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REVIEW

A review of bacterial diseases of rice and its management in Malaysia

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Abstract

Rice (*Oryza sativa* L.) is one of the staple foods in the world including Malaysia. Rice production has been affected due to disease infections that is usually destructive and cause many losses to rice productivity. The common bacterial diseases listed in Malaysia include bacterial leaf blight (BLB) (*Xanthomonas oryzae* pv. *oryzae*), bacterial leaf streak (BLS) (*Xanthomonas oryzae* pv. oryzicola), sheath brown rot (SBR) (*Pseudomonas fuscovaginae*) and bacterial panicle blight (BPB) (*Burkholderia glumae*). Currently, there is less information on the bacterial disease occurrence of rice in Malaysia. Hence, this study aimed to discuss the current report on the severity and the economic losses of rice production due to BLB, BLS, SBR and BPB in Malaysia and the possible management strategies to control the disease that consequently reduce the losses. In general, management strategies for bacterial diseases are challenging due to the lack of suitable chemical control that is not harmful to the environment and human health. Furthermore, other management strategies can be used to control these diseases such as cultural control and biological control. There is a need for the control method to be upgraded to reduce the occurrence of these diseases. All the information provided in this study may contribute as a useful tool for identification of the bacterial disease in paddy fields and as a source of effective strategies to control the disease before it becomes worse.

1. Introduction

Rice (*Oryza sativa* L.) is one of the most important food crops in the world besides oil palm, rubber and cocoa (Vijay and Roy, 2018). Rice is also considered as a staple food where more than 40% population in the world consumes rice, especially Asian people (Nagendran *et al.,* 2013; Shekhar *et al.,* 2020). Moreover, rice is a source of carbohydrates and energy for people who consume rice. At the same time, people can get proteins and calories from rice (Siwar *et al.,* 2014). Besides that, in Asia, rice also contributes to many important aspects, particularly in the economics and the social fields where more than 90% of rice is produced and consumed by the people. In addition, almost 42 countries around the world produce rice with Asian countries being the largest producers and consumers (Rajamoorthy *et al.,* 2015). Japan, Thailand, Vietnam, China, and India are among the major countries in rice production.

To date, rice farming is particularly significant in Malaysia with almost 700,000 ha of land being cultivated every year in Peninsular Malaysia, consisting of eight primary paddy granary areas that contribute to the nation's rice bowl and food security (Firdaus *et al.,* 2020). The primary rice granary areas were developed during the National Agricultural Policy (NAP) of 1984–1991 for the purposes of maintaining and protecting the nation's food security as well as developing the rice sectors (Tang, 2019). Every year, the planted areas produce more than 2 billion tons of rice grains that contribute to the gross domestic product (GDP) of the country (DOA, 2021). The National Agro-food Policy of Malaysia, 2011–2012 highlights the importance of increasing rice production to guarantee the country's demand remains constant in the future (Rajamoorthy *et al.,* 2015; Zaman *et al.,* 2017).

Additionally, there are many strategies that have been implemented by the government to ensure the rice industry in Malaysia is stable in terms of social, political and economic importance. This is because there are

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almost 296,000 rice farmers who are highly dependent on growing rice for household income (Nurulnahar *et al.,* 2020). However, the big challenge in rice production is disease infection which can cause the reduction of rice yield, leading to economic losses. These disease infections may come from fungi, bacteria, nematodes and viruses (Azeem *et al.,* 2019). Bacterial diseases only decrease the level self-sufficiency of in rice from 78.6% to 73.5% starting from 1990 until 2013 (Rajamoorthy *et al.,* 2015). Among the common bacterial diseases reported in Malaysia is bacterial leaf blight disease (BLB) caused by *Xanthomonas oryzae* pv. *oryzae*, bacterial leaf streak disease (BLS) caused by *Xanthomonas oryzae* pv. *oryzicola*, bacterial panicle blight (BPB) caused by *Burkholderia glumae* and sheath brown rot (SBR) caused by *Pseudomonas fuscovaginae*. According to Che Omar *et al.* (2019), if there is no control measure taken after the infection begins, the disease may cause rice yield losses of up to 50%. The bacterial infection is among a biotic stresses that could limit the rice yield in the future (Shamsudin *et al.,* 2019).

Bacterial leaf blight disease (BLB) is caused by *Xanthomonas oryzae* pv. *oryzae* is among the most common rice diseases in Malaysia due to bacterial infection (Chukwu *et al.,* 2019). This disease is primarily associated with the rainy season on irrigated rice. Furthermore, bacterial leaf blight disease is influenced by climatic conditions as it can appear at any stage of the rice crop and shows the symptoms of kresek and leaf blight (Sundin *et al.,* 2016). Bacterial leaf blight was first reported in Fukuoka, Japan by farmers in 1884 (Jackson, 2014) before this disease spread to other countries like Bangladesh, Indonesia and Malaysia (Awaludin *et al.,* 2020). The bacterial leaf blight disease has a significant effect on food security in a country because the disease outbreak can cause severe yield loss of approximately 30% to 50% to the rice crop. It is also considered a highly destructive rice disease (Shamsudin *et al.,* 2019). If the infection on plants is detected at the early stage, it can cause more than 50% yield losses. However, if the infection is observed at the tillering stage, it can cause about 20% to 40% yield reduction (Chukwu *et al.,* 2019). The bacterial leaf blight disease affects all of Malaysia's major rice growing areas causing mild to severe infections and has potential for total crop failure (Zuki *et al.,* 2020).

Another common bacterial disease in paddy crops is bacterial leaf streak disease (BLS) caused by (*Xanthomonas oryzae* pv. *oryzicola*). This disease was first reported in the Philippines back in 1918 and is known as a devastating disease in rice production areas (Sattayachiti *et al.,* 2020). Bacterial leaf streak disease is occasionally reported in Malaysia. However, this disease is dominant in certain areas of rice fields in regions like Asia and Africa causing estimated yield losses of 20–30% which consequently affects the rice crop production and the economy. Apparently, the infection of this disease is also influenced by rice varieties and environmental conditions.

Bacterial panicle blight (BPB) which is also a common bacterial disease in paddy crops is caused by *Burkholderia glumae* and is associated with seed-borne rice bacterial diseases. This disease is one of the most serious diseases in the rice field because it can turn into a major disease from a minor disease with appropriate environmental conditions (Zhou-qi *et al.,* 2016). Under appropriate environmental conditions, this disease is highly destructive and will cause rice losses up to 70% in the quality of yield and milling (Zhou, 2019). Seedling blight, sheath rot, flower sterility, grains aborted and not filling, and milling quality decline are among the effects of this disease in rice. Bacterial panicle blight (BPB) of rice was initially identified and reported in Japan, in 1950 and since then, it has become one of the most serious diseases around the world.

Sheath brown rot disease caused by *Pseudomonas fuscovaginae* is another rice disease that has gradually gained awareness (Miyajima *et al.,* 1983). This disease causes sheath lesions, sterility of the grain and discolouration of the grain. The sheath brown rot can be observed during the seedling stages with a systemic discolouration that can expand to the veins of the leaves. Later, the infected seedling will die. However, the infection could also occur at a later stage of growth, where the infected rice plants will turn into yellowish plants. Generally, this disease causes the lower areas of the sheath to appear light or brownish. In the later phases of infection, the entire sheath of the leaf will become necrotic. Grains developed by the infected panicles are discoloured, malformed and empty (Cottyn *et al.,* 1994). Moreover, the sheath brown rot disease causes a higher yield loss of up to 72.2% which has been reported in Indonesia. In Malaysia, the disease sheath brown rot has been well distributed in Peninsular Malaysia (Ab Wahab *et al.,* 2015), where the first incidence was reported in Seberang Perak, Malaysia (Marzukhi *et al.,* 1991) and caused around 46.0% yield loss to the farmers.

Bacterial diseases of rice such as bacterial leaf blight (BLB), bacterial leaf streak (BLS), bacterial panicle blight (BPB) and sheath brown rot (SBR) are among the most widespread diseases around the world. Hence, the development of management strategies is important and required to overcome the severity of losses due to the infections of bacterial diseases. These diseases can be overcome by applying several methods such as host resistance, cultural control, biological control and

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chemical control. Investigation of the appropriate management strategies is very important to overcome the bacterial disease outbreak of rice in Malaysia. Therefore, such information is necessary to identify a bacterial disease outbreak in the rice cultivation region at an early stage so that these bacterial diseases can be managed and the losses due to the outbreak can be avoided.

Hence, this study aimed to highlight the common bacterial diseases that occurred in the rice cultivation area in Malaysia and their control management. This study can be useful for the agricultural sector especially in the paddy industry to assist growers and farmers in identifying the symptoms and to provide options for appropriate control management strategies to overcome the problems before it becomes severe which can lead to the loss of yield.

2. Bacterial rice pathogens

Bacteria rice pathogens have had a negative impact on rice output particularly in Asia. If this pathogen spreads widely, it might result in up to 60% loss in rice production with millions of hectares of rice land afflicted each year. Bacterial pathogens infection like *Xanthomonas oryzae* pv. *oryzae*, *Xanthomonas oryzae* pv. *oryzicola*, *Burkholderia glumae* and *Pseudomonas fuscovaginae* are common bacterial pathogens in rice cultivation and they can rapidly spread under favourable environmental conditions and can cause significant losses to rice production. Bacterial pathogens are indicated as being easily transmitted from the infected plants to other plants through water which is rain splashing and then spreading to the root rice crop. The bacterial pathogen also can be transmitted to the emerging seedlings by the contaminated seed.

Based on Table 1, the bacterial pathogen can infect rice plants in any part of the plant, including seed, foliar, leaf, sheath, grain, culm and root (Ngalimat *et al.,* 2021). These pathogens are from the bacterial species in the genus *Xanthomonas* such as *Xanthomonas oryzae* pv. *oryzae* which causes bacteria leaf blight and *Xanthomonas oryzae* pv. *oryzicola* which causes bacterial leaf streaks. The numerous bacterial species from the genus *Burkholderia* cause bacterial panicle blight that was just recently reported in the paddy field. Other pathogens are from the genera *Pseudomonas*, *Pantoea*, *Acidovorax*, *Erwinia*, *Enterobacter* and *Diceya*. A series of common bacterial diseases of rice recorded in Malaysia is presented in Table 2.

The presence of bacterial disease in rice is caused by many virulence factors such as degradative enzymes, extracellular polysaccharides, and components of quorum-sensing signalling molecules. These viral factors involve the communication between the host and the pathogen and contribute to rice diseases. Their presence has been discovered through molecular studies such as bacterial pathogenicity, plant pathology and genomic studies (Ngalimat *et al.,* 2021). This discovery reflects the ongoing enthusiasm for the study of molecular plant pathology for the control of bacterial rice pathogens.

The main methods to control bacterial rice pathogens include the use of disease-resistant varieties, cultural practices, natural products or botanical extractions, host resistance and conventional and non-conventional chemicals. However, due to polymorphisms and chemical resistance established in the virulent strains, the efficacy of these techniques is still poor. Interestingly, biocontrol tactics including the use of plant growth-promoting bacteria (PGPB) could be a viable option for

Table 1. Bacterial disease of rice and their caused agent

Plant Part	Diseases	Bacterial Pathogens
Seedling	Seedling blight	*Bukholderia plantarii*
	Bacteria Brown stripe of rice (BBSR)	*Pseudomonas syringae* pv. *panici* *Acidovorax avenae* subsp. *avenae*
Foliar	Bacteria blight (BB) or Bacteria Leaf Blight (BLB)	*Pantoea ananatis* *Pantoea stewartii* subsp. *Indologenes* *Pantoea stewartia* *Pantoea agglomerans* *Xanthomnas oryzae* pv. *oryzae*
	Bacteria Leaf Streak (BLS)	*Xanthomnas oryzae* pv. *oryzicola*
	Halo Blight	*Pseudomonas syringe* pv. *oryzae*
Leaf Sheath and grain rot	Sheath Brown rot	*Pseudomonas fuscovaginae*
	Sheath rot	*Pseudomonas syringe* pv. *syringe*
	Bacteria Panicle Blight (BPB)	*Bukholderia glumae or Bukholderia gladioli*
	Bacteria palea browning	*Erwinia herbicola* *Pantoea ananatis* *Enterobacter cloacae*
Culm and root	Bacteria foot rot	*Erwinia chrysanthemi* *Diceya zeae*

Source: Ngalimat *et al.* (2021).

Table 2. The list of previous study that shows cases of bacterial disease of rice in Malaysia.

No.	Author(s)	Topics
1	Ramachandran *et al.* (2021)	This paper is about the characterization and identification of *Burkholderia glumae* as the causal pathogen of bacterial panicle blight of rice (*Oryza sativa* L.) in Malaysian rice granaries
2	Awaludin *et al.* (2020)	This paper studied the development of a fluorescence-based immunoassay for the early detection of *Xanthomonas oryzae* pv. *oryzae* caused by bacterial leaf blight in rice leaf. The result showed detection of *Xanthomonas oryzae* in plant samples.
3	Hata *et al.* (2019)	This paper was carried out to determine the occurrence, and symptoms of *Xanthomonas oryzae* pv. *oryzicola* on the leaves of rice cultivation areas in different states in Malaysia. Results showed that the bacterium of bacterial leaf streak is widespread in Malaysia, but it is inadequate nowadays.
4	Shamsudin *et al.* (2019)	This paper studied the infection of *Xanthomonas oryzae* on drought tolerance rice variety MR219-4, growing under normal conditions. Results showed the infection does not affect the physiological dynamics of the plant and MR219-4 as drought tolerance paddy is resistant to bacterial pathogen infection even in normal conditions.
5	Lai and Chan (2016)	This paper studied the infection bacterial leaf blight (BLB) in the Sabak Bernam rice cultivation area. Results showed the leaf drying symptom have destroyed the paddy fields and caused the farmers heavy yield losses.
6	Ab-Wahab *et al.* (2015)	This study is about phenotypic characterization and Molecular Identification of Malaysian *Pseudomonas fuscovaginae* Isolated from Rice Plants. Different *Pseudomonas fuscovaginae* were test for pathogenicity.

managing rice pathogens, as it involves the use of disease-suppressive bacteria to control pathogens and consequently improve rice yield.

3. Bacterial leaf blight disease and economic importance

Bacterial leaf blight (BLB) of rice caused by pathogen *Xanthomonas oryzae* pv. *oryzae* is the most important and devastating disease that occurs in worldwide rice growing areas, including both tropical and temperate regions especially where the rice field has poor drainage and potential for flooding (Jackson, 2014; Saha *et al.,* 2015). The favourable condition of this bacterium usually infects rice seed to mature plants through irrigation water and rainy season (Shamsudin *et al.,* 2019). This disease also is considered the oldest bacterial disease as it was first recorded over a century ago in rice cultivation areas, especially in Asia. It was first reported by farmers in Fukuoka, Japan in 1884 (Kannan *et al.,* 2017). Since then, this disease has been observed to be gradually spreading over the other regions of rice-growing areas in Japan. Although the occurrence of bacterial leaf blight in rice cultivation is not a new disease, this disease can have a significant effect on rice production in Asia (Singh and Singh, 2014).

Based on previous studies, rice cultivation infected by this disease had caused more than a 50% reduction in grain yields at various stages, and was influenced by the planting technique of rice, the variety of rice, the growth stage of rice crops, the location, and the environmental condition (Ku Asmah and Sapak, 2020; Jiang *et al.,* 2020). This disease infecting rice plants can be seen at two stages which are the early stage and the tillering stage. Infection at an early stage can cause up to 50% yield loss under conducive conditions, while infection at the maximum tillering stage can cause a yield reduction of about 20% to 40% (Chukwu *et al.,* 2019).

The reduction of rice yields up to 50% can be reached when the infected rice plant shows yellowing to the leaves which leads to the dying of the infected leaf tissue. Usually, the infection can be seen from the tips to the leaves and finally, the leaves are reduced in size (Saad and Habibuddin, 2010). In addition, the pathogens causing this disease are mostly related to seed-borne disease where it is transmitted through the seeds (Ranjani *et al.,* 2018). The common sources of pathogens could make it easier for this disease to widespread. These sources include water irrigation, weed hosts, contaminated seeds, and infected plants. Based on the study by Govindappa *et al.* (2011), the contaminated seeds will produce poor germination and will affect the rice plants at tillering and flowering stages by the formation of chaffy seeds.

The incidence of bacterial leaf blight was first observed in rice fields of Peninsular Malaysia in the early 80 s and was noticed by small-scale farmers. However, the occurrence causes crop loss of approximately 10% to 20% under moderate prevalent conditions (Hasan *et al.,* 2020). To date, this disease outbreak occurred in February 2014 when the first infection case in Malaysia was reported in the paddy fields of Padang Besar, Perlis. Then, from September to December 2016, the disease was detected again in Sekinchan, Selangor and caused 50% to 70% of crop yield losses (Azizi *et al.,* 2019).

The estimated loss for both cases reported is around RM50 million with more than 60,000 metric tons (Jonit

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et al., 2016). After that, the pathogen started to widely spread across rice fields in Malaysia like Kedah, Pulau Pinang, Selangor, Melaka and Kelantan and caused great losses to rice production (Ku Asmah and Sapak, 2020). In recent years, the outbreak of bacterial leaf blight in rice fields of Peninsular Malaysia has shown an increase with almost 12,000 hectares of rice growing areas. This includes Selangor (6,000 ha), Kedah (4,500 ha), Pulau Pinang (620 ha), Terengganu (450 ha), Negeri Sembilan (290 ha), Perak (175 ha), Pahang (48 ha), Perlis (140 ha), Johor (5 ha), Kelantan (1 ha), and Melaka (less than 1 ha) (Bernama, 2018).

The tropical weather in Malaysia is favourable for bacterial leaf blight infection with flood and rainfall throughout the year. The conducive conditions for the pathogen to be transmitted include splashing of rain, plant contact, and movement of irrigated water. This pathogen also can be spread through wounded cells, insects and natural openings. The infection can be detected from a lesion seen on the leaf surface followed by cell death and desiccation of dying tissue (Shamsudin *et al.,* 2019). Based on Singh and Singh (2014), bacterial leaf blight is more favourable in warm temperatures which are from 25°C to 30°C which is mostly related to high humidity above 70% and rainy conditions.

3.1 Symptoms of bacterial leaf blight disease

The symptoms of this disease can be identified in two phases which are the leaf blight phase and the kresek phase that infect rice from the seedlings stage to the mature rice plants (Deng *et al.,* 2016). Besides the damaging of leaves, this disease also can be indicated through reduced numbers of tillers, seeds per panicle, and grain filling which are significant to the yield reduction.

The symptoms for the leaf blight phase begin with the causal agent *Xanthomonas oryzae* pv. *oryzae* entering the rice plant from wound or water pores that are usually located on the margins upper part of the rice leaves and produce lesions when soaked in water (Singh and Singh, 2014). The wound usually occurs through activities that cause injuries to the rice plant such as pulling the seedling from the seedbed, transplanting and being attacked by insects. The entering of pathogens leads to the occurrence of lesions from the leaf margin near the tip causing yellowish to straw colour stripes with a wavy margin and progressing downwards the leaves (Jonit *et al.,* 2016). These lesions may develop at one or both edges of the leaves or along the mid-rib. Early in the morning, can be seen symptoms on young lesions of wavy margins and the appearance of yellow droplet bacterial ooze like milky or opaque if under moisture conditions (Figure 1). After that, the lesions will change from yellow to white. The leaves will dry quickly if the disease is severe (Figure 1). Then, the greyish of the lesions causes another infection which is by saprophytes fungi (Huerta *et al.,* 2019).

Figure 1. (1) Yellow droplets of bacterial ooze, (2) Bacterial ooze dried on leaf, (3) Dried leaf at margins Source: Org *et al.* (2017).

On the other hand, the kresek phase symptoms in the rice field are known as a systemic phase in which the severe wilting of the rice seedlings will take over. The "kresek" is from the Indonesian word where the first symptoms were reported in Indonesia rice growing areas (Jackson, 2014). This symptom usually appears one to three weeks after the transplanting process from the nursery to the rice field when the leaves turn to greyish green, before withering and rolling upwards (Huerta *et al.,* 2019). These symptoms are generally related to the seedling infection that occurs through wounds during the transplanting process that has translocation blockage which directly exposes the rice plant to the bacterial infection (Singh and Singh, 2014). The severity of the symptoms is mostly affected by the stages of infection, in which the earlier seedlings are infected. The early symptoms are shown with the green water-soaking layer along the cut portion or at the leaf tip of the leaves (Naqvi, 2019). Then the leaves wilt and roll up and greyish-green colour turns to yellow. Then, the entire plant wilts completely. The infected mature leaves plant turns yellow or pale yellow while the young leaves will uniformly turn to pale yellow and broad yellow stripe (Shaheen *et al.,* 2019). Under severe conditions, the panicles can remain sterile, unfilled and stunt.

Apparently, the bacterial leaf blight survival in crops is not well understood. This pathogen is probably survived in rice seed, but the survivability of this pathogen in soil is only about five to six weeks. The bacteria or the pathogen can die rapidly in hot weather or dry conditions. Based on Jackson (2014), the survival of a pathogen can be longer if there is an alternate host like a weed.

4. Bacterial leaf streak disease and economic important

Bacterial leaf streak (BLS) of rice is caused by pathogen *Xanthomonas oryzae* pv. *oryzicola* is known as a destructive disease in many rice cultivation areas, especially in humid tropical and subtropical regions in the world. This disease can rapidly spread under favourable conditions and cause serious damage like bacterial leaf blight (BLB) (Sattayachiti *et al.,* 2020). This disease has become a serious concern in rice production because of ongoing climate change especially the intensity and frequency effects of rice growing in Asia and Africa (He *et al.,* 2012).

The outbreak of bacterial leaf streak (BLS) is more recent compared to the bacterial leaf blight (BLB) disease though BLB has existed for for over a century (Mohd-Said *et al.,* 2018). Bacterial leaf streak (BLS) is associated with high temperature and high humidity. To date, the first case was reported in the Philippines back in 1918 and was called stripe disease. Then, the infection in China changed its name to bacterial leaf streak (Saha *et al.,* 2015). After that, this disease has spread to some parts of Asia like Thailand, Indonesia, Malaysia, India, Vietnam, Indonesia, and Bangladesh. However, this disease is seldom reported in Malaysia (Mohd-Said *et al.,* 2018).

The infection of rice by bacterial leaf streak disease can cause critical yield losses under favourable conditions. The favourable conditions provide susceptibility to the disease. These conditions include excessive nitrogen application, weather conditions and age of the plants. The estimation of yield losses is about 2% to 32% depending on the variety or cultivar and the climate conditions (wet and dry seasons) that affect the rice production and the economy of the country (Saha *et al.,* 2015; Jiang *et al.,* 2020).

Based on Org *et al.* (2017), if the bacterial leaf streak infects the mature rice plants, the rice plant will recover rapidly and there will be only minimum grain yield loss. Based on the observation, this disease commonly infects the younger stage growth of rice plants and then will gradually affect them as they mature. This can be indicated by the rice plants are more resistant to this disease as they become older and mature. In addition, if this disease infects the rice plants after the heading stage, it will cause a great yield loss (Hata *et al.,* 2019).

Recently, bacterial leaf streak (BLS) has been reported as a major bacterial disease in West Malaysia due to the severe outbreak detected in major growing rice areas. This disease can transmit the pathogen through the contaminated seed and infected stubbles are left after harvesting for the next season rice planting that present on leaves, water, or other debris. The occurrence of bacterial leaf streak (BLS) in Malaysia was detected in paddy fields at Selangor, Kedah, and Kelantan from March 2014 to May 2015 with the symptoms observed in leaves of rice plants cultivated that became yellowish to brown linear streak lesions (Hata *et al.,* 2019).

4.1 Symptoms of bacterial leaf streak disease

The bacterial leaf streak (BLS) disease is known as a foliar disease. This disease can present at any growth stage of the rice plant. The first sign of this pathogen can be detected with small interveinal of water-soaked streaks along the leaf (Org *et al.,* 2017). The *Xanthomonas oryzae* pv. *oryzicola* is called intercellular pathogen as it enters the plants by penetrating open stomata or wounds. In the sub-stomatal chamber, the pathogen multiplies and colonizes the apoplast of mesophyll cells. The symptoms of ooze caused by pathogens occur from natural openings in strands on the leaf surface and exudates can disseminate the disease directly from plant to plant indirectly through water irrigation or rain splashing (Wonni *et al.,* 2015). Then, it will turn to dark green before the enlargement of translucent interveinal streaks from 1 cm to 10 cm. The streaks will turn yellowish orange to brown, depending on the rice cultivar. After that, the bacterial ooze droplet shows tiny yellow or amber beads causing lesions on the surface of rice leaves and will delimit on leaf veins. After the beads dry, the streaks will expand to the leaves to become larger patches that will consequently cover the entire leaf surface (Figure 2).

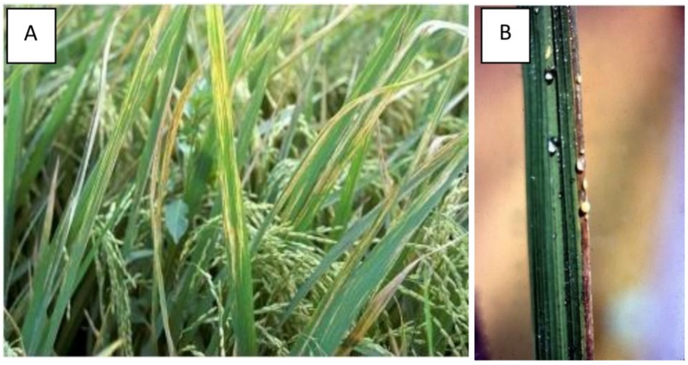

Figure 2. (A) The light brown streaks show severe infestation by bacterial leaf streak side. (B) Bacterial ooze of BLB.

At the later stage, the rice leaves will be completely blighted and in severe cases, the streaks will cause yellow halo (Saha *et al.,* 2015). The damage is commonly associated with rice leaf roll where rice leaf is folded due to the bacteria entering the damaged tissue from the insect feeding. Apparently, this symptom is difficult to distinguish between bacterial leaf streak (BLS) disease and bacterial leaf blight (BLS) disease (Org *et al.,* 2017).

However, the difference between these two diseases can be distinguished only at the later stages of pathogen infection through the shape of the edges of the lesions, the lesions' shape in the bacterial leaf streak (BLS)

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disease is straight while in the bacterial leaf blight disease is wavy (Org *et al.,* 2017).

5. Bacterial panicle blight (BPB) disease and economic important

The bacterial panicle blight (BPB) disease is caused by the pathogen *Burkholderia glumae* (Riera-Ruiz *et al.,* 2014). The occurrence of bacterial panicle blight (BPB) was first detected in Japan back in the 1950s and since then, it has become one of the most serious rice diseases in the world (Zhou-qi *et al.,* 2016). After that, this disease has been reported in many rice-growing countries where it has spread over to 18 countries such as Korea, Vietnam, the Philippines, Malaysia and Thailand. This disease has become a global threat to rice production areas due to the change in environmental conditions (Mondal *et al.,* 2015). Particularly in Asia, bacterial panicle blight (BPB) is one of the three bacterial diseases identified as the most damaging disease in rice cultivation areas. For example, severe outbreaks in Japan by this disease occurred and destroyed more than 70,000 ha and 30,000 ha of rice production areas in 2013 and 2015, respectively (Zhou, 2019).

In Asia, this disease is known as grain rot which is associated with seed-borne disease and the severe symptoms appear at the heading stage with suitable weather conditions throughout the rice growing season (Wamishe *et al.,* 2014). Bacterial panicle blight (BPB) is a highly destructive disease as it can cause severe losses in yield and milling quality up to 75%. The symptoms can be seen through seedling blight, sheath rot, floret sterility and grains aborted (Ham *et al.,* 2011). The pathogen outbreak is commonly triggered by high temperature and high humidity which is more likely to develop during hot and dry weather (Zhou, 2019). The optimal range temperature for bacterial panicle blight disease is between 30 to 35°C and commonly occurs in tropical and subtropical regions.

In Malaysia, the occurrence of BPB in rice granaries areas was first detected in December 2017 in Sungai Ache, Pulau Pinang (Ramachandran *et al.,* 2021). After that, the bacterial panicle blight showed the most severe disease when this disease was detected in paddy fields in Kuala Kurau, Perak in 2019. During the outbreak in Perak, thirty-five farmers in eight villages in Kuala Kurau lost the paddy production that covered about 62 hectares of paddy fields. According to the Perak Public Utilities and Infrastructure, Agriculture and Plantation Committee, this disease causes the grain to be empty when the infestation of the disease on the rice grain is at 95 to 110 days after planting (Zarbafi and Ham, 2019). Because of this incident, many millers refused to buy the paddy from the affected areas.

The disease symptoms appear on the rice leaves and sheath between the emergence and grain development phase as an epiphytic population then spreading upward as the plant grows. This will affect the grain at the flowering stage which can cause grain abortion or decaying during grain filling after the pollination stage (Wamishe *et al.,* 2014). The bacterial pathogen rapidly spreads in emerging panicles which ultimately causes the floral infection shortly after their emergence. During the reproductive stage, under conducive long-term weather conditions such as prolonged high night temperature, the condition will stimulate the outbreak of the disease and cause a loss in paddy yield (Zarbafi and Ham, 2019).

5.1 Symptoms of bacterial panicle blight disease

The initial symptoms were thought caused by abiotic factors like water stress, high temperature and chemical toxicity but later, it was detected caused by bacterial panicle blight (BPB) (Groth *et al*., 2009). The symptoms of bacterial panicle blight (BPB) disease like grain rot, panicle discolouration and sterile florets have commonly appeared at the heading stage and reproductive stage of rice and more frequently outbreaks when rice grown under high night temperatures and rainfalls (Mulaw *et al.,* 2018) (Figure 3). This disease has a significant impact on rice production during severe outbreaks under favourable conditions. Besides, environmental conditions also play an important role in influencing disease resistance (Zarbafi and Ham, 2019).

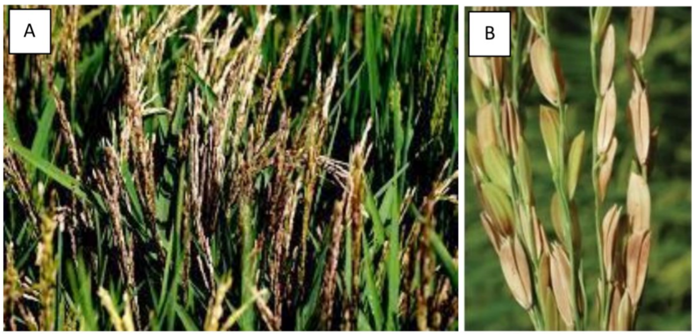

Figure 3. (A) The panicle branches remain green in early infestation. (B) Severe infection by bacterial panicle blight. Source: Kelsey and Mccarty (2014).

The symptoms of this disease can be seen on the leaf, the flag leaf sheath and the panicle. The primary infection is by pathogen on the leaf sheath which might be the source of infection in emerging panicles. The pathogen *Burkholderia glumae* can survive and grow in the leaf sheath of rice plants without showing any signs. The first symptom can be seen in panicle that causes blighted kernel with the appearance of white to light grey with a dark brown margin (Wamishe *et al.,* 2014). During the early stage, the rachis or the panicle branches remain green (Wamishe *et al.*, 2014) (Figure 3). In an emerging panicle, the bacterial pathogen is rapidly multiplying which causes floral infection shortly after emergence.

Then, the pathogen affects the emerging spikelet at the flowering stage which is considered the most sensitive growing stage for the pathogen to grow and rotting the grain (Zhou, 2019). The most important parts for pathogen invasion are lemma and palea which are susceptible for the pathogen to propagate in the parenchyma intercellular space, infecting the healthy tissue (Zarbafi and Ham, 2019). The spikelet infected by the pathogen can be seen from straw-colouring, discolouration and rotting of the grain, and panicle blanking (Org *et al.,* 2017). Under conducive conditions, the pathogens quickly multiply, and the symptoms will appear after three days where the panicles afflicted will gradually increase (Figure 3).

6. Sheath brown rot disease and economic importance

The sheath brown rot is one of the severe diseases affecting rice cultivation. This disease has become more serious because it will destroy the production of rice and influence the income of growers. According to the IRRI (2015), sheath brown rot disease can occur in good altitude areas around 1200−1700 m above sea level, has a low temperature of around 20°C−22°C and is commonly found in both temperate and tropical regions. Sheath brown rot disease produced by the pathogen *Pseudomonas fuscovaginae*, is a severe disease in the more temperate regions of Asia, South America, and East Africa, including Madagascar. According to Miyajima *et al.* (1983), the causal agent of SBR in rice was reported for the first time in 1976 in northern Japan. It has spread to almost all regions where rice is planted, as well as to the Philippines, Indonesia, Nepal, China, Iran, Brazil, Malaysia and Australia. *Pseudomonas fuscovaginae* usually attacks the seedlings and consequently, the seedlings will die. The bacteria SBR causes high yield loss of up to 72.2% which has been reported in Indonesia (Cahyaniati and Mortensen, 1995). In Malaysia, the first report of SBR was recorded in 1991, when the disease caused around 46.0% yield loss in Seberang Perak (Marzukhi *et al.,* 1991). The outbreak was recorded in Seberang Perak. Additionally, results from the findings during the first planting seasons of 2003 across the country's main rice granary fields showed that the disease had spread extensively across Peninsular Malaysia (Saad *et al.,* 2003). To date, the SBR disease has been well-distributed in Peninsular Malaysia (Ab Wahab *et al.,* 2015). This disease has become more serious because it will destroy rice production and affect the grower's income.

6.1 Symptoms of sheath brown rot (SBR) disease

Generally, SBR disease shows symptoms at the seedling or later stage of the growth phase. Initially, the infected seedlings at the development stage will appear yellow to brown on their lower area of sheaths before turning grey, brown to dark brown (Cottyn *et al.,* 1994). Usually, the infected plant that shows early symptoms during the seedling stage will die. However, at the early phase of development, the infected rice plant turns brownish, and the lower parts of the sheath turn light or dark brown. The infected leaf sheath also becomes water -soaked and necrotic (Cottyn *et al.,* 1994). Severely affected panicles can lead to severely discoloured grains and reduce panicles resulting in poorly filled grains (Detry *et al.,* 1991). This disease shows the greatest impact on the crop yield as it causes grain sterility, influencing not only the yield but also the grain quality with unfilled grains, kernel spotting and low-quality grains (Figure 4).

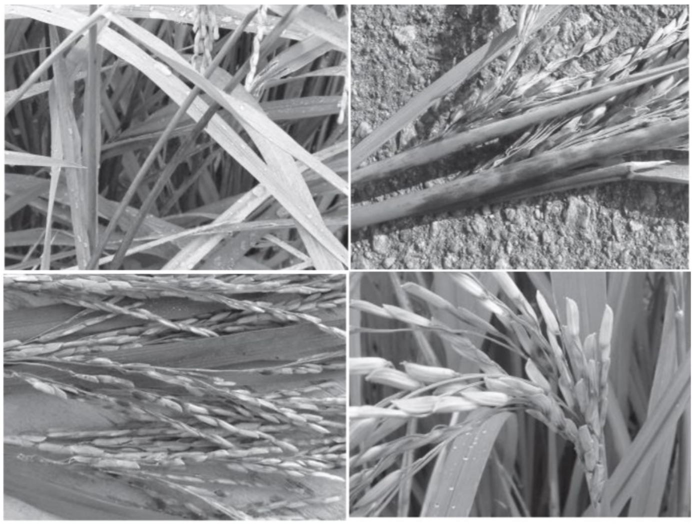

Figure 4. Mature rice plant with brown leaf sheath (Top left and right), discoloured grains (Bottom left and right) naturally infected by the pathogen in sampling areas. Source: Razak *et al.* (2009).

7. Management strategies for bacterial disease of rice

Therefore, management strategies must be used to reduce the damage to a manageable and acceptable level. The disease management strategy is largely depending on the stage or form of pathogen that is responsible for the disease (Haq *et al.,* 2020). The strategies that can be used include biological resistance, cultural control and chemical control. Integrated management strategies such as cultural, biological and chemical controls can be used to control bacterial disease in rice cultivation areas. These strategies are the important keys to the effectiveness and sustainable control of the pathogen (Zhou, 2019) (Figure 5).

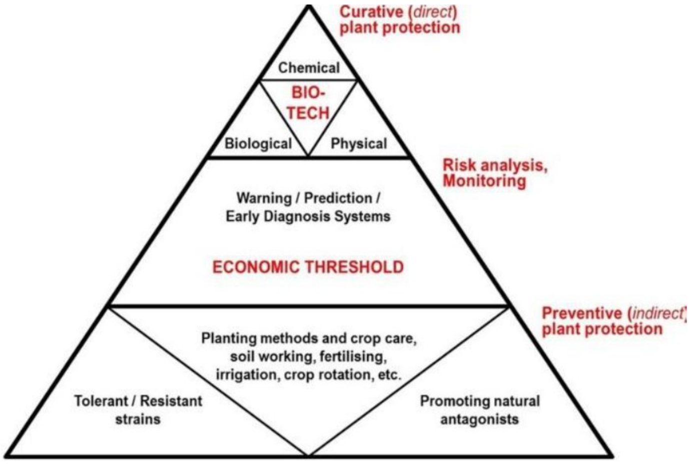

Figure 5. The principles and approaches of integrated plant protection. Source: Zhou (2019).

7.1 Cultural control

Based on the previous studies, cultural practices also can be used to minimize incidents and severity due to bacterial pathogens in the rice cultivation area. Based on Shekhar *et al.* (2020), there are several management diseases in rice cultivation using cultural practices such as good drainage, using resistant and healthy seeds, proper levelling of the field, proper plant spacing, appropriate application of nitrogenous fertilizer (NPK), burning and ploughing the stubble, and straw, leaves and weeds, as well as all the alternate host for pathogens are removed from paddy fields after harvesting. In the nursery practices, the seedlings in the seed beds must be raised to prevent nursery exposure to the inoculum of bacteria. These practices are recommended for uses in paddy fields in Malaysia.

7.2 Biological control

Biological control is one of the crop protection methods which is relatively new in the field of bacterial plant pathology. This method is used to control pathogens by reducing primary inoculum or host disease (Arwiyanto, 2014). In this practice control, bacteria or microorganisms as biocontrol agents are used to reduce the incidence or the severity of disease where it exhibits antagonistic activity towards pathogen, and it is called antagonist agent. These microorganisms have a high potential to suppress the growth and the development of bacterial rice pathogens, hence minimizing or lowering the risk of disease. Recent advances in microbial and molecular approaches it contributed to new insights into underlying mechanisms by which introduced bacteria function. Many previous studies showed the use of *Pseudomonas*, *Bacillus*, Bacteriophage and Trichoderma as biological controls for bacterial diseases in rice (Table 3).

7.3 Chemical control

Chemical control is another prevention technique to prevent outbreaks of the bacterial disease that can be used (Naqvi, 2019). This control is usually based on toxic (poisonous) substances. The functions of chemical control at low concentrations can either kill or limit the multiplication of pathogens by blocking the important metabolic pathway. At the same time, chemical control is considered a vital component in efficient integrated pest management (IPM) systems as a strategic plan to control plant disease. However, the use of chemical control in rice fields has pros and cons which is that chemical control also will affect the non-target organisms and will make undesirable changes in the environment.

Table 3. The list of previous study that shows the biocontrol agent used to control bacterial disease in rice.

No.	Author(s)	Topics	Management Control
1	Ramanamma and Santoshkumari (2017)	This paper studied *P. fluorescence* as a potential biological control agent to control bacterial leaf blight (BLB)	*Pseudomonas fluorescence*
2	Arwiyanto (2014)	This topic discussed the biocontrol agent that inhibit the growth of bacterial rice pathogen and ultimately reduces the bacterial leaf streak (BLS) infection when applied as seed treatment before sowing.	*Bacillus* spp.
3	Shrestha *et al.* (2016)	This paper studied how the use of antagonistic bacteria can be more efficient for the control of bacterial panicle blight (BPB), as well as promoting plant growth activities.	*Bacillus* spp.
4	Ranjani *et al.* (2018)	This study is about the potential of a biocontrol agent in killing the bacterial pathogen in rice seeds. Results showed rice seeds treated with biocontrol agents are free from infection of bacterial leaf blight (BLB).	Bacteriophages
5	Ku Asmah and Sapak (2020)	This paper studied a great potential biocontrol agent in controlling the bacterial leaf blight (BLB) pathogen in vitro and in vivo. Results also showed the potential biocontrol agent could promote the development of rice plants.	*Bacillus* spp.
6	Ngalimat *et al.* (2021)	This paper is about how plant biological control agents can be significant in controlling the bacterial rice pathogen, where it can be an alternative to chemical control. Results showed this control is very effective in increasing rice productivity and promoting an eco-friendly environment.	*Bacillus* spp. *Trichoderma* spp. *Pseudomonas fluorescence*

Table 4. The list of fungicides and the active ingredient.

Treatment	Formulation	Active Ingredient	Mean disease incidence (%)	Disease control over untreated control (%)	Mean yield (kg/ treatment)	Yield increase over untreated control (%)	Yield increase over untreated control (%)
T_1	Cordate 4WP	kasugamycin	11.67^{de}	86.31	89.10^{ab}	2.51	2.90
T_2	Copper oxychloride 50 WP	copper oxychloride	20.00^{cd}	76.48	88.90^{ab}	2.31	2.67
T_3	Flare 72 WP	streptomycin sulphate	6.53^{e}	92.23	89.66^{a}	3.07	3.55
T_4	Castle 50 WP	kasugamycin + copper oxychloride	10.33^{de}	87.97	89.20^{ab}	2.61	3.01
T_5	Nativo 75 WDG	Tebuconazole + trifloxystrobin	26.67^{bc}	68.63	87.72^{bc}	1.13	1.30
T_6	Gem Star Super325 SC	azoxystrobin + difenconazole	31.00^{b}	63.67	87.00^{c}	0.41	0.47
T_7	Bordeaux mixture	copper sulfate: lime: water	13.67^{de}	84.08	89.00^{ab}	2.41	2.78
T_8	Untreated control		85.67^{a}	0.00	86.59^{c}	0.00	0.00
		LSD: 0.05	CV: 6.17		CV: 1.62		

Mean values with different superscripts are statistically significantly different. LSD: Least Significant difference, CV: Coefficient of variant. Source: Nasir *et al.* (2019).

The seed should be treated with fungicides before sowing to protect it from soil-borne bacteria and to give the seedlings faster germination. For example, the study by Shekhar *et al.* (2020) showed that rice seeds soaked in a 0.07% solution of agrimycin and 0.025% streptocycline for hours and then placed in hot water treatment at 52°C to 54°C for 30 mins resulted in 95-100% eradication of pathogen *Xanthomonas oryzae* pv. *oryzae* which reduced the incidence of bacterial blight in the rice field. At the same time, the seed also must be pre-soaked in water for about 8 to 10 hours which is an effective management where that can minimize the incidence of bacterial disease in rice (Nagendran *et al.,* 2013) (Table 4). Next is foliar spray consisting of 20% or 20 g fresh cow dung extract in one litre of water used twice has been reported to inhibit the development of bacterial disease in paddy fields by spraying it right after the initial appearance symptoms of the disease is seen. However, a cost effective chemical control for the bacterial disease has yet to be found. This could be due to the pathogen population's sensitivity to disease-control agents that are highly changeable. Apparently, the use of chemical control can reduce the outbreak but not eliminate all the pathogens.

8. Conclusion

In conclusion, bacterial diseases like bacterial leaf blight (BLB), bacterial leaf streak (BLS), bacterial panicle blight (BPB) and sheath brown rot (SBR) are major constraints in rice fields since the first reports of their occurrence in paddy fields. The occurrence of these diseases is mostly related to a conducive environment for the growth development of pathogens especially in Malaysia where the weather is humid and dry throughout the year. The incidence of bacterial disease in rice fields will have a big impact on rice production which is destructive to the rice crop and causes losses of yield. Knowledge of the symptoms of each disease is very helpful, especially for early detection of the diseases. Then, suitable management strategies are important and required to reduce the losses of rice production due to bacterial disease infestation. There are many management strategies that can be used to overcome these problems such as chemical control, biological control, and cultural control. All the information provided in this review may become a useful tool for the identification of bacterial disease in rice fields and thus, effective strategies can be taken to control the disease before it becomes worse. From this review, biological control is better to use as a control management compared to chemical control which has a good impact in the long-term effect. However, the biological control cannot be commercialized yet due to stability issues. Generally, management strategies for bacterial diseases are quite difficult since there is no suitable chemical control for the bacterial disease in rice, and not harmful to the environment and human health. As for recommendations, the control method should be upgraded and diversified to reduce the occurrence of these diseases.

Conflict of interest

The authors declare no conflict of interest.

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