recent considerable increases in precipitation in parts of the PNG Highlands (at elevations of 1,600 to 2,000 metres) has also reduced crop productivity and resulted in significant post-harvest losses (Bourke et al., 2018).

Consequently, it is crucial to investigate and adopt effective techniques for water preservation and management to protect and enhance both crop production and water resources (Cobon et al., 2016; Hainzer et al., 2022). Lack of sufficient water in those areas prone to extended periods of drought (for example the severe drought of 2015-16) has limited the successful cultivation of onions in Highland areas by reducing growth, yield, and quality (FPDA, 2016). Lack of irrigation water also affected experimental activity at research sites (FPDA, 2016). On the other hand, regions experiencing excessive amounts of rainfall or have witnessed increased pest and disease outbreaks, leading to significant losses after harvest (Kavanamur, nd).

Irrigation in Papua New Guinea

Historically, irrigation in PNG has been rarely used due to excessive moisture being a more important problem than inadequate moisture, particularly in areas experiencing seasonal rainfall patterns (Bourke, 2003). However, the climate variability discussed in the previous section of this paper, notably increasing frequency and severity of drought events, will influence farm irrigation practices in the Highlands.

Irrigation systems for high value crops such as sweet potato, bulb onion, cabbage, broccoli and tomato are therefore becoming more common in the central PNG Highlands. For instance, Hainzer et al. (2022) found that most sweet potato farmers in PNG were considering incorporating irrigation into their farming system. Water plays a critical role in early crop development stages, and is essential for achieving high yield (Malhotra, 2016; Opafola et al., 2018). Farmers in the region increasingly recognise the significance of threats to reliable water availability, and the implications for producing profitable crops at a commercial scale and ensuring ongoing access to commercial markets (Hainzer et al., 2022). Investing in farming technology such as irrigation infrastructure is a way to increase production and profits (Loiskandl & Nolz, 2021; FPDA, 2022a).

Limitations with current irrigation practices

Water sources

In the central PNG Highlands, rain-fed agriculture has historically served as the primary means of food production, with the region benefiting from ample rainfall in most years (Bourke, 2017). However, rainwater harvesting is on the rise to obtain water for small-scale irrigation. Water is also collected from shallow wells and natural springs that are replenished by rainwater. However, in times of drought, these water sources can become unreliable and contaminated (Allen & Bourke, 1997; Gwatirisa et al., 2017). Therefore, farmers must strategically tailor their farming practices to accommodate the alternating wet and dry seasons that are a common feature of the weather pattern of the PNG Highlands or must look for alternate options to supply crops with water (Michael, 2019; Loiskandl & Nolz, 2021; Friedman et al., 2022).

Bulb onion crop seedlings, supplied by nurseries, are transplanted into the field towards the end of the rainy season (Kavanamur, nd). This timing enables the crop to thrive and for bulbs to develop in preparation for the commencement of the dry season. Using supplementary irrigation can decrease the probability of crop failure caused by drought (FPDA, 2017, 2021).

The primary irrigation water source in the Highlands is rivers and streams, accessed gravity fed or accessed via pumping infrastructure (Hainzer et al., 2022). Relatively few farmers use storage tanks to collect and store rainwater throughout the wet and dry seasons, or store supplemented water from nearby rivers to be used during periods of minimal rainfall (FPDA, 2022b). This strategy decreases reliance on groundwater and surface water and minimises water waste. However, over time, this can result in a water shortage and the exhaustion of water supplies (Cobon et al., 2016; Loiskandl & Nolz, 2021).

Manual irrigation

Manual irrigation is the prevailing method of irrigation in the PNG Highlands (Cobon et al., 2016; Loiskandl & Nolz, 2021) and involves physically transferring water to crops. One of the most common methods employed by onion farmers involves using a horse and bucket or watering-can to move water from a water source, such as a storage tank, well or creek, to individual plots (Seta-Waken et al., 2016; Wiles, 2001). This task requires a significant amount of effort and time, particularly during drought (Gwatirisa et al., 2017). Manual methods are also the relatively less effective since they provide less consistent application of water (Seta-Waken et al., 2016). Excess delivery of irrigation water to plants by these means are less beneficial for the plant and can also lead to increased farm runoff (Loiskandl & Nolz, 2021). Nonetheless, this irrigation method is the most cost-effective and simple for farmers in the PNG Highlands and at the time of writing was the sole readily accessible choice (Cobon et al., 2016).

Simple irrigation technologies introduced

The PNG National Agriculture Research Institute (NARI, 2013) suggested three water distribution methods: a gravity-based water flow system; using a rope and washer pump for water extraction; and using a microtube drip irrigation system for water distribution. These systems are affordable in terms of both set-up and maintenance (NARI, 2013; Loiskandl & Nolz, 2021). Irrigation water tanks and pumps are among other technologies used by female farmers (FAO, 2019). Other advantages of the systems recommended by NARI are likely to include most of the components could be manufactured locally; the systems are relatively user-friendly; between the various systems they are suited to any water source; they can be used to transport sufficient water; the pumps are considered to be reasonably efficient; minimal effort is required to set up and operate the systems; and they can be easily moved (Loiskandl & Nolz, 2021). Of the options, the most common method adopted appears to be the gravity-flow system (NARI, 2013; Cobon et al., 2016). However, there is a need for more water storage resources to utilise these irrigation techniques fully. Many farmers may also lack the skills to implement these approaches or awareness of their existence, contributing to less than optimal rates of adoption (FAO, 2019).

Lack of commercial irrigation suppliers

Limited access to irrigation sales and service providers remained a significant obstacle for farmers seeking to implement irrigation systems in the PNG Highlands at the time of writing (Hainzer et al., 2022). This was especially true in more remote rural areas with limited access to resources. Consequently, some farmers relied on expensive and time-consuming avenues to secure equipment and support, increasing the cost of setting up a new irrigation system (FAO, 2019). Farmers therefore relied heavily on assistance from FPDA and Australian irrigation experts to establish irrigation systems through optimal use of available infrastructure (Hainzer et al., 2022). This support involved establishing irrigation systems that used gravity water delivery, drip lines, as well as pumps powered by solar energy generation.

POTENTIAL WATER MANAGEMENT AND IRRIGATION PRACTICES FOR THE PNG HIGHLANDS

There are a variety of techniques to irrigate crops as well as to manage soil moisture effectively. The techniques discussed in the next sub-sections are considered particularly relevant to the PNG Highlands context as they are relatively straightforward and convenient (Loiskandl & Nolz, 2021), and therefore more accessible to small-scale producers of crops such as bulb onions in the Highlands (Cobon et al., 2016; Hainzer et al., 2021).

Drip irrigation

As the technology has evolved, drip irrigation has become a popular irrigation technique in arid agricultural systems globally (Fayed, 2020). Although it appears likely that many farmers in the PNG Highlands were not familiar with drip irrigation at the time of writing, more widespread adoption would enhance output of crops such as bulb onions while also allowing farmers to better regulate water usage (Loiskandl & Nolz, 2021).

Drip irrigation uses hose systems with small holes or nozzles to deliver water directly to the root zone of crop plants (Khamidov and Muratov, 2021). These drip lines and are laid along the crop rows. Gravity enables the slow delivery of water from storage tanks to drip lines. Pumps are used to refill the water storage tanks (Loiskandl & Nolz, 2021).

For bulb onion production, Bhasker et al. (2018) found that a drip irrigation system was more effective than the surface irrigation system in supporting improved plant appearance, productivity and marketable yield. In addition, drip irrigation provided greater water usage efficiency, consistent with previous research (Tripathi et al., 2010; Bagali et al., 2012; Yang et al., 2023). Terán-Chaves (2023) found that drip irrigation was the most favoured technique amongst bulb onion farmers because it made it possible to maintain a steady soil moisture level and reduce water wastage. Drip irrigation is also well-suited with automation, particularly in comparison to surface or sprinkler irrigation techniques (Loiskandl & Nolz, 2021). In addition, drip irrigation with fertigation of NPK nutrients improves plant growth (delivering up to twice the yield of surface irrigation), carbohydrate accumulation and photosynthesis levels, and reducing bolting (Bhasker et al., 2018).

In the specific context of bulb onion production in the PNG Highlands, drip irrigation may be suitable due to its convenience in terms of installation and labour requirements. However, moving drip irrigation systems can pose challenges and potential drawbacks of adoption include the need to acquire drip lines, a water storage tank, and additional equipment (e.g. pressure regulators, filtering equipment), thus contributing to increased costs (Jayant et al., 2022).

Sprinklers

Sprinklers are a widely favoured irrigation method in small-scale farming. They offer a cost-effective option and are exceptionally user-friendly (Finkel, 2019). Growing rates of adoption of sprinkler irrigation have been attributed to two factors. Firstly, the effects of climate change have contributed to less predictable rainfall patterns and prolonged drought, making sprinkler irrigation more necessary solution. Secondly, labour scarcity has favoured the adoption of this irrigation method (Shankar et al., 2015).

Using the sprinkler method, water is pumped from the source to the field through a network of small poly pipes, utilising pressure to deliver it. Connectors are used to attach hose sections to the sprinkler heads, with the sprinkler heads positioned above ground level to enable even water distribution. Compared to manual water delivery methods commonly employed on farms in the PNG Highlands, sprinklers free up labour for other farm activities (Shankar et al., 2015; Seta-Waken et al., 2016; Finkel, 2019).

Sprinkler irrigation is effective on most soil types except heavy clay. It is suitable for crop irrigation in crowded plant areas and in elevated areas relative to the water source, as pumps are utilised to transport water from storage through the sprinkler infrastructure and on to the field. The system is highly efficient, especially on slopes and less dense soil, and can save up to 30-60% in water resources compared to manual irrigation (Shankar et al., 2015; Gwatirisa et al., 2017; Finkel, 2019). Nevertheless, acquiring these systems requires considerable investment in materials. Small-scale farmers may find this level of investment impractical, although farmers with access to a reliable source of water can utilise it effectively, as they preferred easily assembled and locally available technology (FAO, 2019; Loiskandl & Nolz, 2021; Hainzer et al., 2022). Sprinkler systems also require investment of time and resources into their continued upkeep and may be susceptible to external factors such as fire and theft. Due to the significant investment required to establish and maintain sprinkler systems in PNG, very few smallholder farmers have adopted the practice of sprinkler irrigation.

Mulching

For centuries, mulch has been employed globally to enhance agricultural productivity by retaining moisture in the soil, while also delivering other agricultural crop benefits such as soil temperature regulation and improvement of soil quality (Rachel et al., 2018). Mulching is the practice of using organic and inorganic materials to provide a protective layer over the soil surface for crop production. During an extended period of drought and when irrigation is used, mulch can help protect the soil against excessive temperatures and help to preserve moisture in irrigated soils.

Various mulch products including rice straw, sawdust, water hyacinth and other plant waste by-products, and transparent and black polythene films can effectively preserve soil moisture in bulb onion production (Jamil et al., 2005; Anisuzzaman et al., 2009; Islam et al., 2002). Islam et al. (2002) found that using mulches, such as polythene and rice straw had a significant positive impact on the growth and productivity of bulb onions. Mulching helps to support and promote crop growth, particularly during periods of low water availability.

In sloped cropping areas found in parts of the PNG Highlands, mulch can reduce the speed of rainwater flow across the soil surface, leading to a more balanced distribution of moisture and organic nutrients on the slope and reducing erosion risk (Wang et al., 2021; Sun et al., 2023). Mulch provides other important functions including reducing rate of runoff, minimising infiltration rates and soil nutrient loss, thus enhancing the quality and yield of crops (Adnan et al., 2020; Li et al., 2021). Sources of mulch in the PNG Highlands include grass, sawdust, coffee pulp and coffee husk (Ossom et al., 2001).

For onions, mulch can be used to manage soil moisture evaporation, providing soil moisture conservation of higher percentage compared to non-mulched ground (Rachel et al., 2018; Li et al., 2021). Additionally, it can lower soil temperature in the vicinity of plant roots, enhance the presence of organic matter in the soil, suppress the growth of weeds, and curb erosion (Adnan et al., 2020; Ahmad et al., 2022). Agostini et al. (2010) and Pinheiro et al. (2018) demonstrated that the effectiveness of nitrogen fertiliser can be enhanced through mulching, which helps to minimise nutrient loss by reducing nitrate leaching and ammonia volatilisation and increase nitrogen use efficiency. Mulching prioritises the sustainability of on-farm processes and ensures the production of safe and high-quality agricultural products, and enhances bulb onion growth (Adnan et al., 2020; Li et al., 2021).

ECONOMIC ASPECTS OF IRRIGATION AND MULCHING

Drip or sprinkler irrigation usage increases yield compared with non-irrigated bulb onion production (Finkel, 2019; Khamidov & Muratov, 2021). However, drip irrigation is considered more beneficial than sprinkler irrigation. It increases yield and bulb size by using less water more efficiently through more frequent and shallower irrigation (Rao et al., 2019). According to research completed by Bhasker et al. (2018), gross yield of onion increased by 18.16% and marketable yield increased by 24.49% using drip irrigation, compared to surface irrigation. In addition, water use efficiency improved, resulting in 29.36% and 27.12% less water consumption during the dry and rainy seasons, respectively. These results suggest that drip irrigation is the more economic choice in terms of cost and resource use, but also in terms of crop production (Rao et al., 2019).

Mulch improves soil quality, conserves moisture and suppresses weed growth, increases crop yields and helps ensure sustainable production over the longer-term (Rachel et al., 2018; Parsottambhai & Rawat, 2020). In onion production, Tolossa (2020) found that mulching significantly benefited leaf area, length and number as well as plant height under deficit irrigation conditions. The importance of drip irrigation and mulching together as an approach to maximise yields and water efficiency on sandy loam soils has also been demonstrated in previous research (Terán-Chaves et al., 2023). Combining irrigation and mulching can maximise water productivity with limited irrigation resources through efficient delivery of water to plants, and minimising evaporation losses to maintain onion production (Sori et al., 2020).

CONCLUSIONS

Bulb onion cultivation in the PNG Highlands can be highly profitable and therefore popular among farmers. The production of this crop in the PNG Highlands has seen significant growth in recent years due to the support provided by FPDA and other organisations. The economic feasibility of producing and marketing bulb onions at a commercial scale is significant.

As a shallow-rooted crop, bulb onions require considerable water resources for optimal yield and profitability. These crops cannot adjust leaf water potential when water availability is reduced. Water assists with nutrient availability and uptake, crop development, and temperature regulation, and is pivotal for onion growth and development.

Water scarcity hampers bulb onion cultivation, and this issue is expected to worsen in the PNG Highlands due to increasing drought events related to climate change. Using mulch and efficient irrigation systems such as drip or sprinkler can significantly improve soil moisture delivery and retention in droughts and changing climates, while minimising irrigation water wastage during times where irrigation water is likely to be relatively scarce. Mulch can preserve soil moisture, while drip and sprinkler irrigation systems would utilise irrigation water more efficiently than the prevailing manual irrigation methods used by many bulb onion farmers in PNG, with the additional benefit of reducing nutrient runoff on onion farms. Additionally, irrigation technology adoption as well as mulch use can enhance farm productivity and facilitate a shift for more farmers to commercial-scale bulb onion production. However, irrigation technology remains expensive at the time of writing in PNG, and domestic supply lags behind demand. The literature suggests that drip irrigation may be the better economic choice in terms of crop yield, while also allowing farmers to utilise scarce water resources more efficiently.

Further research, development and extension in the form of drip and sprinkler irrigation field trials with farmers in the PNG Highlands is necessary to understand their feasibility and benefits, and to improve rates of adoption. To fully understand irrigation usage in this regional context, it is necessary to evaluate application timing, optimum water quantity, and stress levels at various stages of growth. Access to this information is essential for farmers to optimise onion crop yield while optimising efficient water usage. Hence, it is vital to implement simple irrigation methods and techniques that preserve soil moisture.

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