RESEARCH PAPER

Utilization of Bidens pilosa var. radiata (Sch. Bip.) Sherff integrated with water irrigation for paddy weed control and rice yield production

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The application of allelopathic plant materials combined with an agricultural production method is a concept that can be used to manage weeds during rice production. This research investigated the effects of the utilization of Bidens pilosa var. radiata integrated with water irrigation for weed control and rice production. B. pilosa and water extract exerted more toxicity against Echinochloa crus-galli than the extracted residue applied at the same rates, suggesting that weed control was caused by compounds extracted from B. pilosa. The changes in water properties after the application of B. pilosa were explored. Dissolved oxygen was rapidly reduced after application and then slowly increased within 3–5 days after application (DAA), while the pH also decreased at the early stage and then increased back to normal values within 1–3 DAA. Electrical conductivity increased with increasing rates of application, suggesting that allelochemicals were released from B. pilosa. The concept was studied under field conditions. B. pilosa was applied along with irrigation at 7 days after sowing (DAS) on a direct wet seed system. The results showed that application rates of 2, 4 and 6 tons ha$^{-1}$ decreased the number of weeds by 52.16, 86.73 and 95.18% at 30 DAA and reduced dried weight of weeds by 17.65, 34.69 and 86.82%, respectively. The rice yield showed an increase of 72.73, 81.03 and 73.66% when compared with the nonweeded crop, while herbicide treatment increased by 84.68%. The findings demonstrate that the application of B. pilosa integrated with water irrigation was able to control weeds in a direct seeded rice production system.

Keywords: allelopathy, direct seed rice, integrated with irrigation, paddy weed.

Rice is the main economic crop in Asia. Among Asian countries, Thailand is one of the world’s largest rice producers and is the world’s largest rice exporter. Usually, transplanted rice undergoes a change from a transplanted cropping system to a direct seeded system because of the latter’s reduced requirements of labor and costs. However, the direct seeded system is susceptible to infestation by pests, especially weeds. Weeds are a major threat in rice fields, causing yield losses ranging from 30 to 100% (Dass et al. 2017). The use of herbicides to control weeds is more convenient, fast and effective than other methods of control. However, the continuous use of herbicides contaminates the environment, the product and the humans exposed to them, and its overuse also causes weed resistance (Poonpaiboonpipat et al. 2013). Reducing herbicide use is a target of sustainable agriculture, and allelopathy is one potential means of achieving this goal. Allelopathic plants contain natural compounds that inhibit weed germination and growth. Allelopathic materials release such compounds into the environment. These materials

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may also release some available nutrients and can improve soil quality upon degradation (Adler & Chase 2007).

Bidens pilosa var. radiata (Sch.Bip.) Sherff, a perennial weed widely distributed in Thailand, has been reported to exert allelopathic effects on crops and weeds (Khanh et al. 2009; Gusman et al. 2011; Wang et al. 2014; Krumsri et al. 2015). When it is applied for weed control, the fresh condition has shown more phytotoxicity than the dried condition, probably due to some volatile compounds that are available in fresh plants (Krumsri et al. 2015). A total of 198 compounds have been reported to be present in whole plants of B. pilosa var. radiata (Silva et al. 2011), with the essential oils β-caryophyllene and τ-cadinene described as major compounds (Deba et al. 2008). Fifteen phenolic compounds have also been reported, with caffeic and ferulic acids described as the major phenolics (Deba et al. 2007). The concept of utilizing allelopathic plant material to control weeds has been previously reported. The application of a dry powder form of B. pilosa var. radiata at 2 tons dried weight ha$^{-1}$ after transplanting rice reduced weed dry weight by 80% (Hong et al. 2004a). However, the utilization of allelopathic plant material in directed seed systems has not yet been reported. A new concept of the application of allelopathic plant material combined with a cultural method was introduced by Krumsri et al. (2015). The procedure involved cutting fresh whole plants of B. pilosa var. radiata and then applying this material at 4 tons ha$^{-1}$ together with water irrigation at 10 days after sowing (DAS) seeds directly. The procedure nearly completely inhibited weed growth in pots, leaving the rice seedlings unaffected. Moreover, Poonpaiboonnipattana et al. (2015) reported that the dried powder of Canavalia ensiformis, Crotalaria pallida, Centrosema pascuorum cv. Cavalcade, Clitoria ternatea and Stylosanthes guianensis at 500 kg ha$^{-1}$ combined with water irrigation at 7 DAS also completely reduced paddy weeds while leaving the rice seedlings unharmed. However, whether weed control was affected by shading or by allelochemicals is unknown. Moreover, the potential of applying allelopathic plant material combined with water irrigation to control weeds and to promote rice growth and yield under field conditions is still unknown. Thus, this study aimed to: (i) study the effect of B. pilosa combined with water irrigation on the mortality of Echinochloa crus-galli (L.) Beauv. under glass house conditions; (ii) measure the changes in water properties, including its dissolved oxygen and total phenolic contents after application; and (iii) determine the effect of B. pilosa combined with water irrigation on weed control and rice yield production under field conditions.

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MATERIAL AND METHOD

Plant material

Seeds of B. pilosa were sowed in the agricultural field of Naresuan University, Thailand. Whole plants of B. pilosa were harvested at 60 days after seeding because this stage has shown the highest inhibitory activity against E. crus-galli (Krumsri et al. 2015).

Soil material

Soil that had not been exposed to herbicides for 2 years was collected from a paddy field near the campus. The soil was dried under sunlight and then analyzed physicochemically. The soil’s properties were pH, 5.86; organic matter, 2.51%; cation exchange capacity (CEC), 8.8 mg equivalent (me) per 100 g soil; P$_2$O$_5$, 16.95 mg kg$^{-1}$; and K$_2$O, 31.49 mg kg$^{-1}$.

Testing the effect of fresh material, extracted residue and water extract on E. crus-galli

The material was cut into 1 cm pieces by hand and then separated into three parts. The first part was extracted with 70% aqueous–methanol thrice, and then, the residue was dried in a hot-air oven. The second part was extracted with distilled water at the ratios of 14.14, 28.29 and 42.43 g per 5 L of water. The third part was retained at 7°C for future use.

A pot experiment with a randomized block design was conducted with four replications under glass house conditions. Ten treatments included the following: three treatments of fresh material applied at the rate of 2, 4 and 6 tons f.w. ha$^{-1}$ (14.14, 28.29 and 42.43 g pot$^{-1}$, respectively); three treatments of the water extracts; three treatments of extracted residue applied at 2, 4 and 6 tons f.w. ha$^{-1}$; and one treatment of water alone, which was used as a control.

Plastic pots, 30 cm in diameter, were filled with wet soil at a rate of 5 kg dry weight (d.w.) pot$^{-1}$. Forty seeds of E. crus-galli were sowed in each pot. Five days later, the seedlings were plucked to obtain 20 seedlings pot$^{-1}$. Five liters of water or water extract were applied into each pot at 7 DAS; the water level was approximately 7 cm above soil level. At this stage, E. crus-galli was submerged under the water level. The fresh material or extracted residue was added into the water following the treatments.

Seeding mortality was measured at 1, 3, 5, 7, 14 and 21 days after treatment (DAT). At 21 DAT, the upper part of the surviving seedlings of E. crus-galli was harvested and dried at 60°C in a hot-air oven.
Changes in dissolved oxygen, pH, electrical conductivity and total phenolic content of water

To explain the effects of water after application, the changes in water properties were examined. Another pot experiment was prepared in the same manner as the previous experiment but excluded *E. crus-galli*. The four treatments consisted of water alone (control) and *B. pilosa* fresh material at rates of 2, 4 and 6 tons ha$^{-1}$. After the application of *B. pilosa* material integrated with water irrigation, dissolved oxygen, pH and electrical conductivity were measured every 24 h for 7 days. Five milliliters of water samples were also collected every 24 h for 7 days to analyze the total phenolic and flavonoid contents.

The total phenolics were determined using the Folin–Ciocalteu method as described in Chumyam et al. (2013). Two milliliters of sample were transferred in a test tube before mixing in 10 mL of the Folin–Ciocalteu reagent and 8 mL of 7.5% sodium carbonate. The mixture was allowed to stand for 2 h at room temperature, and then, the reaction was measured using an ultraviolet (UV) spectrophotometer at 765 nm. The total phenolic content of each crude extract (mg g$^{-1}$) was calculated based on a gallic acid (GAE) standard curve.

Field study

Field experiments were conducted from May to August 2017 in the Bangrakrum district, Phitsanulok Province, Thailand (latitude of 16°41’36.4”N and longitude of 100°00’19.0”E). Weed species survey conducted before the experiment found the following weed species: *E. crus-galli*, *E. colona*, *Leptochloa chinensis*, *Ludwigia hyssopifolia*, *Sphenoecea zeylanica*, *Cyperus iria*, *Fimbristylis dichotoma* and *Fimbristylis miliacea*.

A randomized complete block design was used with five treatments, including (i) unweeded control; (ii–iv) *B. pilosa* at the rate of 2, 4 and 6 tons f.w. ha$^{-1}$; and (v) commercial herbicide, propanil + butachlor at 1.5 + 0.75 kg ai ha$^{-1}$. The soil properties were similar to the description above. The soil was tilled with a wheel plow, and then, water was applied and incorporated with a rotary. The wet soil was leveled with a wooden board, and then, water was drained. The field was divided into 20 plots with a size of 4 × 4 m. Wet germinated seeds of rice cv. Phitsanulok 2 were scattered by hand on the water surface. Chemical fertilizer was applied by hand broadcasting at rates of 60, 37.5, 25 kg N, P$_2$O$_5$ and K$_2$O/ha, respectively, at 25 days after rice seeding, and a second application of N was provided at 50 days after rice seeding.

Weed species, the number of weeds and the dry weight of weeds were assessed at 15 and 30 days after application (DAA). Samples were taken randomly in an area of 50 × 50 cm with two replications. The rice height and number of tillers were determined at 30 and 60 DAA and at the harvest period. The rice yield in all treatments was measured.

Data analysis

The data were analyzed using analysis of variance (ANOVA). Whenever ANOVA indicated significant effects (*P* < 0.05), a pairwise comparison of means using Tukey’s studentized range test was carried out.

RESULTS

Fresh material, extracted residue and water extract

Mortality data of *E. crus-galli* are displayed in Table 1, starting at 3 DAT. Fresh *B. pilosa* and water extract at the rates of 4 and 6 tons ha$^{-1}$ exerted 75% mortality, while the extracted residue treatment resulted in no deaths. At 5–7 DAT, fresh *B. pilosa* at 4 and 6 tons ha$^{-1}$ and water extract at 6 tons ha$^{-1}$ induced complete plant mortality. At 21 DAT, the plant mortality induced by *B. pilosa* fresh material and water extract applied at the same rate was not significantly different except for the application rate of 4 tons ha$^{-1}$. In the case of extracted residue, the plant mortality began to be observed at 7 DAT. At 21 DAT, the 4 and 6 tons ha$^{-1}$ application rates induced mortality by 61.25 and 67.50%, respectively.

The dry weight of surviving plants was determined at 21 DAT. Extracted residues applied at the rate of 2 tons ha$^{-1}$ did not differ significantly with the water control. The 2 tons ha$^{-1}$ application of fresh material did not differ significantly with 2 tons ha$^{-1}$ application of water extract.

Changes in dissolved oxygen, pH, electrical conductivity and total phenolic content of water

All treatments of *B. pilosa* rapidly decreased the dissolved oxygen level, starting at 1 DAT and lasting for 3 days. At 2 DAT, *B. pilosa* at 2 tons ha$^{-1}$ started increasing the dissolved oxygen level, while the 4 and
6 tons ha\(^{-1}\) treatments increased their dissolved oxygen levels at 4 and 5 DAT, respectively (Fig. 1).

Changes in pH are shown in Fig. 2. The pH values differed between treatments at 1–3 DAT. The \textit{B. pilosa} material tended to decrease the pH value as the application rates increased for 4 days, after which all treatments were not significantly different.

Field experiments

The nine weed species found in this experiment were \textit{E. crus-galli}, \textit{E. colona}, \textit{L. chinensis}, \textit{L. hyssopifolia}, \textit{S. zeylanica}, \textit{C. iria}, \textit{Cyperus diffomis}, \textit{F. dichotoma} and \textit{F. miliacea}. These were major weeds occurring in direct wet seed systems throughout Thailand. The number of weeds decreased with increasing application rates of \textit{B. pilosa} integrated with water irrigation at 7 DAS.

Table 1. Effect of fresh material, water extract and extracted residue of \textit{Bidens pilosa} integrated with water irrigation on mortality and dry weight of \textit{E. crus-galli}

| Treatments          | Plant mortality (%) | Dry weight (g pot\(^{-1}\)) |
|---------------------|---------------------|-----------------------------|
|                     | Days after treatment (DAT) |                               |
|                     | 1        | 3        | 5        | 7        | 14       | 21       |                     |
| Water sole          | 0.00\(^a\) | 0.00\(^c\) | 0.00\(^f\) | 0.00\(^f\) | 0.00\(^e\) | 0.00\(^e\) | 3.26\(^a\)           |
| Fresh \textit{B. pilosa} | 2 tons ha\(^{-1}\) | 0.00 | 40.00\(^b\) | 35.00\(^d\) | 65.00\(^c\) | 68.75\(^c\) | 68.75\(^c\) | 2.05\(^b\)           |
|                     | 4 tons ha\(^{-1}\) | 0.00 | 75.00\(^a\) | 100.00\(^a\) | 100.00\(^z\) | 100.00\(^a\) | 100.00\(^a\) | 0.00\(^e\)           |
|                     | 6 tons ha\(^{-1}\) | 0.00 | 75.00\(^a\) | 100.00\(^a\) | 100.00\(^a\) | 100.00\(^a\) | 100.00\(^a\) | 0.00\(^a\)           |
| Water extract       | 2 tons ha\(^{-1}\) | 0.00 | 30.00\(^b\) | 63.75\(^c\) | 63.75\(^c\) | 67.50\(^c\) | 67.50\(^c\) | 2.34\(^b\)           |
|                     | 4 tons ha\(^{-1}\) | 0.00 | 75.00\(^a\) | 88.75\(^b\) | 88.75\(^b\) | 88.75\(^b\) | 88.75\(^b\) | 1.10\(^d\)           |
|                     | 6 tons ha\(^{-1}\) | 0.00 | 75.00\(^a\) | 100.00\(^a\) | 100.00\(^a\) | 100.00\(^a\) | 100.00\(^a\) | 0.00\(^e\)           |
| Extracted residue   | 2 tons ha\(^{-1}\) | 0.00 | 0.00\(^c\) | 17.50\(^e\) | 17.50\(^e\) | 17.50\(^e\) | 17.50\(^e\) | 3.24\(^b\)           |
|                     | 4 tons ha\(^{-1}\) | 0.00 | 0.00\(^c\) | 15.00\(^e\) | 47.50\(^c\) | 61.25\(^c\) | 61.25\(^c\) | 2.09\(^b\)           |
|                     | 6 tons ha\(^{-1}\) | 0.00 | 0.00\(^c\) | 12.00\(^e\) | 36.50\(^b\) | 67.50\(^c\) | 67.50\(^c\) | 1.68\(^c\)           |

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**Table 2.** Effect of *Bidens pilosa* fresh material integrated with water irrigation on weed emergence in paddy fields

| A     | B     | C     | D     | E     | F     | G     | H     | I     | Total weed number | Total dry weight |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------------------|-----------------|
|       |       |       |       |       |       |       |       |       | (plants m⁻²)       | (g m⁻²)         |
|       |       |       |       |       |       |       |       |       | [% inhibition]     | [% inhibition]  |
|       |       |       |       |       |       |       |       |       |                   |                 |
| Control | 52.4a | 19.7a | 35.8a | 21.4a | 30.6a | 10.1a | 42.6a | 183.1a | 8.8a | 404.5a           | 4.4a            |
| *B. pilosa* (2 tons ha⁻¹) | 28.9b | 15.8a | 5.4b  | 11.9b | 14.7b | 4.2b  | 14.9b | 89.4b  | 3.2b | 188.4b [53.42%]  | 3.5ab [20.25%]  |
| *B. pilosa* (4 tons ha⁻¹) | 16.8c | 4.8b  | 3.1b  | 2.1c  | 4.2c  | 2.5bc | 4.3c  | 14.9c  | 2.1bc | 54.8c [86.45%]  | 3.2bc [27.27%]  |
| *B. pilosa* (6 tons ha⁻¹) | 8.8d  | 2.2b  | 0.0c  | 0.0c  | 0.0d  | 0.0c  | 0.0d  | 2.1d   | 0.0c | 13.1d [96.76%]  | 1.4cd [68.18%]  |
| Herbicide | 1.6e  | 0.0b  | 0.0c  | 0.0c  | 0.0d  | 0.0c  | 0.0d  | 0.0d   | 0.0c | 3.6e [99.11%]  | 0.4d [90.91%]   |
| Control | 66.9a | 26.4a | 48.7a | 28.9a | 34.6a | 10.8a | 48.2a | 198.4a | 10.3a | 473.2a           | 49.3a           |
| *B. pilosa* (2 tons ha⁻¹) | 31.8b | 17.9b | 13.4b | 12.8b | 16.9b | 5.9b  | 18.7b | 102.6b | 6.4bc | 226.4b [52.16%] | 40.6ab [17.65%] |
| *B. pilosa* (4 tons ha⁻¹) | 17.5c | 5.5c  | 5.6c  | 2.5c  | 5.2c  | 2.3c  | 6.4c  | 14.9c  | 2.9cd | 62.8c [86.73%] | 32.2b [34.69%]  |
| *B. pilosa* (6 tons ha⁻¹) | 12.9c | 3.4cd | 0.0d  | 0.0c  | 0.0d  | 0.0c  | 0.0d  | 6.5cd  | 0.0d | 22.8d [95.18%] | 6.5c [86.82%]   |
| Herbicide | 4.2d  | 1.2d  | 3.6cd | 1.4c  | 5.2c  | 0.0c  | 0.0d  | 0.0d   | 0.0d | 15.6d [96.70%] | 6.0c [87.83%]   |

A: Echinochloa crus-galli, B: Echinochloa colona, C: Leptochloa chinensis, D: Ludwigia hyssopifolia, E: Sphenoecea zeylanica, F: Cyperus iria, G: Cyperus diffomis, H: Fimbristylis miliacea and I: Fimbristylis dichotoma

Mean from four replications with same letters in column is not significantly different at P < 0.05.
Table 3. Effect of *Bidens pilosa* fresh material integrated with water irrigation on rice growth

| Treatments      | 30 days |                      | 60 days |                      | Harvest |                      |
|-----------------|---------|----------------------|---------|----------------------|---------|----------------------|
|                 | Plant height (cm) | No. of tillers (plants m²) | Plant height (cm) | No. of tillers (plants m²) | Plant height (cm) | No. of tillers (plants m²) |
| Control         | 69.70b | 377.2c               | 88.32b | 391.5c               | 89.8b   | 376.4c               |
| *B. pilosa* (2 tons ha⁻¹) | 74.80a | 427.4ab              | 99.00a | 552.5b               | 112.6a  | 564.5b               |
| *B. pilosa* (4 tons ha⁻¹) | 74.20ab | 434.6a               | 102.94a | 585.4ab              | 118.9a  | 576.5b               |
| *B. pilosa* (6 tons ha⁻¹) | 72.10ab | 418.2b               | 102.42a | 619.2a               | 117.6a  | 611.3a               |
| Herbicide       | 71.90b | 449.4a               | 99.66a | 612.6a               | 119.4a  | 608.9a               |

Mean with same letters in column is not significantly different at *P* < 0.05.

5848.2 and 5610.0 kg ha⁻¹, and the herbicide treatment yielded 5966.0 kg ha⁻¹ (Table 4.)

**DISCUSSION**

*B. pilosa* var. *radiata* is a serious annual major weed distributed in many areas of the world (Khanh et al. 2009). *B. pilosa* demonstrates an allelopathic effect in the ecology of both agricultural and nonagricultural areas. Its root, stem and leaf were reported to contain allelochemicals that inhibited seed germination and seedling growth of several crops and weeds (Deba et al. 2007, 2008; Khanh et al. 2009; Gusman et al. 2011).

The utilization of allelopathic plants to control paddy weeds has been previously reported (Xuan et al. 2003a, b; Hong et al. 2004a,b; Khanh et al. 2005). However, these previous reports have focused on transplanted rice, in which the materials were applied at 2 day after transplanting by scattering on the water surface. Our study differs from previous reports in that we focused on the direct wet seed system, which experiences heavy infestations of weeds. The concept of this study was adapted from conventional practice in direct wet seeds systems. Typically, farmers do not allow water to flood a field for 7–15 days in order for rice to emerge and to increase seedling vigor. However, this condition is also suitable for weed emergence, causing competition from weeds. Farmers have always irrigated their fields at 7–14 DAS at a water level of 5–10 cm. At this stage, most of the weeds are submerged by the water, causing flooding stress. However, the paddy weeds can adapt themselves to flooding, becoming tolerant to flooding and eventually surviving. The concept of the application of an allelopathic plant integrated with water irrigation, as described above, was investigated in this research. This concept was nearly to the report of Kong et al. (2008), which integrated weed management with allelopathic rice varieties and the cultural management option without herbicide by flooding depth and showed that the weed inhibition and rice yield did not differ with the cultural management option with herbicide. It was suggested that the cultural management option affected weed control efficacy. Interestingly, our results show that *B. pilosa* fresh material and water extract caused *E. crus-galli* death 3–7 DAA. However, extracted residue mulched on the water surface also caused weed death, although at a lower rate than fresh material and water extract, indicating that the reason of weed death may be the mulching effect in addition to the allelochemicals released from the material (Khanh et al. 2007). Water properties changed in response to

Table 4. Effect of *Bidens pilosa* fresh material integrated with water irrigation on rice yield

| Treatments      | Panicle per m² | Grain no. per particle | Ripened grain (%) | Weight 1000 grains (g) | Yield (kg ha⁻¹) |
|-----------------|----------------|------------------------|--------------------|------------------------|-----------------|
| Control         | 366.4c         | 144.6ms                | 74.2b              | 26.3ms                 | 3230.5c         |
| *B. pilosa* 2 tons ha⁻¹ | 559.5b       | 152.8                  | 77.9ab             | 26.8                   | 5579.7b         |
| *B. pilosa* 4 tons ha⁻¹ | 564.5b       | 154.6                  | 82.1a              | 26.1                   | 5848.2ab        |
| *B. pilosa* 6 tons ha⁻¹ | 589.3a       | 147.9                  | 79.2a              | 26.0                   | 5610.0ab        |
| Herbicide       | 581.9a         | 153.6                  | 80.3a              | 26.6                   | 5966.0a         |

Mean with same letters in column is not significantly different at *P* < 0.05.

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the treatments. The dissolved oxygen rapidly decreased within 24 h after application of B. pilosa and then slowly increased from 3 to 5 DAA. This behavior indicates that dissolved oxygen was probably reduced due to something from the extraction process and by fermentative activity of microorganisms in the water. We also observed changes in the pH and electrical conductivity values. The pH value of the B. pilosa treatment in water was lower than that of the control during the early stage (1–3 DAT), suggesting that a chemical interaction in the water had occurred. The rise in the electrical conductivity of the water was probably caused by the release of compounds from the B. pilosa material. Moreover, phenolic compounds were found in the water; these compounds rose to a maximum level at 3 DAT and then gradually disappeared within 7 DAT. This effect is related to the death of E. crus-galli that occurred at 3 DAT, implying that the released allelochemicals brought about weed death. The major phenolic compounds in B. pilosa var. radiata were caffeic acid, ferulic acid, p-coumaric acid, protocatechuic acid and p-hydroxybenzoic acid. Phenolic compounds inhibit plants by several mechanisms, including via the disruption of plasma membrane integrity, water relationship, phytohormone interactions and enzyme effects, photosynthesis and respiration (Einhellig 2004). Figure 5 presents the concept of allelopathic material application integrated with water irrigation to control weeds for the direct rice seed system.

The successful utilization of allelopathic plant materials combined with the agricultural practice of water irrigation for weed control was proven in this field study. The B. pilosa fresh material was applied together with water at 7 DAS. At this stage, most of the weeds were germinated to the 1–2 leaf stage. Thus, most of the weeds were submerged under the water after irrigation. The data in Table 2 show that the control treatment had approximately 404.5–473.2 weeds in total; the total number of weeds was reduced with increasing application rates of B. pilosa, indicating that the inhibition or killing of weeds under water depended on the application rate. This result is similar to that reported by Xuan et al. (2003b), who showed that the application of kava root powder (Piper methysticum L.) at 6 days after rice transplanting could reduce weed numbers and weed dried weight at levels higher than those observed at 11 days after transplanting. However, B. pilosa treatments resulted in lower yields (5.58, 5.85 and 5.61 tons ha\(^{-1}\)) compared to herbicide treatment (5.97 tons ha\(^{-1}\)). A reduction in the rice yield at the B. pilosa application rate of 2 tons ha\(^{-1}\) was probably caused by weed interference as the number of weeds reached levels of 188–226 plants m\(^{-2}\). On the other hand, the rice yield of B. pilosa at 6 tons ha\(^{-1}\) was lower than that at 4 tons ha\(^{-1}\), probably due to the phytotoxicity by B. pilosa. Therefore, the application rate of 4 tons ha\(^{-1}\) is suitable for recommendation despite the occurrence of weeds at a significant density.

The amount of allelopathic material used in this report is higher than that used in previous reports (approximately 1–2 tons dried weight ha\(^{-1}\)). However, in this research, we used fresh B. pilosa that contains approximately 80–85% of water (Krumsri et al. 2015). Thus, 6 tons fresh weight of B. pilosa should be equivalent to 0.9–1.2 tons dried weight, which is lower than that applied by Hong et al. (2004a), who reported the application of B. pilosa at 2 tons dry powder ha\(^{-1}\) reduced weed dried weight by 81.8%, while 6 tons fresh material ha\(^{-1}\) of this research reduced weed dried weight by 95.15%.

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In conclusion, the application of *B. pilosa* fresh material combined with water irrigation at 7 DAS could suppress the growth of weeds with no impact on rice growth and yield. Although this concept was effective for weed control, the practical application requires more materials and a heavy work load. The development of a more desirable product, such as a pellet formulation, could be a more sustainable alternative for weed management in rice production in the future.

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DISCLOSURE STATEMENT

The authors declare no conflict of interest.

REFERENCES

Adler M.J. and Chase C.A. 2007. Comparison of the allelopathic potential of leguminous summer cover crops: cowpea, sunn hemp, and velvetbean. *HortScience* **42**, 289–293.

Chumyam A., Whangcha K., Jungklang J., Faiyue B. and Saengnila K. 2013. Effects of heat treatments on antioxidant capacity and total phenolic content of four cultivars of purple skin eggplants. *ScienceAsia* **39**, 246–251.

Dass A., Shekhawat K., Choudhary A.K., Sepat S., Rathore S.S., Mahajan G. et al. 2017. Weed management in rice using crop competition-a review. *Crop Prot.* **95**, 45–52.

Deba F., Xuan T.D., Yasuda M. and Tawata S. 2007. Herbicidal and fungicidal activities and identification of potential phytoxosins from *Bidens pilosa* L. var. radiata Scherff. *Weed Biol. Manag.* **7**, 77–83.

Deba F., Xuan T.D., Yasuda M. and Tawata S. 2008. Chemical composition and antioxidant, antibacterial and antifungal activities of the essential oils from *Bidens pilosa* Linn. Var. *radiata*. *Food Control* **19**, 346–352.

Einhellig F.A. 2004. Mode of allelochemical action of phenolic compounds. In: *Allelopathy: Chemistry and Mode of Action of Allelochemicals* (ed. by Macias F.A., Galindo J.C.G., Molinillo J.M. and Cutler H.G.). CRC Press, Boca Raton, 217–238.

Gusman G.S., Yamagushi M.Q. and Vestena S. 2011. Allelopathic potential of aqueous extracts of *Bidens pilosa* L., *Cyperus rotundus* L., and *Euphorbia heterophylla* L. *Biotropica*, Ser. Bot. **66**, 87–98.

Hong N.H., Xuan T.D., Eiji T. and Khanh T.D. 2004a. Paddy weed control by higher plants from Southeast Asia. *Crop Prot.* **23**, 255–261.

Hong N.H., Xuan T.D., Tsuzuki E., Terao H., Matsuo M. and Khanh T.D. 2004b. Weed control of four higher plant species in paddy rice fields in Southeast Asia. *J. Agron. Crop Sci.* **190**, 59–64.

Khanh T.D., Hong N.H., Xuan T.D. and Chung I.M. 2005. Paddy weed control by medicinal and leguminous plants from Southeast Asia. *Crop Prot.* **24**, 421–431.

Khanh T.D., Xuan T.D. and Chung I.M. 2007. Race allelopathy and the possibility for weed management. *Ann. Appl. Biol.* **151**, 325–339.

Khanh T.D., Cong L.C., Xuan T.D., Uezato Y., Deba F., Toyama T. et al. 2009. Allelopathic plants: 20. Hairy beggarticks (*Bidens pilosa* L.). *Allelopathy J.* **24**, 243–254.

Kong C.H., Hu F., Wang P. and Wu J.L. 2008. Effect of allelopathic rice varieties combined with cultural management options on paddy field weeds. *Pest Manag. Sci.* **64**, 276–282.

Krunsi R., Susunnamek U., Homhual W., Laosinwattana C. and Poonpaiboonpipattana T. 2015. Allelopathic effects of *Bidens pilosa* var. *radiata* and its preliminary utilization to control weeds in rice. *J. Agric. Technol.* **11**, 1875–1886.

Poonpaiboonpipattana T., Pangnakorn U., Susunnamek U., Teerarak M., Charoenying P. and Laosinwattana C. 2013. Phytotoxic effects of essential oil from *Cymbopogon citratus* and its physiological mechanisms on barnyardgrass (*Echinochloa crus-galli*). *Ind. Crops Prod.* **41**, 403–407.

Poonpaiboonpipattana T., Susunnamek U. and Laosinwattana C. 2015. Screening on allelopathic potential of 12 leguminous plants on germination and growth of barnyardgrass. *J. Agric. Technol.* **11**, 2167–2175.

Silva F.L., Fischer D.C.H., Tavares J.F., Silva M.S., De Athayde-Filho P. F. and Barbosa-Filho J.M. 2011. Compilation of secondary metabolites from *Bidens pilosa* L. *Molecules* **16**, 10701–1102.

Wang X.F., Hasani D., Cheng Z.W., Wang C.Y. and Wu J. 2014. Allelopathy of the invasive plant *Bidens frondosa* on the seed germination of *Gnorimus japonicus* var. *Chinensis*. *Genet. Mol. Res.* **13**, 10592–10608.

Xuan T.D., Tsuzuki E., Terao H., Matsuo M., Khanh T.D., Murayama S. et al. 2003a. Alifafa, rice by-products and their incorporation for weed control in rice. *Weed Biol. Manage.* **3**, 137–144.

Xuan T.D., Yuichi O., Junko C., Eiji T., Hiroyuki T., Mitsuhiro M. et al. 2003b. Kava root (*Piper methysticum* L.) as a potential natural herbicide and fungicide. *Crop Prot.* **22**, 873–881.

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