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Original Article

Radiofrequency thermal control of *Sitophilus oryzae* L. (Coleoptera: Curculionidae) in stored new rice for Africa

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Abstract

Insect pest control in stored agricultural produce has mainly been done by chemical fumigation in sub-Saharan Africa. The demand for human and environmentally safe foods has made this practice unacceptable, making the search for non-chemical alternatives a global research priority. The impact of radio frequency (RF) heat treatment was studied on the various developmental growth phases of *Sitophilus oryzae* in stored New Rice for Africa (NERICA). After exposure to 27.12 MHz RF at 50 °C for 3 min, only the egg stage recorded 100% mortality. The adult stage of the weevil was the most RF tolerant, but nonetheless, 100% mortality was achieved after exposure to 27.12 MHz RF at 55 °C for 4 min. For economic energy management, taking into consideration the economic strength of farmers, exposure to 27.12 MHz RF at 60°C for 3 min was the most energy-efficient, consuming as little as 0.462 KWh energy to completely kill *S. oryzae*. Analysis of the quality parameters of the rice after exposure to 27.12 MHz RF at 60°C for 3 min revealed no significant quality changes in moisture, protein, free fatty acid, and ash contents. The results have provided a vivid basis for the development and use of RF treatment as a non-chemical energy-efficient alternative for controlling *S. oryzae* in NERICA. RF control could be the needed technical post-harvest protection approach, considering its low labour involvement, minimum energy requirement, and cost-effectiveness, needed to propel Ghana and Sub-Saharan Africa to become competitive in the global rice industry.

Keywords: NERICA, insect control, *Sitophilus oryzae*, radiofrequency thermal, temperature, tolerance

1. Introduction

The Africa Rice Centre (WARDA) in 1999 combined disease (e.g., rice yellow mottle virus, African gall midge, etc.) and pest (e.g., *Sitophilus oryzae, Sitophilus zeamais, Rhizopertha dominica*, etc) resistance traits by an interspecific crossing of the African rice *Oryza glaberrima* Steud. and Asian rice, *Oryzae sativa* L. (Jones, Dingkuhn, Aluko, & Semon, 1997) in order to improve rice production in Africa. This was necessary because *O. glaberrima* was low yielding compared *O. sativa*, though it was also more resistant to environmental stress, namely diseases and pests (Chang, Loresto, & Tagumpay, 1972). From this, WARDA released seven varieties in the year 2000 and named them New Rice for Africa (NERICA). Seven NERICA genotypes were named and released by WARDA in 2000, and eleven more varieties were later characterized and released according to their field performance test (WARDA, 2002). Since then, NERICA has become a popular brand in sub-Saharan Africa (SSA) with about 150,000-200,000 ha of land under production in Uganda, Cote de Ivoire, Guinea, Kenya, Congo, Nigeria, Togo, Mali, and Ghana (WARDA, 2002). Farmers in SSA were introduced to the NERICA varieties through the Community-Based Seed Systems (CBSS) and Participatory Varietal Selection (PVS).

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NERICA varieties are claimed to have disease and pest resistance, drought tolerance and weed competition with higher grain yield over their *O. sativa* parents. However, the sustainable cultivation of these varieties in the agro-ecologies of Africa is still hampered by storage insect pest infestation. According to Ashamo (2006), about 800 insect species infest rice in the field and at storage. Insect pests such as *Sitophilus oryzae*, *Sitophilus zeamais*, *Rhizopertha dominica*, and *Sitotroga cereallela* infest rice grains at storage and in distribution. Predominantly *S. oryzae* causes severe economic damages through quantitative and qualitative losses, which results in seed viability loss (Ashamo, 2006; Prasertsri, 2012). The invasion of milled rice threatens the rice food chain and leads to huge losses, as eight months of infestation makes the grains unfit for human consumption (Prakash, Rao, Pasalu, & Mathur, 1987). *S. oryzae* often invades the seeds in the field before harvesting, and rapidly multiplies at storage, leading to severe damage losses due to its direct feeding habit, and stimulation of fungal contamination. Shivakoti and Manandhar (2000) reported a lifetime daily grain consumption and waste product production of 0.49 mg and 11-12 mg for this insect. Banerjee and Nazimuddin (1985) mentioned that a single *S. oryzae* insect can cause 57% grain damage losses, while Joshi, Karmacharya and Khadge (1991) reported a 15% yearly storage grain loss. To worsen the situation, external infesters whom under normal conditions cannot infest sound seeds turn to do so due to the damages caused by *S. oryzae* larvae. The control of this insect pest is essential to save seed viability, food energy, nutritional value, and to secure marketability at future dates.

Methyl bromide (MeBr) fumigation has generally been the popular method to control *S. oryzae*, but this method was phased out in 2004 due to its attributed negative health and environmental effects (Krittigamas, Vearasilp, von Hoersten, & Luecke, 2012). Alternatively, the use of phosphine gas became popular but it's highly flammable, as well as toxic with easy absorbability and distribution throughout the human body. Besides, a long exposure time of 7-30 days is required for effective fumigation (Lv *et al*., 2006). To compound the problems, Benhalim *et al*., (2004) and Krittigamas *et al*., (2012) found that *S. oryzae* have become resistant to phosphine. In developing countries, the use of fumigants has been restricted since 2010 (United States Environmental Protection Agency **[**USEPA**]**, 2001; World Meteorological Organization, 1995). As a result, the conventional heat treatment of grains before storage has nowadays gained global popularity (Lagunas-Solar *et al*., 2005; Wang *et al*., 2003). Though this approach has proven effective with less human and environmental harm, yet it is difficult to control surface overheating. The method is energy and time consuming, and does not kill insects quickly (Lagunas-Solar *et al*., 2005). One method that has shown effectiveness in controlling rice weevil and also overcame the problems of the conventional heat treatment approach is the Radio Frequency (RF) heat treatment. According to Lagunas-Solar *et al*., (2005), RF effectively avoids surface overheating, consumes less energy and time, and also quickly controls rice weevils when compared to the conventional heat treatment. The NERICA varieties have given hope to rice production in SSA and contribute significantly to the drop in rice importation, but the storage damages caused by *S. oryzae* retard the economic gains of the rural poor farmers. RF treatment has been not much tested on African rice varieties in general, and specifically NERICA has not yet been tested.

In light of the above, this investigation aims to determine the effectiveness of RF to kill *S. oryzae* and also to estimate the appropriate RF heating range suitable to control *S. oryzae* with minimum damage to grain quality.

2. Methodology

2.1 Research location and materials

The investigation was carried out at the Faculty of Agriculture, Natural Resource and Environment, Naresuan University-Thailand. The location is at the GPS coordinates 16.7465° N, 100.1933° E (Figure 1). Unpolished NERICA 3 seeds were sourced from the Savanna Agricultural Research Institute, Ghana. This variety was used for the test because it is highly susceptible to *S. oryzae* infestation (Badii, Asante, & Adarkwa, 2013). The rice seeds were cold sterilized at -20 ºC for 72 hours to kill any available insects. The seeds were afterwards calibrated to room temperature and stored at 14% moisture content for the study. A detailed description of the NERICA 3 variety is shown in Table 1. Grain length, grain width, amylase content, moisture content, and 1000 seeds weight were measured. Grain length and width were measured with a Vernier caliper. Amylase percentage was determined by spectrophotometry (Avaro, Pan, Yoshida and Wada, 2011) and oven drying method was adopted to estimate moisture content (AOAC, 2006). A thousand seeds were randomly counted and weighed for 1000 seeds' weight. Adult *S. oryzae* parental stock was obtained from the Udon Thani Rice Research Center, Thailand.

Figure 1. Research location (Retreived from https://www.google.com/search?client=firefox-b-d&q=16°44'47.4"N+100°11'35.9"E

2.2 Testing insects production

S. oryzae production testing was done according to Swella and Mushobozy, (2009). The parental *S. oryzae* adults were mass bred in a growth chamber on 1500 g of rough rice seeds under 28 ± 2 °C and 75 ± 5% ambient temperature and relative humidity, respectively. 100 pairs of adult *S. oryzae* were transferred onto the 1500 g seeds in a well-ventilated covered jar. Mating and oviposition were allowed for four continuous days. Afterwards, the insects were removed from the seeds, and seeds on which eggs were laid were transferred

Table 1. Detailed description of NERICA 3 variety

Varieties	Grain length (mm)	Grain width (mm)	Grain size	Coat colour	Amylose content (%)	Moisture content (%)	1000 seeds weight (g)
NERICA 3	7.1	2.3	Long	White	23.9	13.0	30.0

with a pooter into a new kilned jar. The jar was well sealed with a white cotton cloth, fastened tightly by a rubber band. The four growth stages (eggs, larvae, pupae, and adults) of *S. oryzae* were harvested from the egg-infested seeds for the test following the method of (Singh, 2017).

2.3 Experimental procedure

The research was done in two steps: Step 1

The egg-infested seeds were examined under a stereomicroscope, and seeds containing only one visible egg-plug were selected. The moisture content of the seeds at this stage was 13%. 50 seeds with visible egg plugs were harvested on day 4, and 50 seeds with larvae and pupae were also harvested on day 12 and 26, respectively. On the 35th day, 25 pairs of the fully grown adult *S. oryza*e were harvested. These various developmental stages of the insect were added to 200 g sterilized NERICA 3 seeds and exposed to heat treatment with a radio frequency of 27.12 MHz at 50°C for 3 min. The purpose was to find out which developmental stage of *S. oryzae* was the most tolerant to RF thermal treatment. After the treatment, the seeds for the various stages were stored under the same conditions above for 5 weeks for any surviving insect in the egg, larval, and pupal stage to develop into an adult. This was because, at the egg, larval, and pupal stages, the insects reside inside the seeds, and mortality could only be assessed after the emergence of the surviving insects. Insect mortality was then estimated as in Equation 1 (Abbott, 1925).

$$\text{Mortality (\%)} = \frac{\text{\%mortality in treatment - \%mortality in control}}{\text{100 - \%mortality in control}} \text{ x 100} \qquad (1)$$

The insects that survived the RF heat treatment were reared on sterilized rice and allowed to mate and oviposit. A control untreated experiment was also set up for comparison. The eggs laid and progeny emergence was examined. The resistibility rate of progenies for the various stages was computed from Equation 2 (Keteku, Badii and Sowley, 2020).

$$\text{Resistibility rate (\%)} = \frac{Cn - Tn}{Cn} \text{ x 100} \qquad (2)$$

with Cn representing the total emerged insects in the control and Tn representing the total emerged insects in the treatment samples. The RF treatment setup is illustrated in Figure 2.

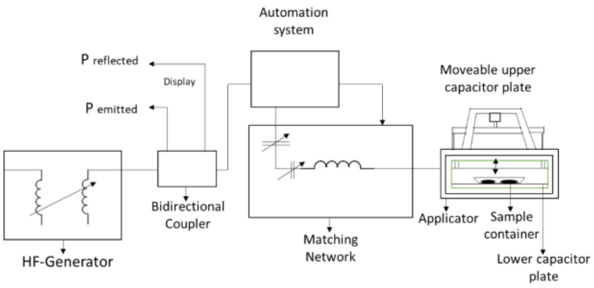

Figure 2. Radiofrequency system setup

The research was done in two steps: Step 2

Adult infested rice sample was treated in RF heat of 27.12 MHz at five different temperatures and four exposure times of 50, 55, 60, 65, and 70 ºC and 1, 2, 3, and 4 min, respectively. Fifty insects were used for each of the factorial treatment combinations. The purpose was to elucidate the minimum temperature and time that effectively kills the most tolerant *S. oryzae* stage. The methods of AOAC (2006) were followed to estimate moisture, protein, free fatty acid, and ash contents immediately after RF treatments for quality assessment. The electrical energy (E_{el} Wh) used by the various RF heat treatments was also estimated as in Equation 3.

$$\text{Electrical energy } (E_{el}\ Wh) = \text{Electrical power } (P_{el}\ W) \text{ x Time } (t) \qquad (3)$$

2.4 Statistical analysis

Square root and arcsine transformations were used on numerical and percentage data. The data were analysed with Statistical Package for Social Sciences (SPSS), version 21, following Fisher's method of Analysis of Variance (ANOVA). Critical differences were compared at $p \leq 0.05$ wherever the F value was significant (Panse & Sukhatme, 1985). Duncan's Multiple Range Test was performed and the results are shown in tables with 'a' indicating the highest value (Duncan, 1955).

3. Results and Discussion

3.1 Response of *S. oryzae* development stages to RF heat treatment

The effects of 27.12 MHz radiofrequency at 50°C for a 3 min holding duration on *S. oryzae* are shown in Table 2. A significant variation ($p \leq 0.05$) was noted among the mortality and progeny emergence (5 weeks of storage after RF treatment) of the various developmental stages of the weevil. Mortality in the control untreated seeds did not vary by the insect's developmental stage but in the RF treatments, the eggs and larvae were the most susceptible. A 100% mortality occurred at the egg stage followed by 97.6% in the larvae. The moisture content of the insects influenced heat absorption and transmission. When exposed to an RF treatment, the insects containing a higher moisture heat up faster (Mitcham *et al*., 2004). Although the water contents of the insect at these stages was not measured in this experiment, Wang *et al*., (2005) and Nelson and Trabelsi (2009) have shown that the moisture content is higher at the egg and larval stages. The direct interaction between the moisture and RF energy at these

Table 2. Response of *S. oryzae* growth phases exposed to 27.12 MHz RF at 50°C for 3 min

Growth phase	Mortality		Progeny		Resistibility rate (%)
	Untreated control	RF treatment	Untreated control	RF treatment	
Egg	3.51±1.63^{a}	100.00^{a}	26.85±3.43^{a}	0.00^{d}	0.00^{d}
Larva	5.53±1.61^{a}	97.55±1.48^{a}	16.88±3.46^{b}	1.23±0.26^{b}	9.76±0.58^{b}
Pupa	6.48±2.10^{a}	89.35±2.71^{b}	21.10±2.23^{b}	2.30±0.45^{b}	10.20±1.24^{b}
Adult	4.54±1.71^{a}	81.65±2.93^{c}	28.68±2.27^{a}	4.83±1.25^{a}	11.94±1.25^{a}
CD ($p \leq 0.05$)	ns	3.28	4.48	1.25	1.72

Note: Data are shown as average ± SD. Column averages followed by similar superscript letters ($^{a, b, c}$) are not significant at $p > 0.05$ (n = 4); SD = standard deviation; CD = critical difference between averages; ns = non-significant.

stages enables directly heating the insects. This rapidly increases the internal temperature of the insect due to the water's dielectric properties (Nelson & Trabelsi, 2009; Wang *et al*., 2005). This caused the insects to heat up faster than the rice they infest. The weevil's adult and pupal stages were the most RF tolerant and recorded lower mortalities of 81.65% and 89.35%, respectively. This observation can be attributed to the exoskeleton and lower moisture contents at these stages. The join cuticle or exoskeleton of coleopterans has a low moisture, and this decreases heat absorption and transmission within the insect, making the adults more tolerant to heat than pupae and larvae (Chapman, 1998; Yoder, Chambers, Tank, & Keeney, 2009). Related results were found by Faikrajaypuan, Chanbang and Verasilp, (2011) for *S. zeamais* in maize and by Sumetha, Chanbang, Hengsawad and Krittigamas, (2009) for *Rhyzopertha dominica*, the lesser grain borer at 27.12 MHz radiofrequency at 50°C for 180s. The weevils that survived the RF treatment were bred and allowed to reproduce. The number of emerged progenies were significantly lesser in the RF treated seeds than in the control. The average number of progenies was 1.23 and 2.30 for the larval and pupal stages, respectively, lesser compared to the adult stage (4.83), due to the greater number of adults that survived exposure to RF treatment. In this study, we observed that most of the eggs laid by the survived weevils from the various development stages did not hatch. RF heat had raptured their sperm cells, ovarian tissue, and spermatozoa, which reduces egg number, egg size, and hatchability rate (Krittigamas *et al*., 2012; Nelson, 1996; Rai, Ball, Nelson, & Stetson, 1974, 1977). Rai *et al*., (1974) also reported lower fecundity in mealworm (*Tenebrio molitor*) after exposure to 39.0 MHz RF thermal treatment. Similarly, less progenies were recorded after treating Angoumois grain moths, *S. cerealella* with 49.6±0.1ºC RF heat in rough rice (Buapud, Chanbang, & Verasilp, 2012). The resistance offered by the weevil against RF destruction in our study was highest (11.94%) in the adults, 10.20% in pupae, and 9.76% in the larvae (Table 2). The egg stage of the weevil was completely killed by 27.12 MHz RF at 50°C for 3 min.

3.2 Response of adult *S. oryzae* to different RF temperatures and durations

Because the adult growth stage was the most tolerant to 27.12 MHz RF at 50°C for 3 min, the adult stage was selected and studied under varying temperatures and times to determine the minimal effective temperature and time combination that can completely kill the most tolerant *S. oryzae*. Higher temperature and exposure time significantly increased *S. oryzae* mortality (Table 3). After exposure to RF heat treatment, complete 100% mortality of the adult was recorded at 55°C for 4 min, 60 ºC for 3 – 4 min, 65ºC for 3 – 4 min, and 70ºC for 2 min and over. The minimum temperature that completely killed the adult weevils was 55 ºC at a minimum exposure time of 4 min. The surviving insects laid eggs that hatched into progenies, and significantly fewer numbers of eggs were counted in the RF treatments compared to the control (Table 4). This situation is explained by the fewer number of surviving adults left in the treatment samples and the effects of heat on reproduction. Even though some adults survived after exposure to 27.12 MHz RF at 60 and 65 ºC for 1 - 2 min, those weevils could not lay eggs. A similar observation was recorded at 70 ºC for 1 min. The rate of mortality increased and the number of eggs laid decreased as temperature and exposure time increased. Insect mortality could be due to a reduction in oxygen as carbon dioxide increases with rising temperature. The oxygen demand further reduces the thermal resistance of the insect (Yan, Haungi, Zhu, Johnson and Wang, 2014). Less mortality with more laid eggs was counted at 50 ºC when compared to the other temperatures. Progeny emergence was active in 50 ºC for all the exposure times and in 55 ºC for 1 - 2 min (Table 5). Again, the minimum temperature that completely stops the surviving adult weevils from laying eggs was 55 ºC at a minimum exposure time of 4 min. However, no progenies emerged after the 55 ºC for 3 min treatment. Thus although the surviving weevils under 55 ºC for 3 min laid eggs, the eggs were not viable, but this cannot be considered as minimum temperature and time because there wasn't 100% adult mortality and the fewer surviving adults can still cause grain damage through feeding activities. The result showed that a minimum temperature and exposure time of 55 ºC for 4 min completely killed *S. oryzae* in rice. Moreover, a temperature above 55 ºC for 3 min will cause 100% mortality of *S. oryzae* adults. This treatment is of lower or similar exposure time and temperature than that of other insect pests of rice. Yan *et al*., (2014) similarly reported complete adult *S. oryzae* mortality at temperatures above 50 ºC. Our findings also concur with previous works conducted on other insect pests. Luechai, Chanbang and Krittigamas, (2008) reported 100% mortality of the rice moth, *Corcyra cephalonica*, at 60°C for 3 min. According to Buapud *et al*., (2012) the pupal stage of the Angoumois grain moth was the most RF tolerant and complete mortality occurred at 72.1 ± 0.4°C for about 4 min. The RF heat treatment that completely kills *Rhyzopertha dominica* is at least 70°C for 3 min (Sumetha *et al*., 2009). The authors further mentioned that a temperature of 73°C or

Table 3. Mean insect adult mortality after exposure to 27.12 MHz radiofrequency at different temperatures for varied times

Temperature (ºC)	Time			
	1 min	2 min	3 min	4 min
50	53.61±2.43^{g}	71.99±3.33^{f}	80.91±2.08^{e}	93.44±3.10^{c}
55	91.27±2.38^{d}	97.20±1.31^{b}	98.83±0.17^{ab}	100.00^{a}
60	98.64±1.20^{ab}	99.37±0.71^{a}	100.00^{a}	100.00^{a}
65	99.58±0.43^{a}	99.82±0.13^{a}	100.00^{a}	100.00^{a}
70	99.16±0.45^{ab}	100.00^{a}	100.00^{a}	100.00^{a}

Note: Data are shown as average ± SD. Column and row averages followed by similar letters ($^{a, b, c, d, e, f, g}$) are not significant at $p > 0.05$ ($n = 4$); SD = standard deviation.

Table 4. Mean eggs oviposition by the surviving adults exposed to 27.12 MHz radiofrequency at different temperatures and time

Temperature (ºC)	Time			
	1 min	2 min	3 min	4 min
Untreated control	23.98±6.19^{a}	24.98±5.25^{a}	22.93±8.04^{a}	23.75±4.50^{a}
50	12.80±3.19^{b}	10.43±2.25^{bc}	6.28±1.72^{bcd}	2.15±0.66^{d}
55	2.80±0.73^{d}	1.80±0.43^{d}	0.88±0.16^{d}	0.00
60	0.00	0.00	0.00	0.00
65	0.00	0.00	0.00	0.00
70	0.00	0.00	0.00	0.00

Note: Data are shown as average ± SD. Column and row averages followed by similar superscript letters ($^{a, b, c, d}$) are not significant at $p > 0.05$ ($n = 4$); SD = standard deviation.

Table 5. Mean progeny emergence after 5 weeks storage of the survived adult *S. oryzae* exposed to 27.12 MHz radiofrequency at different temperatures and times

Temperature (ºC)	Time			
	1 min	2 min	3 min	4 min
Untreated control	27.38±2.28^{a}	24.75±3.77^{a}	25.70±3.51^{a}	25.83±2.48a
50	7.60±1.74^{b}	4.13±0.37^{c}	2.43±0.17^{cd}	1.48±0.13^{cd}
55	1.00±0.22^{d}	0.55±0.38^{d}	0.00	0.00
60	0.00	0.00	0.00	0.00
65	0.00	0.00	0.00	0.00
70	0.00	0.00	0.00	0.00

Note: Data are shown as average ± SD. Column and row averages followed by similar superscript letters ($^{a, b, c, d}$) are not significant at $p > 0.05$ ($n = 4$); SD = standard deviation.

above for a minimum holding time of 220s may kill all rice storage pests.

3.3 Energy requirement for RF heat control

The results in Table 6 represent the energy required for the various temperatures and times of RF treatments. Energy consumption increased with temperature and exposure time from 50 to 70 ºC and from 1 to 4 min, respectively. Among the combinations, 60 ºC at 3 min consumed the least energy of 0.462 KWh while reaching 100% adult insect mortality, followed by 70 ºC at 2 min (0.463 KWh). The most energy (0.687 KWh) was consumed by 70 ºC at 4 min. The energy consumed by RF treatment was lower as an advantage over other heat treatment methods. For instance, Wiset, Srzednicki, Driscoll, Nimmuntayin, and Siwapornrak (2001) reported a high energy consumption coupled with low drying efficiency and poor after-treatment product quality for the conventional hot-air treatment method. The RF system supplied higher heat for a shorter duration and caused insignificant grain damage. Similar observations have been made (Cheenkachorn, 2007; Taweerattanapanish, Soponron narit, Wetchakama, Kongseri, & Wongpiyachon, 1999). In Ghana, stored rough rice moisture content is about 14%, hence RF treatment can offer an effective alternative to control storage pests. The low energy consumption of the RF treatment method is ideal for Sub-Saharan African due to the weak economic strength of rice farmers and the higher price of energy. When established on large scale, the cost per RF treatment will be reduced and becomes affordable to farmers.

3.4 Quality characteristics of rice after exposure to 27.12 MHz RF at 55 °C for 4 min.

The quality parameters of the rice before and after exposure to 27.12 MHz RF at 60 °C for 3 min are shown in Table 7. Based on our results, RF treatment did not significantly ($p \leq 0.05$) influence the quality parameters of rice. Grain moisture and free fatty acid contents decreased slightly after the treatment to 12.23% and 4.17%, respectively, but

Table 6. Energy requirement (kWh) for RF heat control at different temperatures and times

Temperature (ºC)	Time			
	1 min	2 min	3 min	4 min
50	0.126	0.238	0.350	0.462
55	0.182	0.294	0.406	0.518
60	0.238	0.350	0.462	0.574
65	0.294	0.406	0.518	0.630
70	0.351	0.463	0.575	0.687

Table 7. Quality characteristics of rice after exposure to 27.12 MHz RF at 60 °C for 3 min

Treatment	Moisture content (%)	Protein (%)	Free fatty acid (%)	Ash (%)
Control	13. 00	6.79±0.10	4.48±0.24	0.283±0.004
RF	12.23±0.09	6.81±0.40	4.17±0.13	0.285±0.005
$p \le 0.05$	ns	ns	ns	ns

Note: Data are shown as average ± SD. (n = 4); SD = standard deviation; ns = non-significant.

were comparable to the control. Protein and ash contents increased slightly to 6.81% and 0.285%, respectively. Suhem, Matan, Nisoa and Matan, (2013) also reported a 0.3 %w.b reduction in rice water content after RF treatment. Theanjumpol, Thanapornpoonpong, Pawelzik, and Vearasilp (2007) similarly found no significant difference in rough rice water content after RF treatment at 45, 60, 75, and 90 ºC for 3 min. Suhem *et al*., (2013) and Zhou and Wang (2016) consistently found that low-pressure RF treatment does not significantly alter rice protein and ash contents. Some other previous studies reported that fatty acid content does not change significantly immediately and/or within 2 months after RF treatment (Suhem *et al*., 2013; Zhao, Xiong, Qiu, & Xu, 2007; Zhong *et al*., 2013; Zhou, & Wang, 2016). The rice colour also did not change as per our physical observation. This tendency agrees with the findings of (Suhem *et al*., 2013).

4. Conclusions

The radiofrequency treatment proved effective in controlling *S. oryzae* at all the 4 developmental stages (eggs, larvae, pupae, and adults). After exposure to 27.12 MHz RF at 50°C for 3 min, only the egg stage recorded 100% mortality. The adult stage of the weevil was the most RF tolerant, but a 100% mortality was achieved by exposure to 27.12 MHz RF at 55 °C for 4 min. For economic energy management, taking into consideration the economic strength of farmers, exposure to 27.12 MHz RF at 60°C for 3 min was the most energy-efficient alternative, consuming as little as 0.462 KWh energy to completely kill adult *S. oryzae*. Analysis of the quality parameters of the rice after exposure to 27.12 MHz RF at 60°C for 3 min revealed no significant quality changes in moisture, protein, free fatty acid, or ash contents. The results have provided a vivid basis for the development and use of RF treatment as a non-chemical energy-efficient alternative for controlling *S. oryzae* in the New Rice for Africa (NERICA). RF control could be the needed technical post-harvest protection approach, considering its low labour involvement, minimum energy requirement, and cost-effectiveness, needed to propel Ghana and SSA to become competitive in the global rice sector.

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