Chapter 7

Microwave Weed and Soil Treatment in Rice Production

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Additional information is available at the end of the chapter

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Abstract

Herbicides resistance has challenged sustainable rice productivity. Consequently, interest in chemical-free weed management has increased to overcome this constraint. This chapter has demonstrated the effect of pre-sowing microwave soil heating as a new alternative to chemicals for confirmed herbicide resistant weeds of the Australian rice production system. Microwave can superheat weed plants, creating micro-steam explosions in the plant structures to kill weeds. This requires the least amount of energy to achieve weed control and can be likened to a 'knock down' herbicide treatment. Considerably, more microwave energy can be applied to the soil to achieve weed seed bank deactivation; however, there is growing evidence that this strategy also changes the soil biota and nutrient profile in favour of substantial increases in crop yield, when crops are planted into this microwave-treated soil. An energy application of approximately 400–500 J cm^{-2} gave approximately 70–80% reduction in weed establishment in three field trials conducted at two agro-ecological zones of the Australia. In addition, there was a 10 times higher nitrogen use efficiency, and a 37% higher water use efficiency was achieved through this aspect of the microwave technology. There is also evidence that the soil treatment strategy provides persistent effects, beyond a single season; therefore, the rice production is better than when using conventional weed control methods.

Keywords: weeds, herbicide resistance, microwave, soil health, crop health

1. Introduction

Rice (*Oryza sativa* L.) is the staple food of 60% of the world's population [1], 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 70,000 ha, with an annual grain production capacity of 0.69 M t [2]. Direct seeding is a common sowing strategy of rice in Australia due to high labour costs associated with transplanted rice systems. Weeds are one of the major biological constraints to increasing rice yield. Oerke [3] estimated that globally 34% crop productivity losses are due to weeds. However, the global decline in the production of rice, due to weeds, is estimated to be 10.2% [4]. Yield loss in a direct seeded rice crops is high, compared to transplanted rice [5]. Productivity losses of rice crops generally depend on climatic conditions, weed types, weed population density, rice variety, sowing methods and weed management practices.

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*). Among all the weeds, Barnyard grass (*Echinochloa crus-galli* L.) is the major problematic bio-agent of rice [6] and is also considered to be the main weed of several semi-aquatic cropping systems [7]. It follows the C_4 photosynthetic pathway [5] and has indistinguishable morphology to rice at seedling stage, which makes it extremely competitive with the rice crop. A 57% reduction in rice yield was documented, with a barnyard grass population density of 9 plants m^{-2} [8]. Additionally, higher densities of barnyard grass may remove up to 80% of the soil nitrogen, especially during its vegetative growth stages [7]. Seed production is the key element of long-standing weed population dynamics [9]. The average seed production capacity of barnyard grass ranged from 20,000 to 73,000 seeds per plant [10] and 60% of these seed could become part of the weed seed bank. Therefore, effective weed management depends on reducing the soil weed seed bank [11].

1.1. Herbicide resistance

Globally, there are 400 weed species that have developed resistance to herbicides and annually nine new weed biotypes are reported as being herbicide resistant [12]. The overall number of herbicide resistant weed species in various crops is illustrated in **Figure 1**. Cross-resistance in weed flora is described as resistant to two or more weedicides of the same or different chemistry because of one resistant mechanism (RM) [13]. However, multiple resistances in individual weed species are generally characterized by the presence of two or more RMs. These mechanisms might be the mutation at the site of action (SOA) of herbicides (target site) or change in metabolism and translocation (nontarget site), which reduces the phytotoxic effect of herbicides on their SOA [14]. Of particular concern, the numbers of weed species, which have become resistance to glyphosate in Australian agricultural systems are shown in **Figures 2** and **3**. Metabolic resistance is more commonly found in monocot (grasses) than in dicot (broadleaf) weeds [14]. Herbicide resistance in weeds is the greatest threat to sustainable productivity of agricultural commodities in industrialized countries. Therefore, there is a present need of an alternative weed management strategy in exiting cropping system. A series of experiments have been conducted, at Dookie Campus of the University of Melbourne, to assess the effects of microwave energy as an alternative of chemical weed control.

1.2. Water use efficiency

Higher grain production per unit application of water is needed to enhance sustainable rice production for future demands. Australia is the driest inhabited continent on the planet

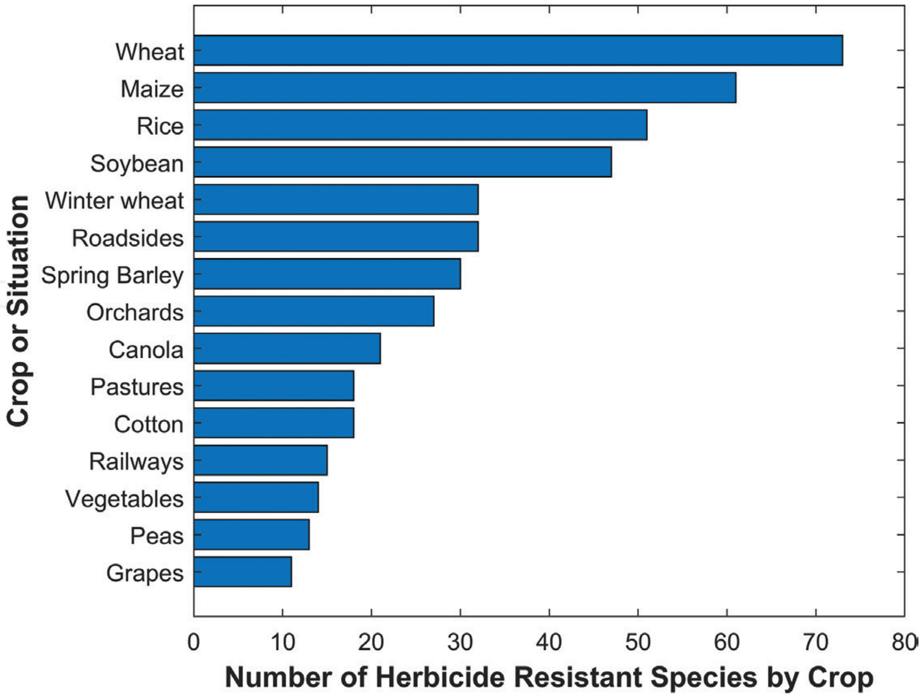

Figure 1. The overall herbicides resistant scenario of weed species in crops. Source: [12].

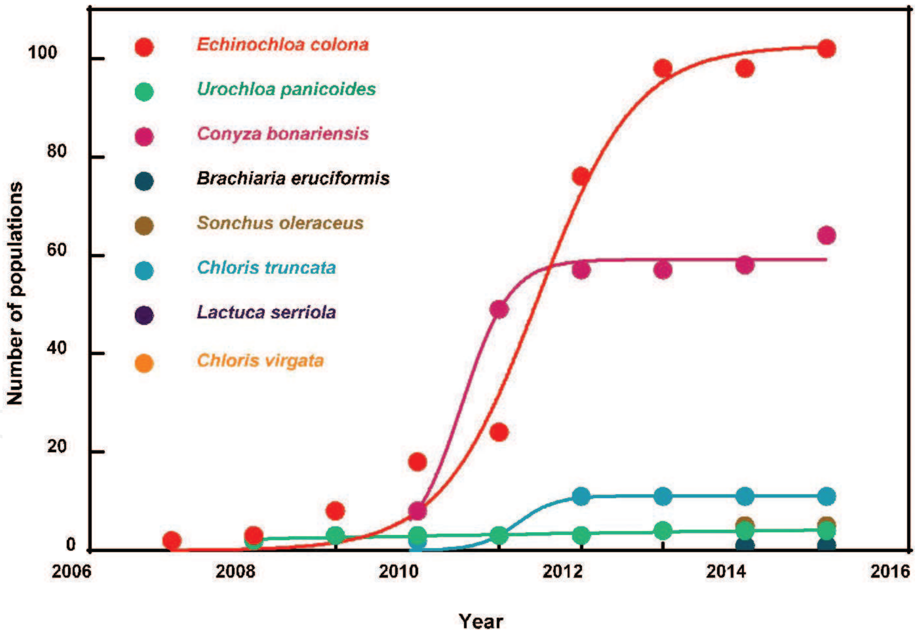

Figure 2. Confirmed glyphosate resistance summer weeds of Australian crop production systems. Source: [15].

and the Australian Academy of Technology and Engineering (ATSE) reported that 62% of Australia's water was consumed by the agriculture sector in 2013–2014. Effective water use, to improve crop yield, can save the sector's water for future generation. The cost of water in Australia is about AU$ 200–300 per Ml, which is consequently increasing the cost of rice production in Australia, independent of direct-drill farming, which postpones permanent flooding of the crop for almost 35 days.

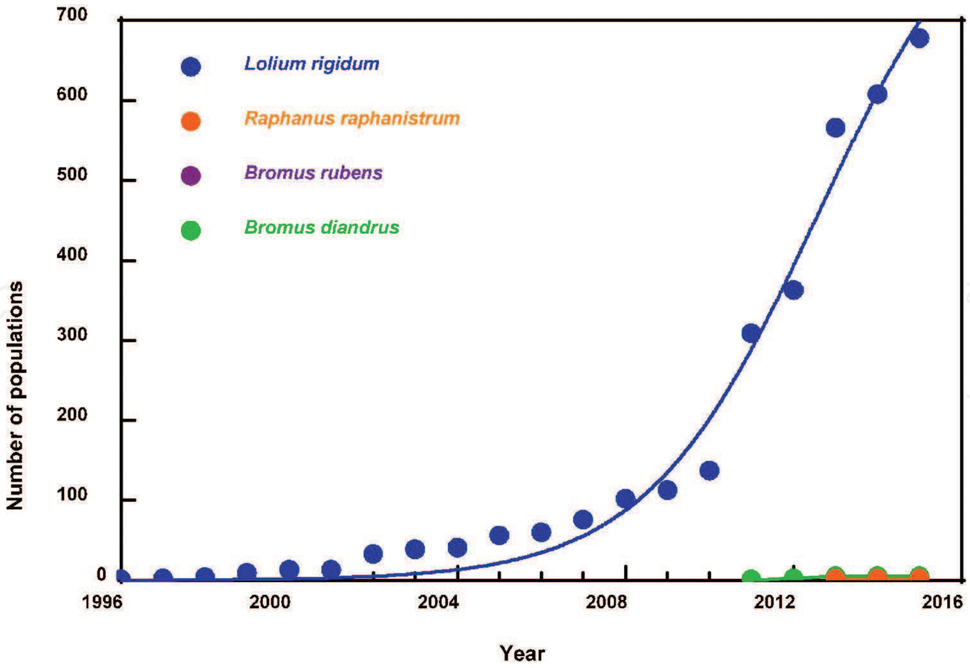

Figure 3. Confirmed glyphosate resistance winter weeds of Australian crop production systems. Source: [15].

Rice production in Australia consumes approximately 2.5–3 Ml ha^{-1} with an average grain harvest of about 1.4 t Ml^{-1}; however, microwave soil treatment increases the production to about 1.92 t Ml^{-1} [16], which is around 37% higher water use efficiency compared to untreated control plots. Globally, an average of 0.003–0.005 Ml of water is required to produce 1 kg of rice (i.e. , a yield of between 0.2 and 0.3 t Ml^{-1}), which is about 2–3 times higher than the water consumption of other cereal crops [17, 18]. Considering this, numerous studies have reported the effects of irrigation water volume on crop yield [19–21]. Interestingly, with a single crop management strategy, it is hard to harvest multiple benefits, including water use efficiency. In the following field studies, we achieved about 37% greater irrigation water use efficiency, where we treated the soil with microwave energy for weed seed bank depletion under field conditions. Therefore, microwave soil heating may also promote effective and efficient water use in Australian rice production systems, in addition to weed management. This assumption needs further research for validation under field conditions.

1.3. Organic rice production

Soil health is the key element in organic farming and as per worldwide agreement; soil fertility in organic farming system should be maintained on a long-term basis. Intensified rice farming has been deteriorating the soil quality [22] in Asian rice growing regions. However, in Australia, limited studies have reported that intensive organic farming enhanced soil fertility as compared to conventional agriculture practices [23]. It has been reported that microwave treatment of soil enhances the humification of soil organic matter [24] and has some positive effects on soil nitrogen availability for crop plants. In a pot trial, Khan et al. [25] reported a persistent effect of microwave soil heating on the second season wheat crop with better grain production benefits than in the first season after a once off microwave treatment, which suggests that there is a persistent effect of this technology on soil health. In addition, the population of ammonia oxidizer bacteria and archaea, studied during this pot trial, showed no significant response to the heating effect of microwave treatment time. The abundance of beneficial microbes is a direct indicator of soil fertility, suggesting that microwave technology can sustain soil health over a long period.

In Australia, weed management in organically produced rice offers extra challenges for the farmer. Sod seeding, where rice is directly sown into a pasture or legume stand, is a common establishment practices in southern New South Wales. The preexisting pasture of legume crop somehow suppresses aquatic weeds like dirty dora, starfruit, arrowhead and water plantain, but has little to no effect on barnyard grass. Another nonchemical weed control strategy is propane gas flame weeder; however, it costs about AU$ 12,000–15,000 ha^{-1}, along with careful water management and post-emergent harrowing [26]. Considering this, organic rice producers are still looking for a nonchemical weed control approach, which could control barnyard grass and sustain organic production.

2. Microwave energy

Microwave frequencies occupy the portion of the electromagnetic spectrum (300 MHz to 300 GHz) that lies between VHF radiowaves and thermal infrared. Their application falls into two categories, depending on whether the wave is used to transmit information or energy. The first category includes terrestrial and satellite communication links, radar, radio-astronomy, microwave thermography, material permittivity measurements, and so on [27]. The second category of applications is associated with microwave heating and wireless power transmission. In case of microwave heating, there is usually no signal modulation and the electromagnetic wave interacts directly with solid or liquid materials.

2.1. Essentials of microwave heating

"It has long been known that an insulating material can be heated by applying energy to it in the form of high frequency electromagnetic waves"([28], pp. 5). Industrial microwave heating has been used since the 1940s ([28], pp. 5). The initial experiments with microwave heating were conducted by Dr. Percy Spencer in 1946, following a serendipitous discovery while he was testing a magnetron [29]. Although Spencer was not the first to observe that microwave energy could impart heat to materials, he was the first to systematically study it. Since then, many heating, drying, thawing [30] and medical applications [31] have been developed.

One key benefit of microwave heating, over conventional convective heating, is speed. The origin of this speed is the volumetric interactions between the microwave's electric field and the material. In contrast, convective heat transfer propagates from the surface into the material, with the final temperature profile depending on the material's thermal diffusion properties [32] and the influence of moisture transport, which often hinders the convective heating process [33].

The factors that contribute to microwave heating include: the physical and chemical structure of the heated material; the frequency of the microwaves [34]; in some cases, such as wood, the orientation of the electrical field relative to the structure of the dielectric material is also important ([35], pp. 13-17); reflections from the interfacial surface of the heated material [27]; electric field strength [34]; the geometry of the microwave applicator [28]; the geometry, size, electrical and thermal properties of the dielectric material [36–38]; the exposure time; and the moisture content of the dielectric material [33, 35].

2.2. ISM band applications

Because microwaves are also used in the communication, navigation and defence industries, and their use in thermal heating is restricted to a small subset of the available frequency bands. A small number of frequencies have been set aside for Industrial, Scientific and Medical (ISM) applications [39]. The main frequencies of interest for industrial applications are 915 ± 13 MHz and 2450 ± 50 MHz [39].

3. Microwave weed treatment

In Australian agricultural industries, the total estimated cost of weed management and loss in crop productivity due to weeds is about AU$4 billion annually [40]. Microwave weed management is an alternative method of weed control in modern agriculture systems. The history of microwave-based weed management is given in **Table 1**. The efficacious application of microwave heating in agricultural systems can substitute for the sometimes hazardous, toxic and environmentally unsafe chemicals that are used to kill weeds [60]. Interest in the use of microwave energy as a tool to weeds control is mainly because of herbicide resistance of various weed species [61] and their long-lasting persistence in the environment [54, 62]. Microwave heating is not influenced by wind direction and speed, therefore prolonging the application periods compared to traditional methods of herbicides spraying [51].

Ayappa et al. [63] reported that the most important features of microwave heating are its accurate control, diminutive start-up time and volumetric heating. Microwave energy density is the most important factor in plant mortality rather than exposure time; therefore, two options for weed management, using microwave energy, become evident: long exposure to diffuse microwave energy; or deliberate application of a strongly focused microwave pulse to quickly debilitate the plants [58].

Microwave radiation, which triggers dielectric heating in plant tissues, is induced by the microwave's electric field. This internal heating ultimately kills or debilitates the plant [54]. Bigu-Del-Blanco et al. [49] treated 2-day-old seedling of maize with microwave energy at a frequency of 9 GHz for 22–24 h. 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, the recent research on fleabane and paddy melon [58] has concluded that a short exposure (≤ 5 s) of high-intensity microwave heating was enough to hinder plant growth. The plant tissues, which were subjected to microwaves, rapidly dehydrated. Whatley et al. [64] stated that low moisture levels in soil attenuated the microwave transmission less than high moisture content. The authors suggested that pre-emergence microwave treatment for weed control should be worked out when the top soil layer (1–2 cm) contains relatively low moisture.

Microwave frequency	**Energy level**	**Irradiation duration (s)**	**Treatment scenario**	**Target species**	**Percent weed-seed destruction**	**Reference**
39 MHz	—	4–37 s	Pre-emergence	Hard red winter wheat	50% seed mortality	Nelson and Walker [41]
2.45 GHz	600 W	60 s	Pre-emergence (Dry, 4 h soaked and 46 h germinated seeds)	*Zea mays, Arachis hypogaea, Prosopis juliflora, Cucumis sativus, Brassica sp., Rumex crispus, Echinochloa colonum, Amaranthus sp., Gossypium hirsutum, Glycine max, Sorghum vulgare and Triticum vulgare*	17% reduction in germination in dry seeds but 100% in case of moist seeds at 10 s of exposure	Davis *et al.* [42]
2.45 GHz	600 W	8 s	Post emergence (Aquatic weed)	Duckweed *(Wolffia punctata)*	50%	Champ *et al.* [43]
2.45 GHz	2000 & 4000 W	Varying exposure time (not mention properly)	Pre and post emergences	Johnsongrass Morningglory Redroot Pigweed Texas panicum Barnyardgrass Sunflower London rocket Rigseed euphorbia	For post-emergence MW treatment 309 J/cm^2 energy was required for 100% control (field conditions) while for pre-emergence MW weed control 73 J/cm^2 gave 85–100% control (glass house conditions)	Wayland *et al.* [44]
2.45 GHz	45–720 J cm^{-2}	No information	Pre-emergence	London rocket (13 cm deep in soil profile) and Sunflower (2.5 cm seeded depth)	87% for London rocket and 93% for sunflower	Menges and Wayland, [45]
2.45 GHz	100–750 W	120–1200 s	Pre-emergence	Clover and Turnip	60–78% reduction in seeds germination	Hightower *et al.* [46]
2.45 GHz	0.1–1.5 kW	Varying exposure time	Pre-emergence of seeds in soil	Black medic, Barnyard grass, Foxtail purslane, redroot pigweed, large crabgrass,	50%	Rice and Putnam [47]
2.45 GHz	—	360 s	Pre-emergence	*Brassica napus, Linum usitatissimum, Avena fatua*	85–95%	Bhartia *et al.* [48]

Microwave frequency	Energy level	Irradiation duration (s)	Treatment scenario	Target species	Percent weed-seed destruction	Reference
9 GHz	10–30 mW/cm^2	22–24 h	Post emergence	*Zea mays*	100% growth inhibitions	Bigu-del-Blanco *et al.* [49]
2.45 GHz	1.2 kW	5–45 s	Pre-emergence	*Trifolium and Medicago*	85% reduction in germination	Crawford [50]
2.45 GHz	500 W	30 s	Pre-emergence	*Avena fatua*	60% (based on seed moisture)	Diprose *et al.* [51]
2.45 GHz	1.5 kW	0, 10, 20 and 30	Pre-emergence	Wild oat & wheat	90–100%	Lal and Reed, [52]
2.45 GHz		120 s	Pre-emergence	Avena sativa and native weed seeds	Reduced weed seeds emergence	Barker and Craker, [53]
2.45 GHz	900 W	4, 8, 16, 32, 64, 128 and 256 s	Post emergence	*Abutilon theophrasti*, Panicum miliaceum, Lucerne and Rapeseed	Complete dehydrating of plants	Sartorato *et al.* [54]
2.45 GHz	800 W	120, 240, 420 and 960 s	Pre-emergence	Rubber vine, Parthenium and Bellyache bush	88% (Rubber vine), 67% (Parthenium) and 94% (Bellyache bush) mortality at 960 s irradiation	Bebawi *et al.* [55]
2.45 GHz	0.10–1.24 kWh m^{-2}	30–300 s	Pre and post emergence	*Malva parviflora and Triticum astevium*	100% destruction of tested specie at 0.65 kWh m^{-2}	Brodie *et al.* [56]
2.45 GHz	700 W	120, 240, 320 and 720 s	Pre-emergence treatment of soil	*Lolium perenne and Lolium rigidum*	100% seed mortality was achieved at 240 s of MW irradiation	Brodie *et al.* [57]
2.45 GHz	750 W	5, 15, 30 and 60 s	Pre and post emergence	Prickly paddy melon	100% debilitation of plants	Brodie *et al.* [58]
2.45 GHz	2 kW	5, 10, 15, 30, 60 s	Post emergence	Ryegrass and wild radish	100% mortality	Brodie and Hollins [59]

Table 1. History of microwave weed management in different scenarios.

Van Wambeke et al. [65] and Benz et al. [66] reported that seeds, fungi and nematodes could be effectively controlled with a short exposure to microwave treatment; however, the efficacy of this short exposure was highly influenced by soil texture, exposure time (sec), soil depth and soil moisture content. Davis et al. [42] conducted an experiment to evaluate the effects of microwave on the seedling survival percentage of twelve species. They described that the seedling (48 h germination) exhibited no survival after short exposure of microwave energy and concluded that susceptibility of young seedlings to microwave heating was highly correlated with moisture content and absorption of energy. Davis et al. [67] proposed that the specific mass and volume of crop seeds were positively correlated to seed mortality during microwave heating. This might be due to the “radar cross-section” [68] attainable by seeds to transmitting microwave. More radar cross-section enables the seed to interrupt, and thus absorbs more microwave energy. This seems to be the cause of death [69].

The use of electromagnetic radiations for post-emergence control of broad leaves and grasses is the least energy-consuming process available for microwave weed control [70]. Brodie et al. [57] stated that, based on microwave energy calculation for seeds and plants on the sandy soil surface, far more energy was required to kill dry seeds as compared to the previously emerged plants. The actual energy requirement on a large scale would depend on plant density and three-dimensional microwave distribution. Hence, the total energy required for weed management might be significantly reduced if weed seeker systems [71] are employed to control the activation of the microwave unit.

Thermal runway, due to the resonance of electromagnetic field inside the structure of dielectric material, is common in dielectric heating [72, 73]. Total energy and time exposure could be dramatically reduced if thermal runway can be induced in weed plants throughout microwave irradiation treatment; therefore, analogous energy requirements to those related with traditional chemical weed control method could be achieved. This temperature-time exposure scenario can only be discovered and understood through more research into the microwave heating of biological materials.

Based on previous findings and the results of recent studies reported by Khan et al. and Brodie et al. [16, 25]; pre-sowing microwave irradiation of soil for 120 s in first field trial and 60 s in two other field trials, in rice crops, gave significant reduction in weed emergence (**Table 2**). It is possible to reduce weed pressure in direct-seeded rice systems through microwave irradiation of soil in Australia; however, more consolidated research efforts are needed to understand the long-term effects of microwave irradiation and weed control in rice.

3.1. Killing emerged plants

It has been confirmed that microwave energy can debilitate emerged weed plants with a very short exposure time [25, 56, 58, 59]. Some specific microwave energy dose responses are shown in **Figure 4**.

3.2. Soil treatment

Soil is a complex three-dimensional living substance. The propagation of microwave energy through soil depends upon the gravimetric (θ_g) and volumetric (θ_v) moisture content [74], bulk density, organic matter content [75], soil texture [57] and specific heat of soil. Among them, the soil moisture content has three major impacts on microwave heating: (1) moisture increases the soil surface reflectivity [76], which ultimately reduced the microwave penetration into the soil [28]; (2) moist soil readily absorbs the microwave energy to generate heat [28] thus less total microwave energy propagated into the soil; and (3) moisture is also responsible for heat-diffusing phenomena in the soil profile [77].

It has been reported that the dielectric constant (ε') of known soil at known θ_g is proportional to the bulk density of soil. The dependence of soil dielectric constant on bulk density is described by the direct dependence of bulk density on fraction of soil moisture volume [78]. The textural composition of soil (particles sizes distribution) affects the dielectric constant (ε'). The higher percentage of clay particles (with bulk density range of 1.0–1.6 g cm^{-3}) increases the dielectric constant of soil [79]. This might be due to higher water holding capacity of clay particles. Therefore, this will increase the absorption of microwave energy by soil for its synchronized functions.

The temperature profile is dependent on the microwave electric field strength (E) within the soil. Brodie [56] has extensively studied the temperature distribution in soil due to microwave energy application through a horn antenna. The temperature profile can be described by Eq. (1). The Nomenclature of Eq. (1) is presented in **Table 3**.

$$T = \frac{n\omega\varepsilon_o\kappa''\left(e^{4\gamma\alpha^2 t}-1\right)}{4k\alpha^2}\left[e^{-2\alpha z}+\left(\frac{h}{k}+2\alpha\right)ze^{-z^2/4\gamma t}\right]\left[\tau\int_{\frac{-B}{2}}^{\frac{B}{2}}\int_{\frac{-A}{2}}^{\frac{A}{2}}\cos\left(\frac{\pi}{A}x'\right)\frac{e^{-j\beta_o\left(\sqrt{(x-x')^2+(y-y')^2+z^2}+\sqrt{R_0^2+(x')^2}+\sqrt{R_0^2+(y')^2}\right)}}{\sqrt{(x-x')^2+(y-y')^2+z^2}}.dx'.dy'\right]^2 \quad (1)$$

Figure 5 compares measured temperature distributions with those predicted by Eq. (1). The highest temperature in the microwave-treated soil was along the centre line of horn antenna and between the 0.02 and 0.05 m below the soil surface. **Figure 6** illustrates the effects of microwave soil treatment using a different system configuration and treatment scenario.

3.3. Effect on soil

3.3.1. Effect of microwave energy on nutritional dynamic of soil

The dynamic of soil key nutrients (Carbon, Nitrogen, Phosphorus, Potassium and Sulphur) is explained by the knowledge of size and turnover rate of plant biopolymers such as C-N compounds, cellulose and hemicellulose and lignin [81]. The soil-microwave interaction is the function of various soil properties such as texture, moisture, salinity, bulk density and temperature [58, 78, 79]. Cooper and Brodie [82] investigated the effect of different durations

Weed parameters	Treatments		LSD	Percentage change from control
	microwave treatment	Untreated control	(p = 0.05)	
Weed density (plants $plot^{-1}$)	17.6^a	94.8^b	37.7	−80%
Weed fresh weight (g $plot^{-1}$)	156.4^a	612.8^b	426.6	−74.6%
Weed dr. Weight (g $plot^{-1}$)	21.6^a	122.6^b	69.6	−82%

Table 2. Effect of microwave energy application for weed seedbank depletion in direct seeded-rice crop under filed conditions in Australia (adapted from [16]).

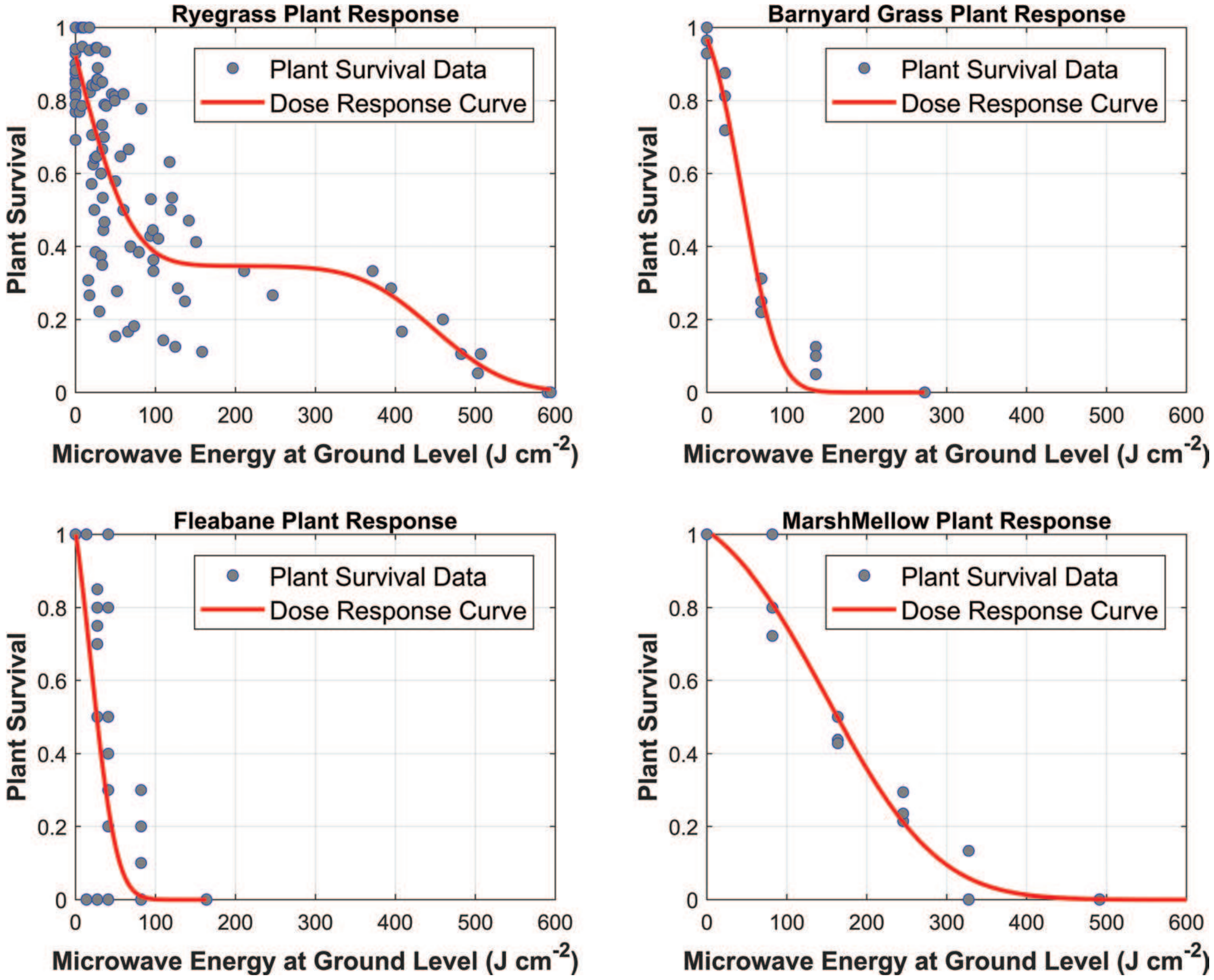

Figure 4. Dose-response curves for microwave treatment of four herbicides resistance weed species using a horn antenna. Source: Khan et al. [25].

of microwave treatment and soil depth on soil nutrient status and pH. They found that microwave treatment of soil had no significant effect on nitrogen, phosphorus, potassium and sulphate concentrations in all the treatment combination, but they reported an increase in nitrite concentration after 120 s of microwave treatment of soil. The nitrate reduction in the irradiated soil could be the principle cause of nitrite formation [83], in their study.

Speir et al. [84] examined the effect of microwave energy on low fertility soil (100 randomly selected cores at depth of 50 mm), microbial biomass, N, phosphorus and phosphatase activity. They reported that an increase in microwave treatment duration (90 s) dramatically increased the N level (106 μg N g^{-1} soils) but the phosphorus concentration declined as treatment time increased. The higher flush in soil N is of microbial origin as microwave has a biocidal effect [85, 86]. The fixation of NH_4^+ or K^+ in soil by inorganic colloids has been well documented [87]. Kittrick [88] hypothesized that the ion fixation in the clay lattice could be described by the expanding and contracting forces in the interlayer position. The contraction is due to electrostatic force of attraction between negatively charged clay mineral and positively charged ions and ion hydration causes the expansion. Fixation occurred when the force of attraction

Parameter	Meaning
n	Scaling factor for simultaneous heat and moisture movement [80]
ω	Angular frequency of electromagnetic wave (rad s^{-1})
ε_o	Permittivity of free space
κ''	Dielectric loss factor
τ	Transmission coefficient of the soil surface
E	Electric field strength (V m^{-1})
γ	Combined diffusivity for simultaneous heat and moisture transfer
α	Field attenuation factor in the soil (m^{-1})
t	Time (s)
A	Width of antenna aperture (m)
B	Height of antenna aperture (m)
Ro	Length of antenna (m)
k	Thermal conductivity of the composite material (W m^{-1} $°C^{-1}$)
x, y, z	Cartesian coordinates of a point in front of the horn antenna (m)
x′, y′	Cartesian coordinates of a point in the aperture of the antenna (m)

Table 3. Nomenclature of mathematical terms.

dominated the cations' hydration energy. Zagal [89] pointed out that the mechanical effect induced by microwave irradiation can stimulate the dispersion of inorganic colloids. This stimulation can increase the decomposition of non-biomass organic matter in soil and release the fixed $NH4^+$. Yang et al. [90] tested the nutrient extractability effect of microwave energy on soil. When fresh soil was exposed to microwave energy, a dramatic increase in the NH_4^+-N concentration was observed for an extended treatment of 120 s. They concluded that this effect was partially from nonmicrobial processes, either from site exchange or from fixed position in inorganic collides (clay minerals).

Alphei and Scheu [91] evaluated the effects of various biocidal treatments on mull-structured soil biota and nutritional dynamics. They reported the survival of soil microorganisms; in particular, higher concentration of ammonium nitrogen and phosphorus was observed when soil was subjected to microwave treatment at high power. The increase in soil C and N mineralization [89] and NH_4^+-N and sulphur oxidation was reported by Wainwright et al. [92]. In contrast, numerous studies documented that the effect of ionizing irradiation (γ-rays) on soil effectively increased the mineralization of NH_4^+-N [93, 94]. They proposed three possible pathways which may be responsible for the release of NH_4^+-N from soil through irradiation: (1) ammonia could be produced by the chemical action of ionizing radiation through a variety of biochemical processes from nitrogenous organic compounds, particularly deamination of amino acid [95] and proteins, (2) several enzymes were functional in irradiated soil including urease, which is active during decomposition and produces ammonia and (3) release of N from dead organisms due to subsequent cell lysis by irradiation [96].

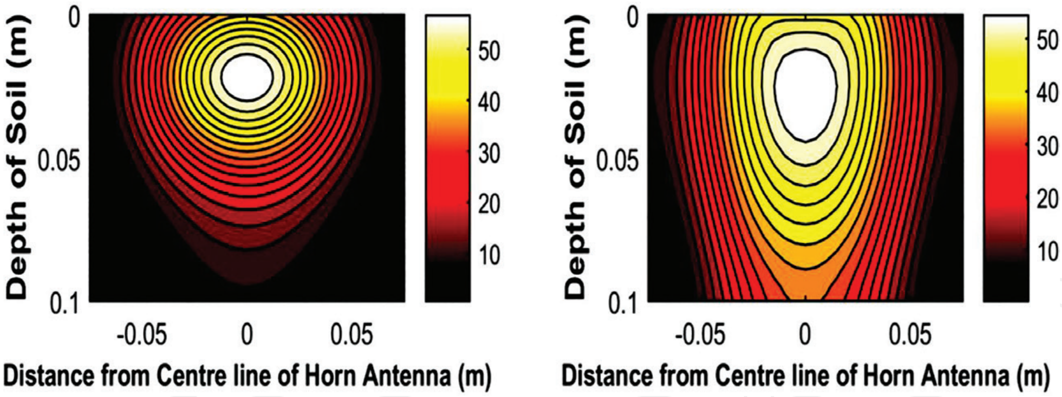

Figure 5. Comparison of expected soil temperature profile with measured soil temperature profile (left) and for the 750 W prototype microwave unit after 150 s of heating. Adapted from [56].

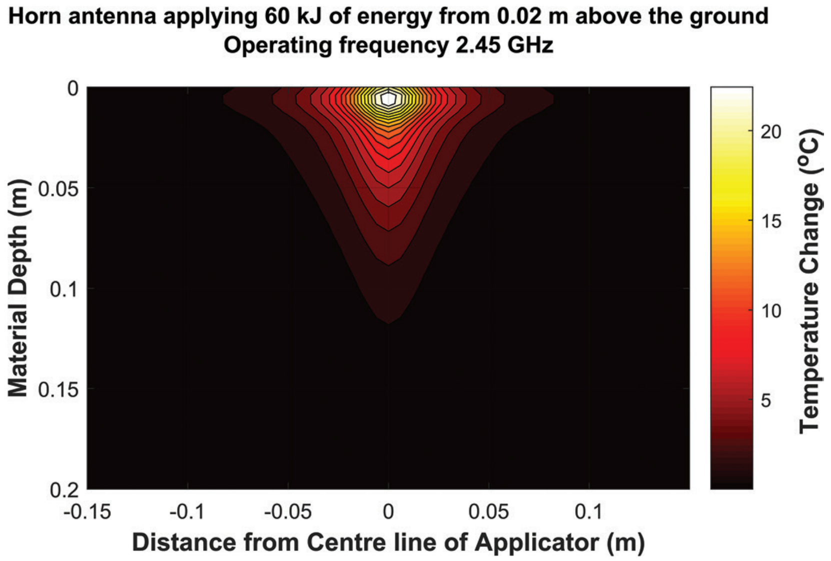

Figure 6. Estimated change in soil temperature treated from the 2 kW microwave system after 30 s with horn antenna at 2 cm above the soil. Adapted from [56].

Soil organic matter (SOM) is an aggregate of organic residues in soil at different degrees of humification [97]. Various biopolymers are serially transferred to humus (fulvic acid, humic acid and humin) in soil through geological SOM development processes such as humification [98]. Protein is the basic structural component of cell and cellular enzymes [99]. Approximately 5–25% of organic inputs are expected to accumulate in soil as proteins, peptides and free amino acids [100]. Amino acids typically incorporate about 10–20% of soil organic carbon and 30–40% of soil org-N [100]. Thermal denaturation of biopolymers induced by microwave irradiation could increase the concentrations of free amino acids for succeeding turnover to CO_2 and ammonia pool NH_4^+. Hur et al. [101] demonstrated that microwave irradiation of soil can enhance the binding efficiency of hydrophobic organic containments with SOM. They irradiated 5 g samples of soil in plastic tubes in aerobic and anaerobic conditions with activated C for 600 s in a lab-scale microwave oven (2.45 GHz) operated at 700 W. They pointed out that MW irradiation significantly alters the physical and chemical properties of SOM and increased its humification. Kim and Kim [24] studied the influences of microwave irradiation on the SOM properties. They reported that thermal cracking induced by irradiation scenario potentially alters the molecular composition (C, H, O and N), chemical structure and humification of SOM. The results of these studies suggest that microwave soil heating has potential to maximize the crop yield.

3.3.2. Enzyme activity as a function of microwave soil heating

Enzymes are essential to ecosystem processes because they arbitrate innumerable reactions that have biogeochemical importance in soil [102]. It has been demonstrated that *in vitro* exposure of microbial cells to microwave energy increased cell membrane permeability [103], released DNA and protein [104], soluble carbohydrate concentration [105] and inhibited growth of cells [106]. The enzymatic activity, selectivity and stability could be improved through high-frequency electromagnetic energy in an aqueous medium [107]. d'Ambrosio et al. [108] found that acid phosphatase was highly stable to the microwave deactivation energy of 280 mW g^{-1}. The hydration state and polarity of the reaction medium directly influenced the enzyme functionality under microwave irradiation. Notably, Carrillo-Munoz et al. [109] performed two lipases esterification reactions in a mono-mode microwave system at temperature of 100°C. They found that a 2–9% higher yield and 2.1–2.5-fold increment increase in protease activity [110] were obtained in microwave conditions compared to conventional heating in the hydration state. Furthermore, Yadav and Lahi [111] investigated the influence of microwave on lipase activity in a highly polar solvent and concluded that microwave noticeably accelerated the enzymatic reaction with an increase in hydrophobicity. Pirogova et al. [112] tested the effect of low frequency microwave energy, in the range of 500–900 MHz and at various power levels (1, 0.1 and 0.01 μW) on the activity of l-lactate dehydrogenase in solution for 300 s. They found a 73% increase in the bioactivity of the studied enzyme in microwave-irradiated samples compared to nonirradiated samples. Asadi et al. [113] tested the physiology of cyanobacterium (*Schizothrix mexicana*) against low power microwave modulation of various frequencies; they found that 9.685 GHz significantly increased growth metabolisms. Dreyfuss and Chipley [114] documented that metabolic enzyme activity of *S. aureus* increased after microwave irradiation. The cell biopolymer excitation induced by MW exposure was suggested to alter the enzymes' functionality.

Kothari et al. [115] studied the effect of low-power microwave on protease and urease activity of nine microorganisms (Bacteria, yeast and fungi). They treated enzyme cultures for different durations (0, 120, 240 and 360 s) in a microwave oven and concluded that the significant increase in the enzymes' activity was an athermal effect of microwave energy on the metabolism of the organisms. Numerous previous studies have shown higher enzymatic activity of industrial importance as a function of microwave in various reaction media at a temperature range of 70–110°C [107] and soil enzymes that are resistant to denaturation stress by heat [116, 117]. In contrast, Yeargers et al. [118] investigated the effect of microwave and conventional heating methods on the sensitivity of two enzyme (lysozyme and trypsin) solutions and found no discernible difference in enzyme activity, but the lysozyme was slightly more heat resistant than trypsin. Elzobair et al. [119] reported that microwave energy of 800 J g^{-1} of soil decreased (<10 nmolg^{-1} h^{-1}) dehydrogenase enzyme activity but 3200 J g^{-1} increased (>20 nmolg^{-1} h^{-1}) its functionality.

3.3.3. Influence of microwave soil heating on soil microbes

Soil biota is known to survive under severe physio-chemical environmental changes [120–122]. Microwave heating of soil can eradicate soil-borne fungi with minimal reduction of prokaryotic organisms [123]. Microbial cell response to microwave irradiation depends on the location, power density, time, frequency, pulses and physiology of cells. The nitrogen fixing bacteria persist, even after relatively high energy dosages. Vela and Wyss conducted a microwave heating experiment on soil *Azotobacter* and found that they survived microwave exposure of 480 s in very moist soil while, they were inactivated after only 20 s of treatment in laboratory culture conditions. Vela et al. [124] found that soil-nitrifying bacteria were highly resistant to microwave energy applied at the rate 40,000 J cm^{-2} to the soil surface. However, nitrifiers (mesophilic) are much more sensitive to high temperature than ammonifying (thermophilic) bacteria. This implies that native habitat and intrinsic environment are the most important factors in resistance of soil organisms to microwave irradiation [125]. Soil bacterial communities are resistant to microwave energy; some scientists concluded that the soil shelters microflora, while others discovered that the rate of proliferation causes resistance. This rate of proliferation is determined by nutrient concentrations. The heat-shock activation of the soil bacterial community was reported by Vela et al. [124]. Bacteria can form various thermal-resistance structure (i.e., spore and cysts), which keep them resistant against harmful effects of physical environments [126]. Based on work done by Hollins [127], she reported that a sharp reduction in colony forming unit of *E. colie* with 10 s of treatment of 2.3 kg soil (**Figure 7**), treated through 2 kW microwave system under horn antenna and complete soil sterilization was achieved through 120 s of irradiation.

3.4. Effect on crop growth

Rice productivity is strongly influenced through weed management strategies. Recently, a field experiment was conducted to evaluate the effect of pre-cropping microwave soil heating for weed seedbank depletion in direct-seeded rice crop based on the above soil heating methodology [16]. In addition to weed suppression (**Table 1**), the application of microwave energy (2.45 GHz; 120 s; 560 J cm^{-2}) into soil significantly ($P = 0.05$; **Table 4**) increased the tiller density (419 m^{-2}), dry biomass yield (27.8 t ha^{-1}) and grain yield (9.0 t ha^{-1}) of rice, compared to the untreated control scenario 292 m^{-2}, 22.8 t ha^{-1} and 6.7 t ha^{-1}, respectively. These results are strongly supported with findings of Brodie [128], who found that in pot trial maximum rice grain yield was attained with energy application of 600 J cm^{-2} to soil before crop sowing. The higher crop productivity could be attributed to 70–80% reduction in weed establishment achieved through microwave irradiation of soil, ultimately leaving more room for crop growth. 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. [129] 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 temperature regime (70–80°C) that was acquired by microwave 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.

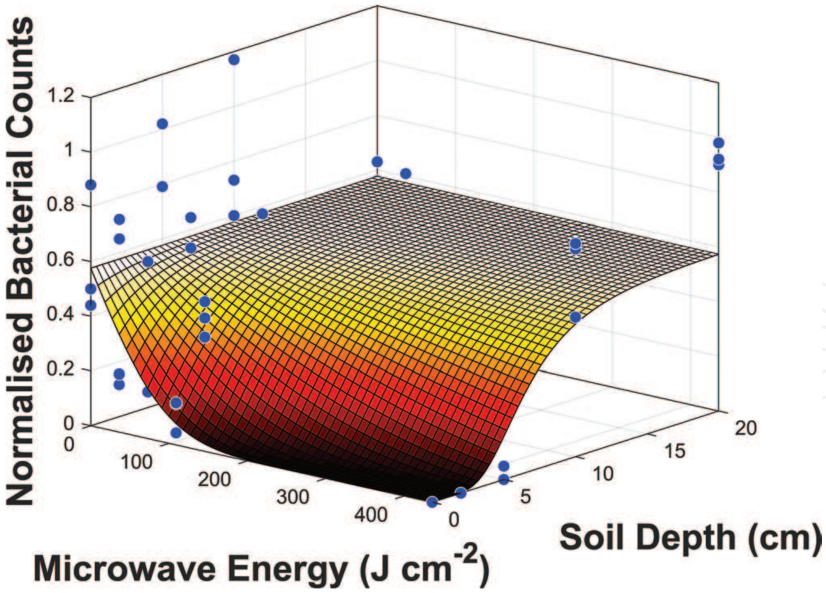

Figure 7. Assessment of E. coli survival in top 2 cm of soil as a function of applied microwave energy (Source: [127]).

For further validation of this yield changing effect with microwave soil heating, two field trials were conducted during October, 2016 to April, 2017 in a randomized complete block design with five replications at two different locations. The first location Dookie Campus of the University of Melbourne (36.395°S, 145.703°E) is a central grain growing region of the Goulburn Valley, which is in north of the state of Victoria, Australia; part of this region grows temperate rice. This region has a temperate climate with an average annual rainfall of 575 mm and an average monthly temperature range of 9.4–20.9°C (Australian Bureau of Meteorology). Soil at this experimental site is medium clay and classified as an Upotipotpon Clay [130] or an Orthic Basic Rudosol [131]. Historically, the same paddock has since been used for sheep grazing and highly invaded with a numerous grass species. The second location Old Coree, Jerilderie, New South Vales (35.210 °S, 145.440 °E) is the rice research farm a totally owned property of the Rice Research Australia Pty. Ltd. – SunRice™. Soil was treated using a prototype 2 kW microwave system, it has four independently controlled, 2 kW microwave generators operating at 2.45 GHz. The trailer is powered from two on-board 7 kVA, three-phase electrical generators [25]. Treatment was applied for 60 s and the temperature achieved through microwave energy application into soil was about 70–75°C in top soil layer (0–5 cm) at both study locations. Brodie reported that the microwave energy application to soil of about 400–500 J cm^{-2} gave 1.2–1.5 t extra grain yield compared to untreated control soil (**Figure 8**). The same range of microwave energy has used to treat the soil in the above field experiments. Therefore, the microwave soil treatment for pre-emergence weed suppression gave substantial increase in rice crop yield at both study location (**Table 4**; **Figures 9** and **10**). This is an additional benefit of soil heating through MW energy; we assumed that temperature has influenced on the soil nutrient profile particularly nitrogen.

3.5. Evaluation of rice crop production potential

Sustainable production of rice crop is the present need of the agriculture sector to fulfil increasing demand. In general, herbicide resistance, lower water use efficiency and

Rice parameters	Dookie location 1					Jerilderie location 2				
	Treatments		LSD $_{(p = 0.05)}$	P-value	Percentage change	Treatments		LSD $_{(p = 0.05)}$	P-Value	Percentage change
	Microwave treated	Untreated control				Microwave treated	Untreated control			
Number of tillers (m^{-2})	387 a	268 b	62.0		44.4%	480 a	418 a	145.2	0.29	44.4%
Dry biomass weight (t ha^{-1})	16.90 a	14.0 a	4.2	0.14	20.7%	19.80 a	17.05 b	0.57	<0.001	16.1%
Grain yield (t ha^{-1})	3.88 a	2.56 a	1.76	0.12	51.5%	9.21 a	7.63 b	0.65	<0.001	20.7%
Harvest Index	22.3 a	17.4 a	8.08	0.19	6.1%	46.77 a	44.59 a	4.29	0.26	6.1%
¥Water use efficiency (t Ml^{-1})	1.3	0.85	—	—	—	3.07	2.54	—	—	—
ψPartial factor productivity of nitrogen (kg rice grain per kg application of N)	31.04	20.42	—	—	—	73.68	61.04	—	—	—

Note: different letters in a row reflecting a significant difference at 5% probability level.Note: different letters in a row reflecting a significant difference at 5% probability level.

ψPartial factor productivity of nitrogen (PFP) $= \frac{Y_0}{N_r} + \frac{\Delta Y}{N_r} = \frac{Y_0}{N_r} + \frac{\Delta Y}{N_r}$, change in crop yield with nitrogen application was calculated based on work done by [132]. Note: Applied nitrogen during cropping period was 125 kg N ha^{-1} at both study locations.

¥Water use efficiency was calculated based on the change in grain yield per unit application of water. Note: Irrigation water volume was about 3 Ml ha^{-1} as per recommendation of Ricegrowers Association of Australia.

Table 4. Influence of pre-sowing microwave soil heating for weed seedbank depletion on rice productivity at two different agro-ecological zones of the Australia.

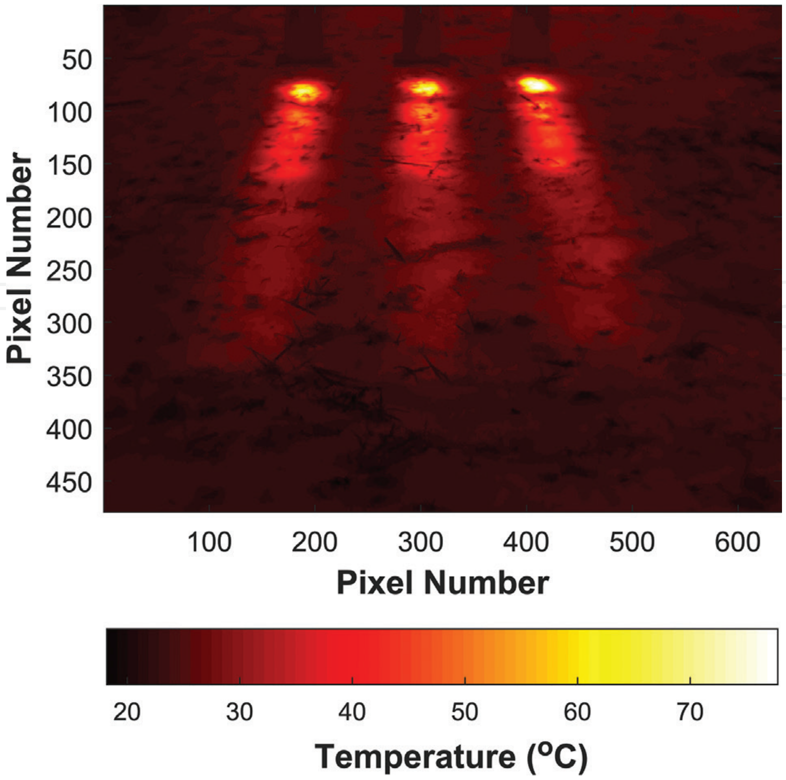

Figure 8. Infrared thermal images of microwave treated plot for weed seedbank depletion in rice crop under field conditions.

Figure 9. Comparison of early growth establishment of rice crop. Plants on left collected from microwave treated plot and plants on right collected from untreated control plot. (Left image taken from Dookie Trial Site and right image taken from Old Coree, Jerilderie site).

nitrogen use efficiency are key sustainability limiting factors, globally. For herbicide resistant weed suppression, Khan et al. [16] compared a microwave energy cost in rice crop with pre-sowing soil fumigation [133, 134] and reported that in terms of fuel

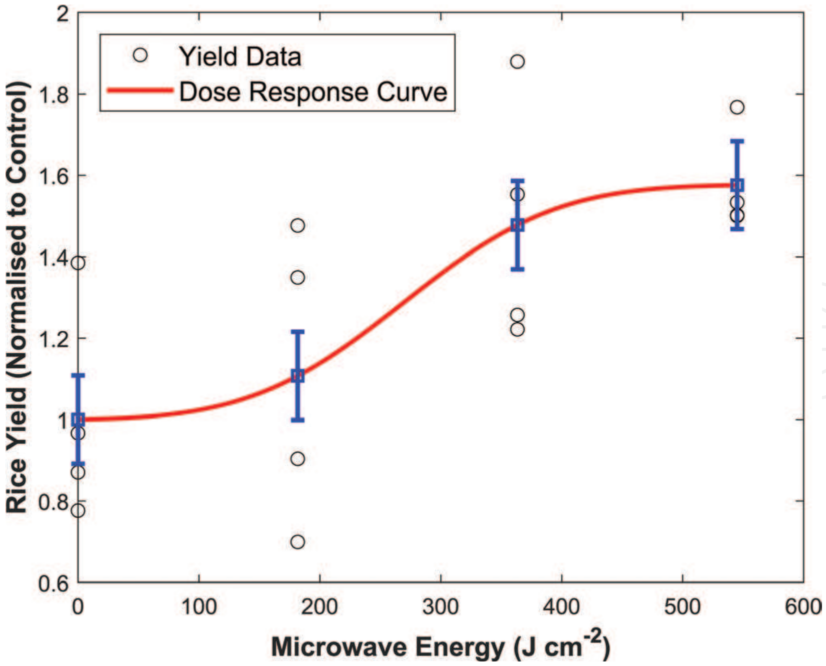

Figure 10. Relative increase in rice grain yield as a function of applied microwave energy. Source: [128].

consumption, the microwave system used in their study was quite comparable or better than soil fumigation and soil steaming treatment done by Samtani et al. [135]. Higher rice crop productivity without soil nutrient depletion has been confirmed with microwave soil heating methodology with an average of 20–50% increase under field conditions (**Table 4**). The microwave soil heating did not significantly alter the grain mineral concentration of rice (**Figure 11**), which suggests that higher yield producing crops effectively utilize the yield-changing nutrients from the soil. Based on this estimate, the profitability of rice production through this technology is better than conventional weed control technology. In other domain, however, soil health and persistence effects of the treatment for up to two growing seasons give an additional productivity advantage to rice farming community.

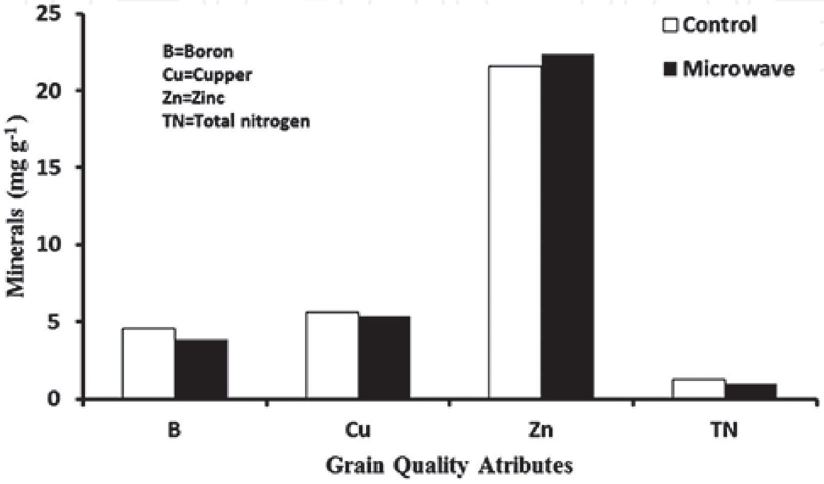

Figure 11. Effect of microwave soil heating on quality related parameter of rice grain. Adapted from [16].

4. Discussion

Weed seedbank is a resting place of dormant seeds in the top soil horizon. Various biotic and abiotic factors have a tremendous effect on seed viability. Among the many abiotic factors, however, soil temperature has an ability to debilitate weed seeds *in situ* [136, 137]. Therefore, it was hypothesized that the projection of non-ionizing energy into a top soil layer through a horn antenna may cause thermal devitalisation of weed seeds. The results of field studies have strongly supported our hypothesis and achieved about 70–80% reduction in rice weeds establishment. Overall, energy of a microwave system for weed management program has a direct relationship with application duration. Therefore, for a pre-emergence weed control under field conditions, Wayland et al. [44] reported an energy level of $80 < \mathrm{J\ cm^{-2}} < 160$, which is quite low compared to the present investigation. In contrast, for a post-emergence weed control Sartorato et al. [54] tested the efficacy of microwave energy on seedling of *Abutilon theophrasti* and *Panicum miliaceum*. They reported that an energy range of $101.5 < \mathrm{J\ cm^{-2}} < 343.3$ gave significant reduction in dry weight of about 90%. However, it is highly unlikely that certain set of MW energy may give a same control spectrum, because soil moisture [74] and seed geometry [38, 67] have a considerable influence on microwave absorption. These vary according to cropping system.

Independent of soil heating methodology for weed control; various studies also reported the profound effect of high temperature on weed establishment. Gay et al. [133] reported on a soil steaming experiment with various duration (0, 6, 8 and 10 min) in a soil, to depths of about 1.5–16.5 cm, giving a temperature gradient of 100–37°C (decreasing with depth), in a lettuce crop for weed control. They found an average weed density of less than 50 plants $\mathrm{m^{-2}}$ in the case of soil steam treated plots compared to untreated control plots (400 plants $\mathrm{m^{-2}}$). Vidotto et al. [129] found that exposure of a soil-seed mixture to high temperature gradually decreased seed germination. Almost all the tested weed species seeds were completely devitalized through soil thermal treatment at a temperature between 70°C and 80°C.

The same temperature distribution was achieved through microwave application in the present study, which might have a degrading effect on the weed seedbank and ultimately led to a significant weed reduction. Therefore, based on previous findings and the results of this study, it may be possible to minimize the weed pressure through microwave irradiation of soil in no-till wheat production systems of Australia. However, a further research effort is needed to understand the long-term effects of microwave soil irradiation for weed control in crops. Furthermore, the fuel cost associated with a pre-sowing microwave weed management has been previously estimated by Khan et al. [16], therefore, about 0.98 L diesel $\mathrm{m^{-2}}$ were consumed in their experiment. Samtani et al. [135] calculated the fuel cost for pre-sowing steam treatment for weed control and reported a diesel consumption of between 0.81 and 2.16 L $\mathrm{m^{-2}}$. Considering the fuel consumption, the MW system used in the present investigation for soil heating was comparable or even better than soil steaming used by Gay et al. [133] and Samtani et al. [135].

In addition to weed suppression, a few previous studies have reported the supplementary effect of microwave energy on soil nutrient dynamics; Yang et al. [90] tested the nutrient extractability effect of microwave on soil. When fresh soil was exposed to microwave energy a dramatic increase in the $\mathrm{NH_4^+}$-N concentration was observed for an extended treatment of 120 s. They concluded that this effect was partially from nonmicrobial processes, either from site exchange or from fixed position in inorganic collides (clay minerals). Hur et al. [101] demonstrated that microwave irradiation of soil can enhance the binding efficiency of hydrophobic organic containments with soil organic matter. They irradiated 5 g samples of soil in plastic tubes in aerobic and anaerobic conditions with activated C for 600 s in a lab-scale microwave oven (2.45 GHz) operated at 700 W. They pointed out that MW irradiation significantly alters the physical and chemical properties of soil organic matter and increased its humification. In another study, Kim and Kim [24] studied the influences of microwave irradiation on the soil organic matter properties. They reported that thermal cracking induced by irradiation potentially alters the molecular composition (C, H, O and N), chemical structure and humification of soil organic matter. Based on these previous findings, we assumed that thermal denaturation of recalcitrant humic substance induced by microwave irradiation may increase the concentrations of free amino acids for succeeding turnover to CO_2 and ammonia pool NH_4^+, which might have substantially increased wheat productivity in the present investigation. Moreover, microwave soil heating gave 10 times higher nitrogen use efficiency and about 20–50% higher irrigation water use efficiency in those field experiment conducted to manage the herbicides resistance weeds.

5. Conclusion

Based on these experiments, we conclude that microwave weed and soil treatment can be implemented as an alternative method of weed control in direct-seeded rice crop. Additional benefit of this technology has prompted a motivation for further research in this area to enhance sustainability in agricultural industry.

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