MICROWAVE (2.45 GHz) SOIL TREATMENT for WEED MANAGEMENT in RICE (*Oryza Sativa* L.)

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ABSTRACT

Interest in chemical free weed management practices has increased to overcome herbicide resistance in sustainable crop production systems. Rice yield is strongly influenced by weed management strategies. A field experiment was conduct to elucidate the effect of pre-emergence microwave (2.45 GHz) irradiation of soil for weed management in a randomized complete block design with five replication of irradiation treatment in direct seeded rice. The projection of 560 J cm^{-2} of microwave energy into soil induced a 70 – 80% reduction in weed establishment compared to untreated control and therefore, a 34% increase in the grain yield of rice (9.0 t ha^{-1}) was achieved, compared to the non-microwave scenario (6.7 t ha^{-1}). Microwave based weed control could be effective to manage herbicide resistant weed biotypes in cropping system.

Key words: Herbicide resistance; Microwave energy; weed suppression; thermal devitalisation; rice grain yield

1. Introduction

Rice (*Oryza sativa* L.) is the staple food of 60% of the world's population, performs a significant role in the socio-economic constancy of the world, and is grown in a vast range of agro-ecological conditions. In Australia, rice farming is done in the Murray-Darling Basin, on an area of 7 M ha, with an annual grain production capacity of 6.9 M t (ABS, 2015). Direct seeding is a common sowing strategy of rice in Australia due to high labour costs and water shortages.

Weeds are one of the major biological constraints to increasing rice yield. Oerke (2006) estimated that globally 34% crop productivity losses are due to weeds. However, the dramatic decline in the production of rice due to weeds all over the world is 10%. The probability of yield loss in a direct seeded rice crop is as high as 50 – 91% as compared to transplanted rice, because there is neither a difference in weed-crop size nor a destructive effect of flooding on weed establishment at the vegetative stage of transplanted rice.

Chemical and mechanical weed control methods are most commonly used in existing cropping systems. Agronomists normally use fire, flaming, grazing, soil fumigants, mechanical eradication, and biocontrol agents in various cropping system to control weeds below the economic threshold in the absences of weedicides. In Australia, no-till farming practice has increased the use of chemicals for weed management, which has ultimately shifted the weed flora to herbicides resistance. Globally, 51 weed species are resistant to various chemistry herbicides in rice crops (Heap, 2016).

The troublesome weeds of the Australian rice growing belt are barnyard grass (*Echinochloa crus-galli*), dirty dora (*Cyperus difformis*), arrowhead (*Sagittaria montevidensis*) and starfruit (*Damasonium minus*) (Pratley *et al.*, 2004). Among all the weeds, Barnyard grass (*Echinochloa crus-galli* L.) is the major problematic bio-agent of rice and is also considered to be the main weed of several semi-aquatic cropping systems. A 57% reduction in rice yield was documented with the population density of 9 plants m^{-2} of barnyard grass (Maun and Barrett, 1986). Additionally, higher densities of barnyard grass may remove up to 80% of the soil nitrogen, especially at vegetative growth stages. Seed production is the key element of long-standing weed population dynamics. The average seed production capacity of barnyard grass ranged from 20,000 – 73,000 seeds per plant and 60% of produced seed could become part of the weed seedbank. Therefore, effective weed management depends on reducing the soil weed seed bank (Burnside *et al.,* 1986).

Microwaves (MW) are non-ionizing electromagnetic waves with a frequency range of 300 MHz < f < 300 GHz and the wavelength range of 1 m – 1 mm (Banik *et al.,* 2003). Interest in the interaction of MW energy with biological system dates back to the mid-twentieth century. MW absorption is primarily influenced by the dielectric and roughness properties of the load.

The absorption of MW energy projected into the soil can be affected by numerous unknown factors (Nelson, 1996). The propagation of MW energy through soil depends on the gravimetric (θg) and volumetric (θv) moisture content, bulk density, organic matter content, soil texture and specific heat of soil. Bigue-Del-Blanco *et al.,* (1977) treated two days-old seedlings of maize with microwave energy at a frequency of 9 GHz with a very low power density of 10–30 mW cm^{-2} for time periods of 22–24 hs. The authors revealed that more exposure time to microwaves even at very low energy densities significantly dehydrated the maize plants and retarded their growth. In contrast, recent research on fleabane and paddy melon has concluded that a short exposure (≤ 5 seconds) of high intensity MW (2 kW) heating was enough to dehydrate plant (Brodie *et al.*, 2012). Therefore, the application of microwave in agricultural systems has potential to substitute the hazardous, toxic and environmentally-unsafe chemicals used for weeds management (Wayland *et al.,* 1978; Sartorato *et al.*, 2006). This study evaluated the effect of pre-emergence microwave irradiation of soil for subsequent weed management in direct-seeded rice crop under field conditions.

2. Methods

A field experiment was conducted between October, 2015 and April, 2016 at Dookie Campus (36.395 °S, 145.703 °E), The University of Melbourne, Victoria, Australia. The climate of the experimental area is temperate, with annual rainfall of 575 mm. Soil type of the experimental field area was classified as Currawa Loam (Downes, 1949). Historically, the field is a grazing paddock with predominantly grass species. An area of 73.5 m^2 was excavated and manually levelled into a turkey-nest pond so the area could be flood irrigated to grow Rice. The individual experimental plot sizes were 2.0 x 2.0 m, which were arranged in a randomised complete block design (RCBD) with five replications, and with a 0.5 m untreated buffer zone between each experimental plot. The experiment consists of two treatments: an untreated control (MW_0 = 0 sec) and microwave treated (MW_1 = 120 sec).

A MW prototype was developed for soil irradiation (Figure 1). It was based on the magnetron of a commercial microwave oven (EMS8586V; Sanyo; Tokyo, Japan) operating at 600 W with a frequency of 2.45 GHz, which was assembled with a rectangular waveguide of 86 × 43 mm channelling the MW to a pyramidal horn antenna with aperture dimensions of 110 x 55 mm.

Simulating Power Density from a Horn Antenna for Soil Irradiation

MW heating is directly governed by the dielectric properties of the soil and electrical field strength (E_o) of the microwave source (Brodie, 2008), hence it is important to understand the distribution and intensity of the MW field on the soil surface. The direct measurement of MW electrical field intensity is unsafe and needs sophisticated instrumentation, near the applicator; therefore it is crucial to estimate the field energy density using electromagnetic theory. The electric field in the rectangular waveguide has a sinusoidal distribution across the width of the waveguide. The maximum electric field strength (E_o) in a rectangular waveguide had been explained by Cronin, (1995), and is given in equ. 1;

$$E_o = \sqrt{\frac{8\pi f \mu_o P}{ab\sqrt{\left(\frac{2\pi f}{c}\right)^2 - \left(\frac{\pi}{a}\right)^2}}} \tag{1}$$

The MW's electric field distribution across the width of rectangular horn antenna, as calculated from the centre line of the waveguide, is given in equ. 2;

$$E = E_o \cos\left(\frac{\pi}{a} x'\right) \tag{2}$$

There is some field expansion between feeding waveguide and the antenna aperture; therefor the electrometric field in the antenna aperture is:

$$E_a = E_o cos\left(\frac{\pi}{A} x'\right) . \frac{a}{A} \tag{3}$$

The determination of MW field intensity in front of the antenna, which has been applied to the soil, is crucial to understand the field intensity at the soil surface. Based on the design of a horn antenna (Figure 2), this problem can be explained by; (Brodie and Hollins, 2015):

$$E_p = \frac{E_a}{4\pi} \int_{-B/2}^{B/2} \int_{-A/2}^{A/2} cos\left(\frac{\pi}{A}\ x'\right) \frac{e^{-j\beta_o\left(\sqrt{(x-x')^2+(y-y')^2+z^2}+\sqrt{R_o{}^2+(x')^2}+\sqrt{R_o{}^2+(y')^2}\right)}}{\sqrt{(x-x')^2+(y-y')^2+z^2}}\ .dx'.dy' \qquad (4)$$

Several options exist for solving equation (5). These include: explicit solutions of a simplified integral equation; numerical integration; and finite difference time domain (FD-TD) analyses, which was originally developed by Yee (1966).

Equation (4) can be assessed numerically through Simpson's numerical surface integral approximation. This numerical integration was coded using Matlab® (The Mathworks Inc., Natick Massachusetts, USA). This was used to estimate the field energy on the soil surface. The applied MW energy density in the treated plots, accounting for MW energy reflections from the soil in the absence of using any wave-guide tuning, was approximately 560 J cm^{-2}.

In field condition, soil moisture in the top 1 – 2 cm is required to optimize MW effectiveness. The dielectric constants of loamy soils are directly proportional to volumetric moisture content at MW frequencies. The soil was lightly irrigated prior to MW treatment for proper attenuation. The MW application was performed by standing the prototype orthogonally to the soil surface and treating the soil for 120 sec. Infrared thermal images, captured with an infrared camera (C2; FLIR Systems Inc; Wilsonville, Oregon, USA) immediately after irradiation of the rectangular area (60.5 cm^2) under the horn antenna, were used to evaluate the treatment. The vertical temperature profile in the top 5 – 6 cm of soil was approximately 75 – 80 °C, evidenced through thermal images (Figure 3), and a thermometer. The experimental area remained undisturbed for 24 hs after MW treatment. The experimental plot was then flooded to a depth of 5 cm and the pre-germinated seeds of the rice variety OPUS was broadcasted in the bays at a seeding rate of 125 kg ha^{-1}.

Phosphorus (80 kg ha^{-1}), potassium (60 kg ha^{-1}) and zinc (4 kg ha^{-1}) were applied to the entire experimental area at the time of sowing. Three split doses of nitrogen, using urea, equivalent to a total rate of 120 kg ha^{-1}, were applied during the growing season. Netting was fixed over the experimental bay to reduce bird scavenging during the early stages of crop establishment. Irrigation for 'OPUS' rice variety was scheduled according to Ricegrower Association of Australia, Yanco, NSW.

The leaf area index and chlorophyll content of the fully expanded flag leaf were measured using a Ceptometer (LP-80; Decagon Devices, Inc. Pullman; WA) and SPAD-502 ((Soil-Plant Analysis Development); Spectrum Technologies, Inc. Aurora, Illinois, USA)), respectively. The number of tillers, fresh biomass and dry biomass were measured for a randomly selected 0.25 m^2 quadrat drawn from each of plots. Biomass was dried in an air circulation oven (Nabertherm; TR1050 27124; Germany) for 24 h at 65 °C and final crop yield was converted into tonnes per hectare bases. Weed population and biomass accumulation was counted from whole experimental plot areas (4 m^{-2}). Data were subjected to Analysis of Variance (ANOVA) using MATLAB R2015b (The Mathworks Inc., Natick Massachusetts, USA), and a least significant difference test was used to compare the treatment means at 5 % probability level.

3. Results

3.1. Inhibitory Effect of Microwave on Weeds Establishment:

The predominant weed species found at the experimental site were bermuda grass (*Cynodon dactylon*), barnyard grass (*Echinochloa crus-galli*) and dirty dora (*Cyperus difformis*). The MW (2.45 GHz, 600 W, 120 sec) treatment of soil significantly ($P=0.05$; Table 1) reduced the weed density (17.6 plants plot^{-1}), weed fresh biomass (156.4 gm plot^{-1}) and weed dry biomass accumulation (21.6 gm plot^{-1}) compared to the untreated control; 94.8 plants plot^{-1}, 612.8 gm plot^{-1} and 122.6 gm plot^{-1}, respectively. The pre-emergence microwave irradiation of soil induced a 70 – 80% reduction in weed establishment.

Table 1: Effect of pre-emergence microwave irradiation of soil on weeds parameters. Superscripts sharing different letters are significantly differ to each other at 5% probability level.

Weed Parameters	Treatments		LSD $_{(p=0.05)}$	Percentage Change
	Microwave Treated	Untreated Control		
Weed Density (plants plot^{-1})	17.6^{a}	94.8^{b}	37.7	−80 %
Weed Fresh Weight (gm plot^{-1})	156.4^{a}	612.8^{b}	426.6	−74.6 %
Weed Dry Weight (gm plot^{-1})	21.6^{a}	122.6^{b}	69.6	−82 %

3.2. Influence of Microwave Irradiation of Soil on Rice Growth:

Rice productivity is strongly influenced by weed management practices. The projection of MW energy (2.45 GHz; 120 sec; 560 J cm^{-2}) into soil for pre-emergence weed management significantly ($P=0.05$; Table 2) increased the tiller density (419 m^{-2}) and grain yield (9.0 t ha^{-1}) of rice, compare to the untreated control scenario 292 m^{-2} and 6.7 t ha^{-1}, respectively. The significant difference was observed in case of dry biomass at maximum tillering stage (Table 2), but no statistical significant difference was observed at harvesting between microwave treated plots (27.8 t ha^{-1}) and untreated control plots (22.8 t ha^{-1}).

In the present investigation, there was no-significant difference in leaf chlorophyll content, plant height (cm) and spike length (cm). But, the crop leaf area index (4.0) was found to be significantly high in MW treated soil. The flag leaf area is a key component responsible for maximum photosynthetic rate and biomass accumulation, and there was a positive correlation between leaf area index and tiller production ($r^2 = 0.77$; Figure 1).

The grain quality was assessed at harvesting and there was no significant difference in response to microwave irradiation of soil for weed management (Figures 7 and 8). These results suggest that increase in soil temperature through MW irradiation did not affect the quality characteristics of rice, and the crop effectively utilize the yield-limited nutrients for higher yield.

Table 2: Effect of pre-emergence microwave soil treatment for weed management on yield components of rice crop. Superscript sharing different letters differs significantly at 5 % probability level.

Rice Parameters	Treatments		LSD $_{(p=0.05)}$	Percentage Change
	Microwave Treated	Untreated Control		
Plant Height (cm)	94.4^{a}	92.6^{a}	3.4	1.8 %
Spike Length (cm)	16.7^{a}	16.1^{a}	2.2	3.7 %
Chlorophyll Content (SPAD)	42.3^{a}	43.6^{a}	3.3	−3 %
Leaf Area Index	4.0^{a}	2.6^{b}	1.5	56 %
Number of Tillers (m^{-2})	419^{a}	292^{b}	113.9	43 %
Fresh Biomass Weight ($t\ ha^{-1}$)Ϯ	46.3^{a}	25.1^{b}	9.4	84.6
Dry Biomass Weight ($t\ ha^{-1}$) Ϯ	10.1^{a}	5.6^{b}	2.1	80.5
Dry Biomass Weight ($t\ ha^{-1}$)ƅ	27.8^{a}	22.8^{a}	6.04	20.1 %
Grain Yield ($t\ ha^{-1}$)ƅ	9.0^{a}	6.7^{b}	2.04	34.38

Ϯ = Data collection at maximum tillers establishment
ƅ = Data collection at crop harvesting

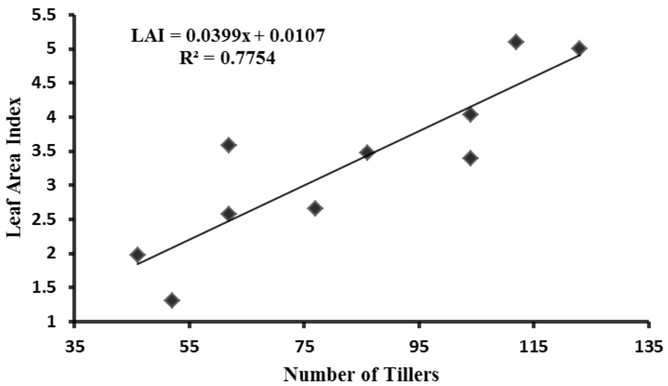

Figure 1: Relationship between leaf area index and fertile tillers (r^2 = 0.77).

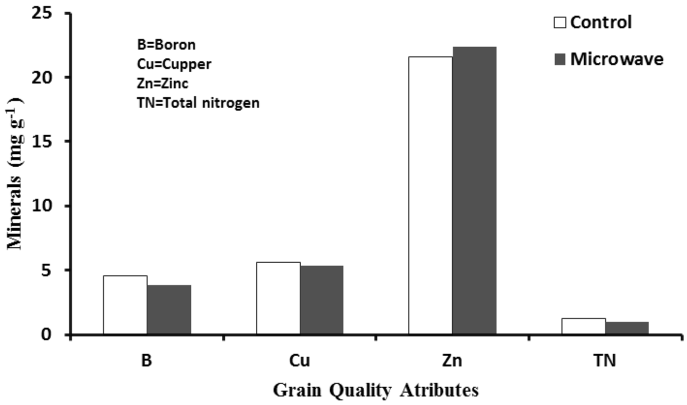

Figure 2: Influence of pre-emergence microwave treatment of soil for weed management on grain mineral accumulation of rice crop.

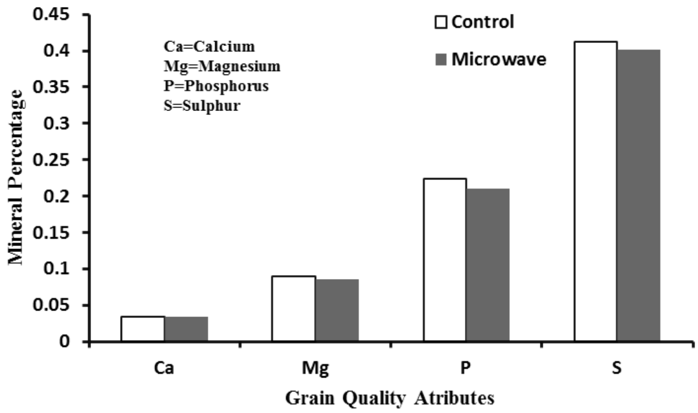

Figure 3: Influence of pre-emergence microwave treatment of soil for weed management on grain minerals accumulation of direct-seeded rice crop.

4. Discussion

Pre-sowing microwave irradiation of soil significantly reduced weed establishment in a direct seeded rice crop. Increase in the temperature gradient in the top layer of soil could reduce the viability of indigenous weed seeds. The results are associated with findings of Bodker and Noye (1994) who reported a 90% reduction in indigenous weed seedling emergence achieved through increasing the soil temperature to about 60 °C, and a further 10 °C increase in temperature gave a substantial reduction of 99% weed emergence.

In the present study, an 82% reduction in weed dry weight was attained through application of MW energy (560 J cm^{-2}) to the soil. This is strongly supported by findings of Sartorato *et al.,* (2006), who estimated the MW energy doses for 90% reduction in the dry weight of *Abutilon theophrasti* (101.5 J cm^{-2}) and *Panicum miliaceum* (343.3 J cm^{-2}). However, this energy for satisfactory post-emergence control is moderately low compared to the energy consumption in the present investigation. Wayland et al., (1975) examined the phytotoxicity of pre-emergence MW energy of 35 – 325 J cm^{-2} application to weed seedbanks in sandy loam soil under field conditions. They achieved 91% control in germination of broadleaved weed species and 81% reduction in germination of grasses with energy threshold of 183 J cm^{-2}. Therefore, based on previous findings and the results of this study, it is possible to reduce the weed pressure in direct-seeded rice system through MW irradiation of soil in Australia, however, more research efforts are needed to understand the long-term effect of MW irradiation and weed control in rice.

Thermal devitalisation of weed seedbanks in the vertical soil profile may be the possible cause of minimum weed interference with the rice crop. This was evidenced by Vidotto *et al.,* (2013), who explored the effectiveness of high temperature on seed viability of six weed species including *Echinochloa crus-galli*: the problematic weed of rice growing regions globally. They stated that 80 – 100% germination reduction was achieved through raising the soil temperature to 79.6 °C. The same range of temperature regime (70 – 80 °C) that was acquired by MW irradiation of the soil in the present study. This effectively induced an inhibitory effect on the weed population and therefore increased the rice crop yield. Brodie *et al.,* (2015) demonstrated that MW energy (576 J cm^{-2}), applied to the soil, significantly increased the grain yield of wheat by 189 % and in canola by 650 % compare to the control. These results explain that MW treatment of soil could also enhance the growth and yield of rice. Furthermore, the possible reason for the increase in growth related parameters of rice may be due to the more availability of nitrogen and other nutrients to the plants. This postulate has recently been explored by Khan *et al*., (2016), who documented that pre-sowing MW irradiation of soil for 120 s significantly increased the grain and biomass yield of wheat, and also enhanced the agronomic efficiency of nitrogen, compared to non-microwave conditions.

In addition to weed suppression, numerous studies have reported the supplementary effect of MW irradiation of soil on crop growth. However, the exact reason for good crop growth and development in MW treated soil is still in question. It has also been demonstrated that MW irradiation markedly alters the physical and chemical properties of soil organic matter (SOM) and enhances the humification of SOM. Relevant to this, SOM is aggregates of organic residues in soil at different stages of humification. Approximately 5 – 25% of organic inputs are expected to accumulate in soil as proteins, peptides and free amino acids. Amino acids typically incorporate about 10 – 20% of soil organic carbon and 30 – 40% of soil organic nitrogen. Thermal denaturation of these biopolymers induced by MW irradiation could increase the concentrations of free amino acids for succeeding turnover to CO_2 and the ammonia pool (NH_4^+), which might have led to higher yield of the rice crop in MW treated soil, in the present investigation. Brodie, (2016) simulated the supplementary effect of soil microwave energy application on crop yield. He stated that once-off MW irradiation for soil seedbank depletion gives a benefit of 1.5 full crops, but when this once-off treatment is coupled with 55% increase in crop productivity, MW treatment may give a cumulative advantage of 2.05 additional crops in a cropping system. This simulation has evidenced through the results of present study where we achieved an 80% reduction in weeds establishment (Table 1) and 34% increase in grain yield (Table 2). The future efforts should focus on the cumulative effect of microwave on soil nutrient dynamics.

5. Conclusion

Based on the result of this study, we infer that pre-emergence microwave irradiation of soil could gain a wide acceptance for chemical-free weed management in direct seeded rice cropping system. Consequent increases in crop productivity through microwave treatment of soil may attract the interests of the farming community, but the microwave's supplementary effect on increasing yield is still unexplored.

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7. Reference

Australian Bureau of Statistics, 2015. 7121.0 - Agricultural Commodities, Australia (http://www.abs.gov.au).

Bødker L & Noye´ G., 1994. Effekten af varmebehandling af overfladejord i na˚ letræssa˚ bede over for ukrudt og rodpatogene svampe. (Effect of heat treatment of surface-soil in raised seedbeds with conifers against weeds and root pathogens) (with English summary). In: Proceedings 1994 11th Danish Plant Protection Conference/Pests and Diseases, Nyborg, Denmark, 239–248.

Brodie, G., 2016. Derivation of cropping system function for weed management: Part 2 – Microwave Weed Management. Global J. Agri. Innovation, Res. and Development, 3, 1-9.

Brodie, G. and Elosie H., 2015. The effect of microwave treatment on ryegrass and wild radish plants and seeds. Global J. Agri. Innovation, Res. and Development, 2, 16-24.

Cronin, N. J., 1995. *Microwave and Optical Waveguides*, Bristol: J W Arrowsmith Ltd.
Heap, I. (2016). International Survey of Herbicide-Resistant Weeds. Weed Science Society of America (WSSA). http://www.weedscience.org

Khan M. J., Graham, B. and Dorin, G., 2016. Invited paper: Effect of microwave (2.45 GHz) on agronomic efficiency of nitrogen in wheat.In *IMPI's 50th Microwave Power Symposium*, Orlando, Florida, USA, pp. 91-93.

Sartorato I., G. Zanin, C. Baldoin, and De-Zanche C., 2006. Observations on the potential of microwaves for weed control.Weed Res.,46(1),1–9.

Vidotto, F., Depalo, F. and Ferrero, A., 2013. Effect of short-duration high temperatures on weed seed germination. Ann. Applied Bio. 163 (3), 454-465.

Wayland, J. R., Davis F. S. and Merkle. M. G., 1973. Toxicity of an U.H.F. device to plant seeds in soil. Weed Science 21(3), 161-162.