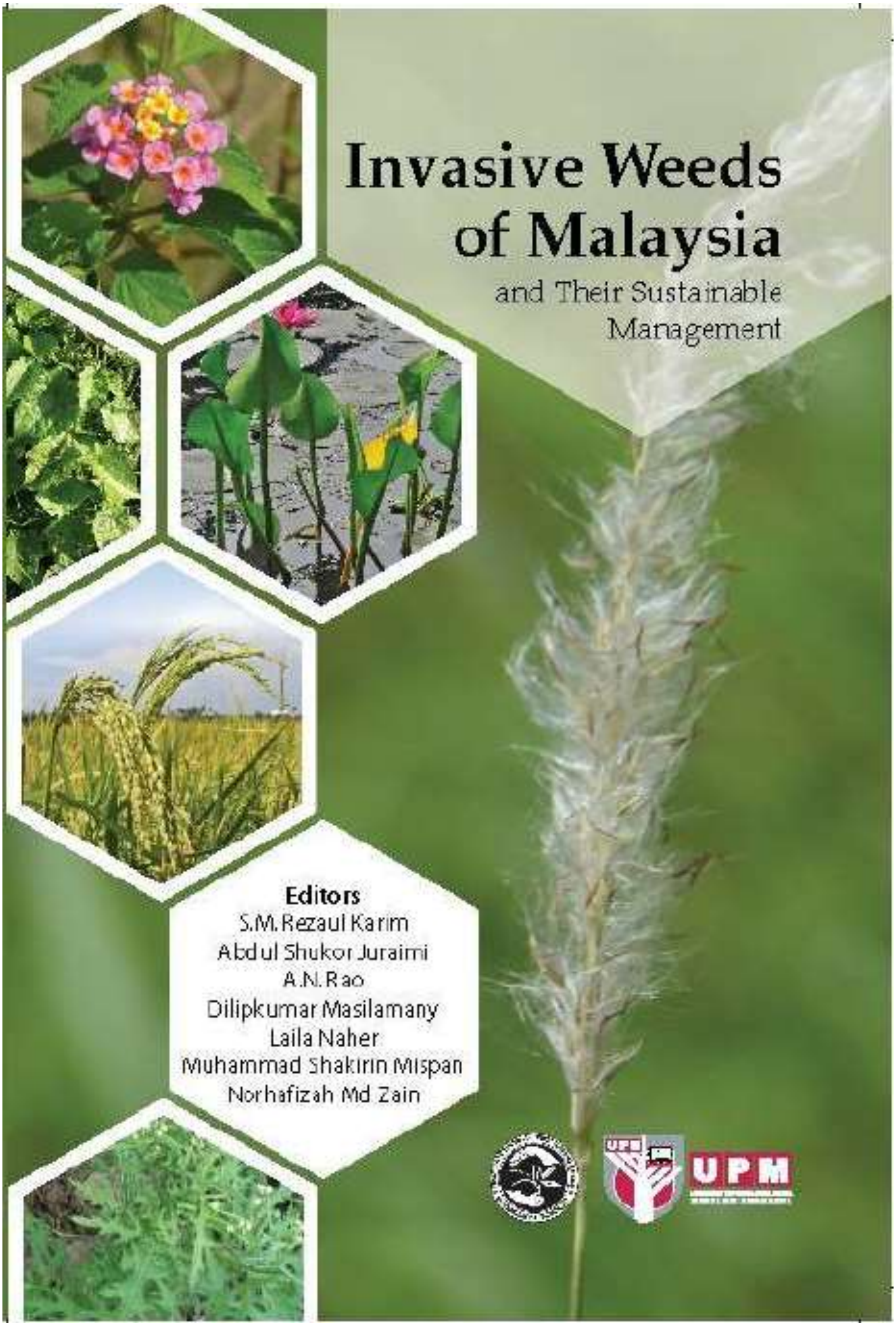
Invasive Weeds
of Malaysia
and Their Sustainable
Management
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Echinochloa crus-galli (L.) P. Beauv

(English Name: Barnyardgrass; Malay Name: Rumput sambau)

A.N. Rao, Sreenath Dixit & A. S. Juraimi

INTRODUCTION

Echinochloa crus-galli (L.) P. Beauv., a C_4 annual grass, is locally known in Malaysia as Rumput Sambau and in English as Barnyardgrass. *E. crus-galli* was included in the Global Compendium of Weeds and is considered one of the world's worst weeds (Randall, 2017) in rice and earlier it was also listed as a weed in at least 36 other crops in 61 countries throughout tropical and temperate regions of the world (Holm et al., 1991). *E. crus-galli* is also considered an environmental weed that has become invasive in natural grasslands, coastal forests and disturbed sites in Asia, Africa, Australia, Europe and America (FAO, 2014; USDA-ARS, 2014). In Malaysia, it was detected in 1925 (NWGIAS, 2014) and suspected to be introduced unintentionally through contaminated seeds (Moody, 1989). Since then, the weed has spread and becomes the most important weed in all rice growing areas. Ministry of Natural Resources and Environment (2009), Malaysia has included *E. crus-galli* as one of the Invasive Alien Species (IAS) that affects all sectors such as agriculture, forestry, fishery, marine and animals. In Malaysia, the adoption of double cropping and more rapidly maturing cultivars in rice cultivation and a shift from transplanting to direct- seeding has resulted in grasses such as *E. crus-galli*, largely replacing the previously dominant broadleaved weeds and sedges (Ho & Zuki, 1988). The limited success in the suppression of *E. crus-galli* is a concern (Begum et al., 2005, 2005a). In this paper synthesized information is included on the ecology, current scenario of infestation, losses caused and management of *E. crus-galli* in Malaysia.

TAXONOMY, BIOLOGY AND ECOLOGY

E. crus-galli belongs to: Kingdom: Plantae; Sub kingdom: *Tracheobionta;* Super division:Spermatophyta; Division: Magnoliophyta; Class: Liliopsida; Subclass: Commelinidae; Order: Cyperales; Family: Poaceae / Gramineae; Genus: *Echinochloa* P. Beauv.; Species: *Echinochloa crus-galli* (L.) P. Beauv.

The correct species identification is botanically and economically important because *E. crus-galli* is an aggressive invader that is difficult to manage. It is an annual, grows tall, with culms 30-200 cm, spreading, decumbent or stiffly erect; nodes usually glabrous or the lower nodes puberulent. Plant branches from the base. First leaves are dull or greyish green and the youngest leaf is rolled. Leaf blades are glabrous, hairless, elongate, 5-20 mm wide, 8-60 cm long, with a white midrib. Ligule and auricles are absent. The panicle is erect or nodding, green or purple-tinged, 5-20cm long. 9-12 racemes, 2-4 (-10) cm long, spreading, ascending, sometimes branched. Spikelet crowded, about 3-4 mm long excluding the awns. First glume is 1/3 as long as the spikelet; second glume and sterile lemma with short bristly hairs. No awns or when present on the nerves, mostly 5-10 mm long. The propagation is by seeds. Fruit is small; compressed dorsoventrally. Hilum is short, 2.5-3.5 mm long, whitely glumes. The chromosome number reported for *E. crus-galli* varies from 2n=36, 42, 48, 54 to 2n=72 (FAO, 2014).

E. crus-galli includes many botanical varieties and sub-species. Although the morphological features of these varieties are similar, they can exhibit differences in response to management practices. The main differences between the two major *E. crus-galli* types (Figure 11.1) found in Malaysia are: *E. crus-galli* var. *formosensis* possesses short awn, open panicles, shiny spikelets, while *E. crus-galli* var. *crus-galli* has long awn (sometimes awn is absent), closed panicles (Itoh et al., 1992). *E.crus- galli (L.)* P. *Beauv. var. crus-galli* was reported to have originated from Central America, East Asia, Europe, India (Solbrig,1980; Baki, 2004; Randall, 2017), while *Echinochloa crus-galli* (L.) P. Beauv. var. *formosensis* Ohwi from East Asia, Taiwan (Azmi, 1994; Baki, 2004; Randall, 2017). Ecotypic differences were observed in the average emergence date, heading times, and growth duration with ecotypes from Perlis, Kedah, Penang and Johor emerging and heading relatively earlier than other ecotypes (Tasrif et al., 2004). Six groups were classified based on the cluster analysis of Malaysian ecotypes of barnyardgrass. RAPD-PCR markers revealed relatively low genetic variation between the ecotypes (Tasrif et al., 2004a; Juraimi et al., 2005). The genetic diversity was attributed to the diversity among individual ecotypes from divergent locations. These ecotype populations may respond differently to different management practices (Juraimi et al., 2005).

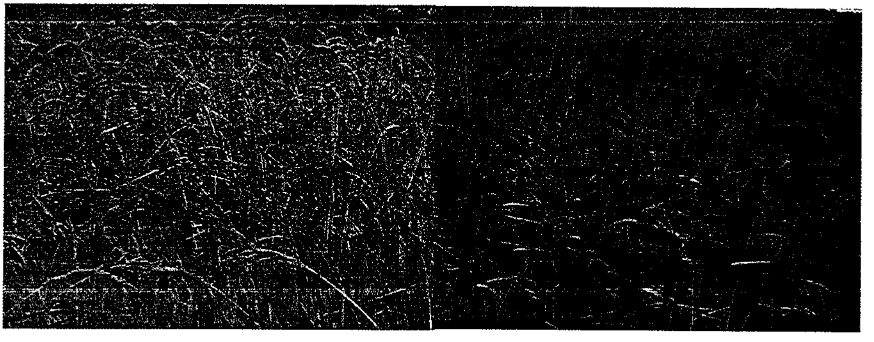

Figure 11.1 *E. crus-galli* (L.) P. Beauv. var. *crus-galli* (left) and *E. crus-galli* (L.) P. Beauv. var. *formosensis* Ohwi (right), which are predominant in Malaysia (Photos credit: Dr. Azmi bin Man)

Phenotypic plasticity and genetic change play major roles in the establishment and spread of invasive species. The success of *E. crus-galli* may be attributed to morphology and phenology (Maun & Barrett, 1986), production of many easily dispersed seeds and its ability to flower in a wide range of photo periods. *E. crus-galli* will flower over a wide range of photoperiods (8-13 hour day lengths) and responds to short days by flowering quickly (Holm et al., 1991). In direct-seeded rice fields of Malaysia, *Echinochloa* varieties were observed to produce abundant tillers, up to 40,000 seeds per plant (Ho, 2003) with completion of their life cycles within 85-95 days after emergence, i.e. prior to completion of direct-seeded rice (DSR) life cycle by 115 to 120 days (Azmi, 1988). The large numbers of seeds in the seed bank serve as seed reservoirs and perpetuate perennial infestation of *E. crus-galli* in rice ecosystem and open space. The potentiality of seed bank in augmenting existing populations of *E. crus-galli* was low with only 2.32 - 3.95% of the total seed rain emerged as seedlings per season (Baki & Azmi, 2001). Seeds can germinate (germination minimum temperature requirement between 10–20°C) at various times of the year with a 42-64 days life cycle and 3-4 months dormancy. Seed viability varied considerably according to the soil moisture contents and this ranged from 27-36% under rain-fed soil conditions to 12–16% in inundated fields (Baki & Azmi, 2001). Azmi et al. (1995) suggested that seed longevity of barnyardgrass in rice fields was shorter than three years. *E. crus-galli* showed better germination (above 30%) up to 24 dS m^{-1} salinity level and was regarded as salt-tolerant weed species (Hakim et al., 2011, 2014). Barnyardgrass emerges in several flushes and grows extremely competitive due to its high growth rate and intensive tillering characteristics. Its seedling emergence can occur when seeds were at the soil surface and even when its seeds were sown at a depth of 5 cm in saturated soil (Sahid & Hossain, 1995). It grows well in moist areas or wetlands and normally grows in direct-seeded rice fields (Rao et al., 2007) and at field capacity or saturation (Juraimi et al., 2011, 2012). Flooding depth has detrimental effect on *E. crus-galli* survival, and no seedling survived at 15 cm depth (Sahid & Hossain, 1995). An increase in *E. crus-galli* survival was observed with the delay in flooding. The decrease in shoot biomass and shoot and root length was also observed with increasing flooding depth. Barnyardgrass seeds can survive in the soil for as long as 6 cropping seasons (3 years) (Azmi, 1994). It spreads exclusively by seed; dispersed by wind, water or as a contaminant in soil, seed crops, and agricultural machinery (Rao et al., 2017). Barnyardgrass can propagate when lower nodes of the stems develop roots. The critical period of its competition in DSR is between 15 and 30 days after sowing (Azmi, 1988).

CURRENT INFESTATION SCENARIO

Echinochloa aggregates in Malaysia comprise of several species and binomials, all of which are noxious weeds in rice fields, fruit orchards, vegetable farms, abandoned farms and derelict areas (Baki & Azmi, 2001). About 76% of the planted area of rice is in Peninsular Malaysia, 18% in Sarawak and 6% in Sabah. Irrigated rice constitutes 87% of total cultivated area and is mainly concentrated to eight granaries (Muda, Kemubu, North West Selangor, Kemasin-Semarak, Kerian-Sungai Manik, Pulau Pinang, Ketara and Seberang Perak) and many mini granary areas (Haron, 2014).

Wet-seeded rice is predominant in Malaysia and *E. crus-galli* is particularly problematic in rice in all methods of rice establishment in Seberang Perai (Penang) and Muda in Northern Peninsular (Aqilah et al., 2012; Hakim et al., 2013, 2013a) and is the second most competitive weed with rice after 'weedy rice' in all rice granaries of Malaysia (Azmi 1992; Azmi et al., 2007; Rao et al., 2007; Hakim et al., 2010, 2011a; 2013, 2013a; 2014; Dilipkumar et al., 2017) (Figure 11.2). The barnyardgrass was documented to occur in 22 countries in dry seeded rice and in 15 countries in wet- seeded rice (Rao & Moody, 1994; Rao et al., 2007). Marchini et al. (2018) reasoned that invasive plants adaptation is the consequence of post-introduction selection leading to genetic differentiation. In rice ecosystem, *E. crus-galli* over time became the most dominant weed due to its seedling's similarity with rice seedlings (Rao & Moody, 1988) that made it escape hand weeding frequently, when hand weeding was used in earlier days. A rapid change in rice crop establishment practices from transplanting to direct-seeding (DS) occurred during the late 1980s and about 80% of the Muda granary was direct sown by the late 1990's (Morooka & Jegatheesan, 1996). The change in method of rice establishment from transplanting to direct seeding with the use of herbicides for weed management, grasses such as barnyardgrass have largely replaced the previously dominant broadleaved weeds and sedges in the Muda area (Ho & Zuki, 1988). *E. crus-galli* was observed to be dominant in direct-seeded rice plots with repeated application of 2,4-D amine (Azmi & Baki, 1995; Azmi, 2002). In all direct-seeded rice (DSR) areas of Peninsular Malaysia, the *E. crus-galli* complex consisting of *E. crus-galli* var. *formosensis* and *E. crus-galli* var. *crus-galli* was reported to be troublesome (Azmi & Baki, 2007), competing vigorously with the crop from its early growth stages causing significant rice yield reductions. In the Muda granary area, *E. crus-galli* var. *crusgalli* was reported to be dominant (Begum et al., 2005a, Azmi & Baki, 2007), while in the coastal zone of Kedah and Seberang Perai and Barat Laut Selangor areas, *E. crus- galli* var. *formosensis* is predominant (Azmi & Mashhor,1996; Hakim et al., 2013).

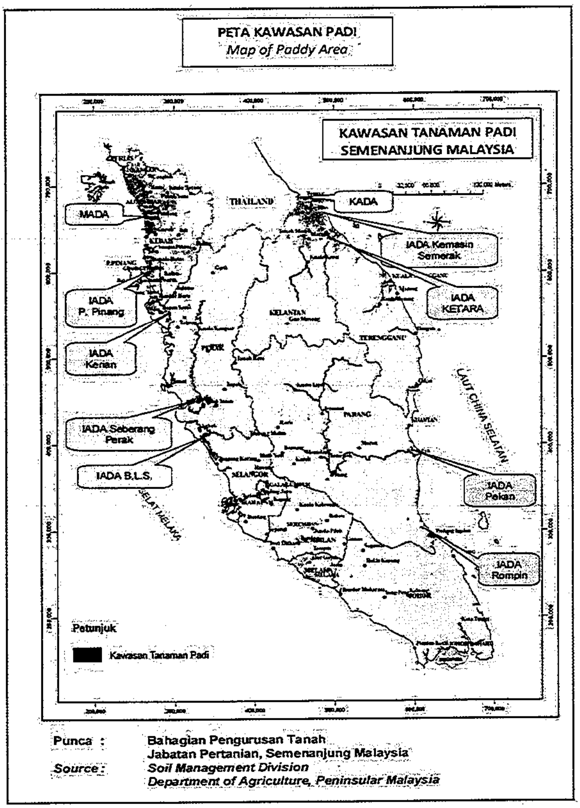

Figure 11.2 Rice growing areas in Peninsular Malaysia, where barnyardgrass is a problematic weed

IMPACT OF *E. crus-galli*

Crop Yield Loss

Direct seeding method of rice establishment (DSR) began as an alternative to traditional transplanting in the late 1970s in the main granaries of Malaysia and by 2000 more than 90% of the total rice area was planted as direct wet-seeded rice (wet- DSR) (Azmi et al., 2005; Haron, 2014). In wet-DSR, both *E. crus-galli* and rice seeds germinate at the same time, but the weed grows faster and mature earlier. One measure of the invasiveness of a weed species is its aggressivity index. This index is density-mediated and is affected by the duration of crop-weed competition. Others employed path analysis to generate path coefficient values to delineate the direct and indirect effects of crop-weed competition on growth and yield components (Baki et al., 2005). Under intense inter-specific competition from *E. crus-galli*, rice at densities lower than 217 plants m^{-2} spent only a marginal amount of its resources for reproductive components thereby registering only ca. 0.01 in reproductive effort values (Baki, 2004). It was estimated in Malaysia, that using a scale of 1-10 (10 = complete weed cover) there was a 7% rice yield loss for every unit increase of *E. crus-galli* infestation compared with no infestation (Lo et al., 1992). Significant negative relation between the rice yield and the intensity of *E. crus-galli* infestation [Y = 4043 - 265.9x kg/ha (r^2 = 0.83)] was observed by Lo et al. (1992). Based on the 5% level of yield loss, the critical period in the off-season was between 2-71 days after sowing (DAS) in saturated condition and 15-73 DAS in flooded condition. In aerobic rice, critical period (considering an acceptable yield loss at 5%) was found to be from 11-74 DAS (Michael et al., 2013). In the main season, the critical period was between 0-72 DAS in the saturated condition and 2-98 DAS in the flooded condition (Juraimi et al., 2009).

Azmi and Othman (1987) reported variation in rice yield reduction (22-71%) with the rice varieties cultivated in which tall rice genotypes (Seberang, MR79 and Makmur) showed the least reduction in yield. High infestation of *E. crus-galli* can remove from the soil up to 80% of the nitrogen (Holm et al., 1977). Thus, it has the capability to reduce crop yields and cause forage crops to fail by removing the available soil nitrogen. The yield loss by grasses (mainly *E. crus-galli*), broadleaved weeds and sedges were estimated as 41, 28 and 10%, respectively (Azmi, 1992). *E. crus-galli* alone reduces the number of tillers, panicles and spikelet/panicle and can reduce yields by 41% compared with losses from sedges and broadleaved weeds of 10 and 28% respectively (Azmi, 1988). Significant rice yield reductions of about 18% (i.e. 1 t ha^{-1}) was reported with only 10 plants m^{-2} (Azmi & Mashhor,1992). The critical period of *E. crus-galli* competition in wet-DSR is between 15 and 30 days after sowing (Azmi, 1988; Azmi & Mashhor,1992). Direct dry-seeded rice (dry-DSR) appears to be more prone to infestation than wet-DSR (Hamed et al., 1988). In Malaysia, rice yield loss by *E. crus-galli* was about 41% (Tosiah et al., 2009).

DSR yield losses due to weed competition in unweeded treatments were 60% in main season, when *E. crus-galli* dominance was more and 54% in off-season, when its dominance was less in the weed community (Juraimi et al., 2010). Yield loss due to weed competition was higher in the saturated condition (54.5%) where *E. crus-galli* dominance in weed community was more than in the flooded condition (35.2%) where its dominance was less (Juraimi et al., 2009).

The barnyard grass apart from causing direct yield loss also acts as an alternative host to a wide range of crop pests including several mosaic virus plant diseases (Maun & Barrett, 1986). The weed serves as an important alternative food plant for *Leptocorisa oratorius* and the presence of the cored pest in rice fields during fallow periods allows the pest to survive (Shah, 1989). The loss in rice yield due to *Leptocorisa* sp may be aggravated in the presence of *E. crus-galli* (Supaad et al., 1989). In addition, Holm et al. (1977) reported that *E. crus-galli* accumulates high levels of nitrates which can poison livestock while at the same time the weed also negatively affects other native species by outcompeting them.

MANAGEMENT OF BARNYARDGRASS

Cultural Control

Tillage practices can control invasive annuals like *E. crus-galli*. In rice, land preparation, including puddling and harrowing, provides weed-free environment at planting, which aids in good rice establishment while minimizing weed growth and proliferation in the established rice (Azmi, 1994., Panetta, 1993). Adequate land leveling is critical for uniform flooding in the field which also helps in managing weeds. The site-specific influence of tillage in suppressing weed populations in the established rice crop varies depending on the soil type, soil moisture, herbicides used and existing soil seed bank and propagules (Baki, 2004).

Water-seeding of rice (water-DSR) was found to be an effective method of crop establishment to address the problems of serious weedy rice or grassy weed infestations (Azmi & Johnson, 2008). Grassy weeds like *E. crus-galli* and some sedges can be suppressed by standing water under water-DSR and transplanted rice (TPR) system resulting in reduced herbicide application and consequently environmental pollution (Azmi & Johnson, 2009). Water-DSR, however, requires good land preparation, level fields and better irrigation water management for acceptable rice establishment.

Biological Control

In Malaysian rice granaries, several efforts were made to use biological control to manage *E. crus-galli*. *Exserohilum* is the most frequently isolated fungi species in studies conducted to test potential fungal pathogens for barnyard grass biological control (Tosiah et al., 2009). The mycelium was found to infect barnyard grass much faster (less than 24 h) than the conidia (Ng et al., 2012). In surveys conducted, Tosiah et al. (2009) found *Exserohilum monoceras* (Drechslera) Leonard & Suggs, *Exserohilum longirostratum* and *Curvularia lunata* (*Cochliobolus lunatus*) among the fungi present on diseased *E. crus-galli* plants. Among 82 isolates from 12 fungus genera that were isolated and tested, *E. monoceras* 1125 was consistently found associated with the disease, virulence, stability and has the ability to produce spores profusely in culture suggesting that it can be used as biological control agent for the grass (Tosiah et al., 2009). Several isolates of *E. monoceras* screened for its potential as biological control agent for barnyard grass showed variation in ability to produce spores (Hailmi et al., 2011) and degree of infectivity on the grass (Tosiah, 2010). When treated with *E. monoceras* 1125 spore suspensions at about 2.5×10^7 spores/ml concentration in glasshouse conditions supplemented with 24 h dew, the disease index of *E. crus-galli* var. *crus-galli*, *E. crus-galli* var. *formosensis* were 4 (dead) (Tosiah et al., 2010). *E. monoceras* did not infect selected rice varieties in Malaysia, such as MRQ 50, MRQ 74, MR 219, MR 220 and MR 84. *E. crus-galli* var. *crus-galli* ecotypes: K-02, PK-04, KN-02, CJ-01 and L-01 were the most susceptible to the leaf blight pathogen (*E. longirostratum*) (Juraimi et al., 2006). Thus, a variable response to the fungal pathogen was observed within an intraspecific barnyard grass collection. *E. crus-galli* var *formosensis* was more susceptible than *E. crus-galli* var *crus-galli*. The fungus *E. longirostratum* applied either in the form of conidia or mycelium was effective against barnyard grass under field conditions (Ng et al., 2011). The moisture availability and temperature influenced *E. monoceras* infections. The optimum temperature for infection was within the range of 25–35°C. The fungus needed a minimum of 12 h of humidity to cause severe disease on the host (Tosiah et al., 2012). *E. monoceras* caused a high level of disease on *E. crus-galli* with appearance of symptoms within 24 h of inoculation. It induced eyespot lesions and induced a severe 'burnt' appearance on the foliage of *E. crus-galli*. The leaf tissues in the vicinity of heavy infestation were completely killed (Hailmi et al., 2011). The type of growth medium and the nutritional and physical environments of mass conidia production are of paramount importance as they greatly influence the number, type, stability, durability and virulence of the bio-herbicide. The solid media such as agar was observed to be an excellent growth media and spore production was influenced by the nutrient content of the media. Half strength V8 juice agar was the best medium for pathogens sporulation (Hailmi et al., 2011a). Maxigreen®, an adjuvant, when mixed with sunflower oil in the ratio of 0.5:7 is ideal for formulating the conidia production (Hailmi et al., 2011a).

The potential of *E. monoceras* as a bio-herbicide for barnyard grass control was suggested by Tasrif et al. (2003). Severe infection was observed on barnyard grass inoculated with *E. monoceras* at all plant densities as indicated by high AUDPC values (ranges from 610.35-468.28 unit^2) and fast disease progress rates (rL=0.48 logit/day) indicating the ability of the fungus in reducing the competitive ability of *E. crus-galli* and thus provides new opportunities for the future of biological weed control in Malaysia (Kadir et al., 2008). Caunter et al. (1997) reported highly virulent actions on barnyard grass with >85% infection after 11 days of inoculation of isolates of *Bipolaris/Exserohilum* sp.

In Peninsular Malaysia, *Enosima leucotaeniella* is a moth, the larva of which is a selective stem borer which infests only *Echinochloa* spp. including *E. crus-galli* var. *crus-galli*, *E. crus-galli* var. *formosensis*, and hence has the potential for its control (Goto & Itoh, 1994). Goto (1992) reported that larvae of the moth *Emmalocera* sp bore and tunnel into the stems of *E. crus-galli,* while Itoh (1991) noted that the insect *Tagosodes pusanus* (syn. *Sogatodes pusanus*) was specific to *E. crus-galli.* Caunter (2000) while summarizing the progress in bio-herbicidal studies in South East Asia opined that a mindset change among practical weed control practitioners is needed to enable bio-herbicides to become a component of a true integrated weed control program.

ALLELOPATHY

Allelopathic or weed competitive rice varieties and the use of allelopathic crops in rotation or allelopathic plants residues as mulch are a few options that may be employed for managing *E. crus-galli*. Toosi and Baki (2012) observed deleterious effects of the crude ethanol extracts (10.8, 14.28, 18 and 30 gL^{-1} of leaf, stem and root materials) of Malaysian brassica [*Brassica juncea* (L.) Czern. var. Ensabi] on root and shoot growths of barnyard grass and they suggested that the allelopathic potentials of *B. juncea* could be utilized as a bio-herbicide to control the germination of barnyardgrass and seedling establishment. An examination of the allelopathic potential of aerial parts of *Tinospora tuberculata* on seed germination and the radicle and hypocotyl lengths of *E. crus-galli* indicated higher suppressive effects when the methanol extracts of *T. tuberculata* stem or leaf in comparison to the water extracts (Aslani et al., 2016; 2016a). Of 11 identified compounds from the extracts trans- cinnamic acid and benzoic acid had the highest allelopathic activity while chlorogenic acid and orientin had the lowest on the basis of the rank values. Aslani et al. (2016; 2016a) surmised that *T. tuberculata* could be a potential source of natural inhibitor compounds employable for eco-friendly agriculture in Malaysia. *Melastoma malabathricum* L (Faravani et al., 2008), *Brassica juncea* (L.) Czern.var. Ensabi (Toosi & Baki, 2011), *T. tuberculata* (Aslani et al., 2014) have all shown to some degree allelopathic effect on *E. crus-galli* and hence may be useful as soil additives to control weeds for sustainable agriculture.

The emergence and seedling growth of barnyard grass were inhibited by 80–100% with increasing concentration of sunflower leaf extract from 10–15% (w/v) suggesting the possibility of using sunflower leaf extract as a pre-emergence bio-herbicide and, when used in combination, have potential to reduce rate of pretilachlor depending on soil types and growth stage of rice (Dilipkumar et al., 2012) for inhibiting seedling growth of *E. crus-galli* without injuring the rice seedlings (Dilipkumar & Chuah, 2013). The ED_{95} values (rate that causes 95% inhibition) of pretilachlor for emergence and shoot fresh weight of *E. crus-galli* were reduced by 79 and 82%, respectively, when mixed with sunflower leaf extracts in sandy loam soils (Dilipkumar et al., 2012). The degree of synergism increased progressively with the increased ratio of sunflower leaf extracts:herbicide, but antagonism was evident at the lowest ratio indicating that the ratio of allelopathic crop water extracts in combination with herbicide is an important factor in influencing the potency of phytotoxic activity (Dilipkumar & Chuah, 2013, 2013a).

A few traditional (Padang Gelap, Acheh Puteh, Pasir, Singgora, Merah Isi, Chatek Kuning, Anak Naga and Anak Didek 3) (Azmi et al., 2000) and modern rice varieties (Kataribhog, WooCo, WITA12, Dular, Lalpaika, BRRI dhan27, WITA3, FARO8, BR26, BRRI dhan39, IR64, WITA8, Dharial and Nizersail) have exhibited allelopathic suppressive effects on weeds, especially *E. crus-galli* (Karim et al., 2014). The allelopathic potential of nine rice (*Oryza sativa* L.) varieties/lines (BR-5331-93-2-8-4, BR-5620-9-1-2, BRRI Dhan27, BR-5615-3-1-2, Lalparija, BR11, BR21, BR23 and BR25) using double-pot technique with barnyardgrass as indicator plant has indicated higher API values for BR23 (40.51%); BR21 (39.48%);BR25 (39.42%) and BR11 (34.76%) (Karim et al., 2012). Based on average percentage inhibition of root length of *E. crus-galli* by rice varieties dried stem and leaves aqueous extracts, varieties were ranked in the following order: WITA-12>WITA-4> Fukuhibiki >Kalizira>Woo-Co>WITA-3 (Alam et al., 2018). Weed-competitive (Sunyob et al., 2015) and allelopathic rice varieties (Karim et al., 2012, 2014) must be identified and integrated with other methods for effective management of *E. crus-galli*.

HERBICIDES

Weed management in Malaysia is mainly dependent on herbicides (Dilipkumar et al., 2017), even though other control measures such as cultural, physical, biological, and mechanical methods are often integrated. Of 49,199 tons of active pesticide ingredients used in Malaysia, a large percentage about 83% (or 41,061 tons) was herbicide usage during 2014 (FAOSTAT, 2019). Of the total expenditure on herbicides, 7% is used in rice, where *E. crus-galli* is a major problem (Karim et al., 2004). Most of the direct-seeded rice area is sprayed with herbicides for managing weeds like barnyardgrass, weedy rice and other weeds (Normiyah & Chang, 1998; Dilipkumar et al., 2017). The herbicides that were found effective on *E. crus-galli* are listed in Table 11.1 Variation in efficacy of herbicides during different seasons was observed due to variation with dominance of weed flora (Juraimi et al., 2010). Pretilachlor followed by bentazon/MCPA, bispyribac-sodium followed by bentazon/MCPA and penoxsulam+benthiocarb followed by bentazon/MCPA were effective during the off-season, where *E. crus-galli* was dominant (Juraimi et al., 2010).

The combination of imidazolinone-tolerant varieties (MR 220CL1 and MR 220CL2) (Azmi et al., 2008) with imidazolinone herbicides is known as the Clearfield Production System (Engku et al., 2016) which was introduced to Malaysian farmers in 2010 (Azmi et al., 2012) and has been in cultivation in Malaysia mainly for managing weedy rice (Sudianto et al., 2013). The Clearfield Production System (CPS) could able to effectively control weedy rice for which no other herbicides or system can provide a control in wet-DSR. Clearfield rice cultivars were introduced to eight granary areas in Malaysia, in Kedah, Perlis, Terengganu, Kelantan, Perak, Selangor, Penang and Perak, with satisfying outcome to manage weedy rice (Engku et al. 2016; Azmi et al., 2012). The efficacy of the CPS on diverse types of weeds that infest rice, including *E. crus-galli*, has been proven (Bzour et al., 2018; Tan et al., 2005). However, the challenge is to sustain this technology adoption by minimizing the evolution of herbicide-resistant weedy rice as the rice-rice system followed where the risk of outcrossing with weedy rice are expected to be several times higher (Sudianto et al., 2013; Mispana et al., 2019). The negative effects of this CPS technology adoption could be minimized by integrating weed management practices in combination with the adoption of proper Stewardship Guidelines to reduce the menace of proliferation of herbicide-resistant weedy rice.

The evolution of resistant weeds in the Malaysian rice ecosystem was first reported in 1989 (Heap, 2019). Even though The International Survey of Herbicide Resistant Weeds has not included barnyardgrass in the list, several biotypes of *E. crus-galli* were recognized to be resistant to PS II inhibitor (ureas and amides) + synthetic auxins + ACCase inhibitor (Propanil + quinclorac + cyhalofop-butyl) (Chuah & Ismail, 2010; Rahman et al., 2010; Dilipkumar et al., 2017). *E. crus-galli* (KB 1 population) collected in Kedah survived a quinclorac dose that was 10 times higher than labeled dose and the resistant weed was also >17 times more resistant to cyhalofop-butyl, making it very difficult to control with the recommended dose of herbicides (Rahman et al., 2010). Resistant biotype KB1 was controlled by combined application of quinclorac and propanil at rates of 0.30 and 5.50 and kg a.i. ha-1 or quinclorac and cyhalofop-butyl at rates of 0.30 and 0.80 kg a.i. ha-1, respectively (Rahman et al., 2010).

Table 11.1 Herbicides recommended for managing *Echinochloa crus-galli* in rice in Malaysia

Herbicide	Dose a.i. ha^{-1}	Time of application	Type of rice culture	Reference
Bensulfuron-methyl + Quinclorac	30 g +200-300	10 DAS applied either as full coverage or strip sprays; 10 DAS	WSR	Chang (1988), Azmi & Anwar (1989)
Benthiocarb/ Propanil	1.2/2.4 kg	10 DAS	WSR	Azmi (2012), Juraimi et al. (2013)
Benthiocarb + pyrazosulfuron	2.0 + 0.01 kg	10-14 DAS	WSR	Azmi & Supaad (1990)
Bispyribac sodium	0.015 – 0.04 kg	10-14 DAS	WSR	Baki (2004), Azmi (2012), Juraimi et al. (2013)
Cinmethylin and fenoxaprop-ethyl	0.05-0.1 kg	7 DAS and as a late POE		Azmi & Supaad (1992)
Cyclosulfamuron + pendimethalin	20.40 + 330 –750 g	5 –12 DAS or 3 DAT	WSR and TPR	Baki (2004)
Cyhalofop-butyl + bensulfuron fb bentazon/MCPA	0.1 kg + 0.06 kg fb 0.6/0.1 kg	10 fb 30	Aerobic rice	Anwar et al. (2013)
Fenoxaprop-ethyl	0.05-0.12 kg	26-30 DAS	WSR	Ismail & Azmi, (1989), Baki & Azmi (1992), (1994), Baki (2004)

cont'd Table 11.1

Fentrazamide + propanil	1.5 to 2 kg	4-7 days after sowing	WSR	Yew et al. (2001), Azmi (2012); Juraimi et al. (2013)
Florpyrauxifen -benzyl	30 g	2-3 leaf stage of rice	WSR and TPR	Nguyen et al. (2015)
Glufosinate ammonium	0.35 – 1.7 kg	Prior to tillage or zero tillage in transplanted- or dry or water-seeded rice.		Baki (2004)
Molinate	2.0 kg	10 DAS	WSR	Baki & Azmi (1992)
Molinate + 2,4-D	3.0 to 4.0 + 0.5 to 0.75 kg	14-20 or 21-25 DAS	WSR	Baki & Azmi (1992), Azmi (2012), Juraimi et al. (2013)
Molinate + 2,4-D IBE	2.5 + 0.75 kg	10-14 DAS	WSR	Azmi & Supaad (1990)
Molinate + 2,4-D isobutyl ester	3 + 1 kg	10 DAS		Azmi & Anwar (1989)
Molinate + bensulfuron	2.5 to 3 + 0.03 kg	10-14 DAS	WSR	Azmi & Supaad (1990), Azmi (2012), Juraimi et al. (2013)
Penoxsulam + Cyhalofop-butyl	@12.5 g +62.5 g	6-10 DAS	WSR	Azmi (2012), Juraimi et al. (2013), Lap et al. (2013)
Pretilachlor + safener	0.350-0.6 kg	1 day before sowing or 4 DAS	WSR	Ooi & Chong (1988), Baki & Azmi (1994), Azmi (2012), Juraimi et al. (2013)

cont'd Table 11.1

Pyrazosulfuro n-ethyl	14 and 21 g		WSR	Ooi (1988), Baki (2004)
Quinclorac	0.225-0.250 kg	7-14 DAS and 20-24 days after emergence.	WSR	Weerd et al. (1988)
Quinclorac	300 g	10 DAS	WSR	Lo (1988)
Quinclorac + bensulfuron	0.25 + 0.03 kg	10-14 DAS	WSR	Azmi & Supaad (1992), Azmi (2012), Juraimi et al. (2013)
Quinclorac + cinosulfuron + pretilachlor	0.7 + 0.15 + 1.0 %	at the 2-leaf stage	WSR	Baki (2004)

DAS = days after seeding; WSR = wet-direct-seeded rice; TPR = transplanted rice

INTEGRATED WEED MANAGEMENT

Baki and Azmi (2001) suggested integrated weed management (IWM) to manage *E. crus-galli* populations below the economic thresholds of 1-3 plants m^{-2} in rice fields, at the critical period of competition (CPC) between *E. crus-galli* and rice var. MR84 at 15-30 days after seeding (DAS) to attain a yield increase. Various combinations as components for IWM were suggested by Baki and Azmi (2001) to manage and control *E. crus-galli* infestation. Planting taller rice varieties with droopy leaves to enhance competitiveness against barnyardgrass; field inundation at 3–6 DAS to reduce the weed infestation; delayed flooding at 15 DAS coupled with weed-free field conditions at the CPC to enhance tiller production and improved crop yields; manual weeding at 15-30 DAS or treatment with herbicides such as bensulfuron at 0.05 kg ha^{-1} a.i. applied at 10 DAS followed by manual weeding at 30 DAS or pretilachlor + cinosulfuron (at 0.35 + 0.0075 kg ha^{-1} a.i.) applied at 4 DAS followed by manual weeding at 30 DAS or a combination of molinate + bensulfuron (at 3.0 +0.03 kg ha^{-1} a.i.) applied at 10 DAS. Integrated weed management practices for managing weeds including *E. crus-galli* were summarized (Karim et al., 2004; Azmi & Baki, 2006; Juraimi et al., 2013).

Although barnyard grass is reputed to be one of the worst weeds in rice, it also has some uses. On it were laid the largest numbers of eggs by *Cyrtorhinus lividipennis* (Reut.) which is an important predator of the eggs and adults of the brown planthopper (BPH) (*Nilaparvata lugens* (Stål). In addition, highest oviposition and hatchability were observed on *E. crus-galli* and hence it may be used for enhancing this natural enemy of BPH (Sivapragasam, 1983). The barnyardgrass is used in some countries as a fodder and food crop; folk remedy for several diseases; soil reclamation and wastewater treatment in constructed wetlands. Those opportunities may be exploited in Malaysia as a component of its integrated management.

Intensive herbicide uses to manage *E. crus-galli* has led to the evolution of resistance to several herbicides (Rao et al., 2007). Hence, in Malaysia herbicides as a component of IWM must be used judiciously, as for example, by using herbicide mixtures or sequential application of products with different modes of action from year to year. Application of wider spectrum of chemicals may help delay in the development of herbicide resistance in *E. crus-galli* and other weeds in Malaysia. The adoption of IWM will help in managing *E. crus-galli* control effectively, economically and above all ensure a safer environment. Investigations aimed at reducing the evolution of herbicide resistance in barnyard grass ought to include further studies and research on the understanding of biological and ecological mechanisms with a view to provide better management practices.

CONCLUSION

Of the proposed four options (prevention; early detection; eradication and control) for dealing with invasive species (Wittenberg & Cock, 2001), the best option for managing *E. crus-galli* anywhere is to prevent its spread to newer areas through early detection and managing it in prevailing rice fields, while in other troublesome areas by judiciously integrating available components of IWM. The primary source of infestation of *E. crus-galli* is impure crop seeds and the use of good quality rice seeds free of weed seeds help prevent the spread of weed infestations (Ho, 2003). The available weed management options like preventive measures, crops rotation, tillage, water management, competitive cultivars, biological control, hand weeding and mechanical control are to be integrated with judicious herbicides use while making sure increased herbicide resistance is avoided. The IWM technologies available should be taken to the local farmers for effective weed management. Well conducted on-farm demonstrations, appropriate campaign message, the formative evaluation of prototype materials, as well as adequate training and motivation of extension agents and farmers are the prerequisites for a successful implementation and management of *E. crus-galli* in Malaysia.

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