3 A Brief Overview of Radio Frequency and Microwave Applications in Agriculture

There is great potential for using radio frequency and microwave technologies to solve problems associated with agricultural production. Studies have been undertaken to use radio frequency and microwave energy: to improve crop handling, storage and preservation; to provide pest and weed control for agricultural production; for food preservation and quarantine purposes; for land survey; for automatic data acquisition and communication; and for preconditioning of products for better quality and more energy efficient processing. This chapter is concerned with radio frequency and microwave applications in the agricultural industries for purposes other than human food processing. Many of these applications will be more fully explored in subsequent chapters.

3.1 Heating Applications

3.1.1 Crop Drying

Many studies have investigated the application of radio frequency and microwave energy to speed up crop and wood drying (Manickavasagan, et al. 2006, Setiady, et al. 2009). Microwave drying provides an alternative to traditional drying methods. Polar molecules are affected by radio frequency and microwave radiation; therefore polar molecule, such as free water, in a given matrix can be directly heated (Beary 1988). Bound water molecules are more difficult to volatilize because the fixed bond inhibits rotation (Beary 1988).

Microwave drying is a rapid drying technique that can be applied to specific foods, particularly high value products such as fruits and vegetables (Zhang, et al. 2006). Increasing concerns over product quality and production costs have motivated industry to adopt radio frequency and microwave drying technologies. The advantages of these systems include: shorter drying time, improved product quality, and flexibility in producing a wide variety of dried products (Zhang, et al. 2006); however current applications are limited to small categories of fruits and vegetables due to high start-up costs and relatively complicated technology as compared to conventional convection drying (Zhang, et al. 2006).

3.1.2 Quarantine

Dried timber, nuts and fruits are commonly treated by chemical fumigation to control field and storage pests before being shipped to domestic and international markets.
Because chemical fumigants such as methyl bromide are no longer available (Carter, et al. 2005), there is a heightened interest in developing non–chemical pest control. An important key to developing successful thermal treatments is to balance the need for complete insect mortality with minimal impact on the product quality. A common difficulty in using conventional hot–air disinfection is the slow heating rate, non–uniform temperature distribution, and possible heat damage to heat–sensitive commodities (Wang, et al. 2003). A more promising approach is to heat the commodity rapidly using radio frequency (RF) or microwave dielectric heating to control insects (Nelson 2001, Wang, et al. 2003).

Interest in controlling insects, using electromagnetic energy, dates back nearly 70 years. Headlee (1929, 1931), cites one earlier report of experiments determining lethal exposures for several insect species to 12 MHz electric fields and the body temperatures produced in honey bees due to dielectric heating. Nelson (1996) has shown that microwaves can kill insects in grain; however one of the challenges for microwave insect control is to differentially heat the insects in preference to the grain that surrounds them. Nelson (1996) shows that differential heating depends on microwave frequency. It appears that using a 2.45 GHz microwave system, which is the frequency used in domestic microwave ovens, heats the bulk grain material, which then transfers heat to the insects; however lower frequencies heat the insects without raising the temperature of the surrounding material beyond 50 °C (Nelson 1996).

Nzokou et al (2008) investigated the use of kiln and microwave heat treatments for the sanitisation of emerald ash borer (Agrilus planipennis Fairmaire) infested logs. Their microwave treatment method was conducted in a 2.8 GHz microwave oven (volume: 0.062 m³, power: 1250 W) manufactured by Panasonic (Panasonic Co., Secaucus, New Jersey). Due to the limited volume of the microwave oven, two runs were necessary to treat logs assigned to each microwave treatment temperature. Their results showed that a temperature of 65 °C was successful at sanitising the infested logs. Microwave treatment was not as effective as kiln treatment, probably because of the uneven distribution of the microwave fields and temperature inside the treated logs. This uneven temperature distribution is partly due to the nature of microwave heating, but may also be due to their choice of microwave chamber used during their experiments.

Park, et al. (2006) studied the survival of microorganisms after heating in a conventional microwave oven. Kitchen sponges, scrubbing pads, and syringes were deliberately contaminated with wastewater and subsequently exposed to microwave radiation. The heterotrophic plate count of the wastewater was reduced by more than 99 percent within 1 to 2 minutes of microwave heating. Coliform and E. coli in kitchen sponges were completely inactivated after 30 seconds of microwave heating. Bacterial phage MS2 was totally inactivated within 1 to 2 minutes, but spores of Bacillus cereus were more resistant than the other microorganisms tested, requiring 4 minutes of irradiation for complete eradication.
Microwave heating for quarantine control of pests in dry materials, such as wood, has been accepted internationally. This technology is now recognised by the Food and Agriculture Organisation (FAO) and implemented in the “International Standards for Phytosanitary Measures” (ISPM 15) (Bisceglia, et al. 2009).

A prototype for continuous pasteurisation of liquids and fruit preparations using radio frequency heating techniques has been available for several years. The product is pumped inside Teflon pipes and then heated up when it passes through the electromagnetic field generated between two facing metallic plates. The product is uniformly and quickly heated at the rate of 1°C/sec. As with many radio frequency and microwave heating applications, these systems provide faster product processing, better temperature control, and better energy efficiency than conventional pasteurisation processes (Meggiolaro 2014).

### 3.1.3 Effect of Microwave Heating on Seeds and Plants

Interest in the effects of high frequency electromagnetic waves on biological materials dates back to the late 19th century, while interest in the effect of high frequency waves on plant material began in the 1920’s (Ark and Parry 1940). In many cases, short exposure of seeds to radio frequency and microwave radiation resulted in increased germination and vigour of the emerging seedlings (Tran 1979, Tran and Cavanagh 1979); however, long exposure usually resulted in seed death (Bebawi, et al. 2007).

Davis et al. (Davis, et al. 1971, Davis 1973) were among the first to study the lethal effect of microwave heating on seeds. They treated seeds, with and without any soil, in a microwave oven and showed that seed damage was mostly influenced by a combination of seed moisture content and the energy absorbed per seed. Other findings from their studies suggested that both the specific mass and specific volume of the seeds were strongly related to seed mortality (Davis 1973). This could be due to the “radar cross-section” (Wolf, et al. 1993) presented by seeds to propagating microwaves. Large radar cross-sections allow the seeds to intercept, and therefore absorb, more microwave energy. The geometry of many seeds can be regarded as ellipsoids or even spheres, so the microwave fields are focused into the centre of the seed. Therefore larger seeds focus more energy into their core, which results in higher temperatures at the centre of the seed, leading to higher mortality rates. Seeds whose geometry can be approximated as being cylindrical will also focus more energy into their core as their dimensions increase.

Microwaves can kill a range of weed seeds in the soil (Davis, et al. 1971, Davis 1973, Brodie, et al. 2009), however fewer studies have considered the efficacy of using microwave energy to manage already emerged weed plants. Davis et al. (1971) considered the effect of microwave energy on bean (Phaseolus vulgaris) and Honey Mesquite (Prosopis glandulosa) seedlings. They discovered that plant aging had little effect on the susceptibility of bean plants to microwave damage, but honey mesquite’s
resistance to microwave damage increased with aging. They also discovered that bean plants were more susceptible to microwave treatment than honey mesquite plants.

Bigu-Del-Blanco, *et al.* (1977) exposed 48 hour old seedlings of *Zea mays* (var. Golden Bantam) to 9 GHz radiation for 22 to 24 hours. The power density levels were between 10 and 30 mW cm\(^{-2}\) at the point of exposure. Temperature increases of only 4 °C, when compared with control seedlings, were measured in the microwave treated specimens. The authors concluded that the long exposure to microwave radiation, even at very low power densities, was sufficient to dehydrate the seedlings and inhibit their development. On the other hand, recent studies on fleabane (*Conyza bonariensis*) and paddy melon (*Cucumis myriocarpus*) (Brodie, *et al.* 2012a, b) have revealed that a very short (less than 5 second) pulse of microwave energy, focused onto the plant stem, was sufficient to kill these plants.

In weed control, microwave radiation is not affected by wind, which extends the application periods compared with conventional herbicide spraying. Energy can also be focused onto individual plants without affecting adjacent plants (Brodie, *et al.* 2012b). This would be very useful for in-crop or spot weed control activities. Microwave energy can also kill the roots and seeds that are buried to a depth of several centimetres in the soil (Diprose, *et al.* 1984, Brodie, *et al.* 2007).

### 3.1.4 Microwave Treatment of Animal Fodder

Hay is an important feed source for ruminant animals so every effort should be made to improve its feed conversion efficiency and reduce the risk of importing weed seeds as hay is transported from one location to another. Similarly, cereal grains are the base of most horse rations, because they are a valuable source of digestible energy; however their use is always associated with some risk.

The major concern when feeding cereal grains to horses is the risk of incomplete starch digestion in the small intestine, which enables significant amounts of starch to pass through to the caecum and colon. When starch is able to reach these organs it rapidly ferments producing an accumulation of acidic products, which place the horse at risk of developing serious and potentially fatal illnesses such as laminitis, colic and ulcers (Bird, *et al.* 2001).

Dong *et al.* (2005) discovered that organic matter degradability of wheat straw in the rumen of yaks was increased by around 20% after 4 min of treatment in a 750 W, 2.54 GHz, microwave oven. Sadeghi and Shawrang (2006a) showed that microwave treatment of canola meal increased *in vitro* dry matter disappearance, including substances that were deemed to be ruminally undegradable. Sadeghi and Shawrang (2006b) also showed that microwave treatment reduced the rumen degradable starch fraction of corn grain and decreased crude protein degradation of soya-bean meal (Sadeghi, *et al.* 2005) compared with untreated samples. No studies of microwave treatment of horse feeds could be found in the available literature.
Small scale *in vitro* pepsin-cellulase digestion experiments (Brodie, *et al*. 2010), similar to the technique developed by McLeod and Minson (1978, 1980), demonstrated that microwave treatment: increased dry matter percentage with increasing microwave treatment time; increased *in vitro* dry matter disappearance with increasing microwave treatment time; but had no significant effect on post-digestion crude protein content.

When 25 kg bags of lucerne fodder were treated in an experimental 6 kW, 2.45 GHz, microwave heating chamber (Harris, *et al*. 2011) were subjected to a similar *in vitro* pepsin-cellulase digestion study, dry matter disappearance significantly increased compared to the untreated samples; however there was no significant difference attributable to the duration of microwave treatment. Feeding 12-14 month old Merino sheep on a “maintenance ration” of microwave treated Lucerne resulted in a significant increase in body weight instead of the relatively constant body weight that would be expected from a maintenance ration. By the end of the 5 week feeding trial the control group was only 0.4 % heavier than when they started, which would be expected from a maintenance ration. However the group being fed the microwave treated lucerne gained 7 % of their initial body weight in the second week of the trial and maintained this body weight until the end of the trial. Their finishing weight after 5 weeks was 8.1 % higher than their starting weight (Brodie, *et al*. 2010).

### 3.1.5 Microwave Assisted Extraction

During microwave assisted extraction (MAE), plant materials such as wood, seeds and leaves are suspended in solvents and the mixture is exposed to microwave heating instead of conventional heating. Enhanced rates of plant oil extraction have been observed for a range of plant materials. Chen and Spiro (1994) examined the extraction of the essential oils of peppermint and rosemary from hexane and ethanol mixtures and found that yields were more than one third greater in the microwave assisted extractions. Saoud *et al*. (2006) studied MAE of essential oils from tea leaves and achieved higher yields (26.8 mg/g) than conventional steam distillation (24 mg/g).

Chemat *et al*. (2005) studied the extraction of oils from limonene and caraway seeds and found that MAE led to more rapid extraction as well as increased yields. Scanning electron microscopy of the microwave treated and untreated seeds revealed significantly increased rupture of the cell walls in the treated seeds. MAE also led to a more chemically complex extract, which was thought to be a better representation of the true composition of the available oils in caraway seed.

Industrial scale microwave assisted extraction systems have been developed and used in several countries. Several approaches to industrial microwave-assisted extraction techniques have been developed. These include: continuous-flow reactors; small-scale batch stop-flow protocols; or large-scale single-batch reactors (Hoz, *et al*. 2011).
One of the limitations of microwave scale-up technology is the restricted penetration depth of microwave irradiation into absorbing materials (Hoz, et al. 2011). This means that solvent or reagents in the centre of large reaction vessel are heated by convection and not by direct ‘in core’ microwave dielectric heating (Brodie 2008a).

Although less well described in the literature, an alternative approach for utilizing microwave heating of plant based materials has been to treat the materials with microwave energy prior to conventional extraction processes (Miletic, et al. 2009). Microwave preconditioning of sugar cane prior to juice diffusion studies led to significant decreases in colour and significant increases in juice yield, Brix %, purity and Pol % (Brodie, et al. 2011). Microwave treatment significantly reduced the compression strength of the sugar cane samples (Brodie, et al. 2011), especially while the cane was still hot from the microwave treatment. This treatment option reduced the compressive strength of the cane to about 18 % of its original strength, implying that much less energy would be required to crush the cane for juice extraction.

### 3.1.6 Microwave Assisted Pyrolysis and Bio-fuel Extraction

Three different thermo-chemical conversion processes are possible, depending on the availability of oxygen during the process: combustion (complete oxidation), gasification (partial oxidation) and pyrolysis (thermo-chemical degradation without oxygen). Among these, combustion is the most common option for recovering energy. Combustion is also associated with the generation of carbon oxides, sulphur, nitrogen, chlorine products (dioxins and furans), volatile organic compounds, polycyclic aromatic hydrocarbons, and dust (Fernandez, et al. 2011); however gasification and pyrolysis offer greater efficiencies in energy production, recovery of other compounds and less pollution.

Most studies of pyrolysis behaviour have considered lingo-cellulosic materials, which comprise of a mixture of hemicellulose, cellulose, lignin and minor amounts of other organic compounds. While cellulose and hemicelluloses form mainly volatile products during pyrolysis due to the thermal cleavage of the sugar units, lignin mainly forms char since it is not readily cleaved into lower molecular weight fragments (Fernandez, et al. 2011). Wood, crops, agricultural and forestry residues, and sewage sludges (Dominguez, et al. 2005) can be subjected to pyrolysis processes to recover valuable chemicals and energy.

Conventional heating transfers heat from the surface towards the centre of the material by convection, conduction and radiation; however microwave heating is a direct conversion of electromagnetic energy into thermal energy within the volume of the material (Metaxas and Meredith 1983). In microwave heating, the material is at higher temperature than its surroundings, unlike conventional heating where it is necessary for the surrounding atmosphere to reach the desired operating temperature before heating the material (Fernandez, et al. 2011). Consequently, microwave heating
favours pyrolysis reactions involving the solid material, while conventional heating improves the reactions that take place in surroundings, such as homogeneous reactions in the gas-phase (Fernandez, et al. 2011). In microwave heating, the lower temperatures in the microwave cavity can also be useful for condensing the final pyrolysis vapours on the cavity walls.

Microwave assisted pyrolysis yields more gas and less carbonaceous (char) residue, which demonstrate the efficiency of microwave energy (Fernandez, et al. 2011). The conversion rates in microwave assisted pyrolysis are always higher than those observed in conventional heating at any temperature. The differences between microwave heating and conventional heating seems to be reduced with temperature increase, which points to the higher efficiency of microwave heating at lower temperatures (Fernandez, et al. 2011).

Bio-fuel extraction is facilitated when microwave energy is used to thermally degrade various organic polymers to facilitate extraction of sugars for fermentation (Tsubaki and Azuma 2011). These sugars can then be fermented and distilled to create fuel alcohols. Woody plant materials are commonly subjected to microwave assisted bio-fuel extraction; however other materials such as discharge from food processing industries, agriculture and fisheries can also be processed using these techniques. Other materials that have been subjected to microwave assisted bio-fuel extraction include: soybean residue; barley malt feed; tea residues; stones from Japanese apricots; corn pericarp, which is a by-product from corn starch production; and Makombu (*Laminaria japonica*), which is a kind of brown sea algae.

### 3.2 Sensor Applications

#### 3.2.1 Assessment of Wood

Early non-destructive detection of biological degradation in wood, such as decay or termite attack, is important if remedial treatments are to be effective. Wood and wood based materials are relatively transparent at microwave frequencies (Torgovnikov 1993, Daian, *et al.* 2005); however their level of transparency decreases as moisture or other materials are added to the wood. Conversely, wood’s transparency increases as wood material is softened due to fungal decay or other biological degradation.

When microwaves are transmitted through wood (Figure 3.1), the wave will be partially reflected, attenuated and delayed compared to a wave traveling through free space (Lundgren 2005, Brodie 2008b). Wave attenuation; reflections from the surface; and internal scattering from embedded objects or cavities causes a “shadow” on the opposite side of the material from the microwave source. An x-ray image is a good example of the information that can be derived from wave attenuation and phase delay measurement.
The transparency of wood, or any other material, to electromagnetic waves is linked to the complex dielectric properties of the material under study (James 1975, Torgovnikov 1993, Olmi, et al. 2000). The real part of the complex dielectric properties determines the wave length of the electromagnetic wave inside the object and therefore influences the speed of wave propagation through the object. The imaginary part of the complex dielectric properties determines the amount of energy that the material will absorb from the wave as it travels into or through the object.

![Figure 3.1: Schematic of a simple “look through” system for assessing wood status using microwave energy (Source: Brodie, et al. 2014).](image)

### 3.2.2 Radar Systems

Active sensors provide their own source of energy to illuminate the target. Active sensors are generally divided into two distinct categories: imaging and non-imaging. The most common form of active imaging sensor is RADAR.

Non-imaging sensors include altimeters and scatterometers. Radar altimeters transmit short microwave pulses and measure the round trip time to targets to determine their distance from the sensor (Canadian Centre for Remote Sensing 2003). Scatterometers are used to make precise quantitative measurements of the amount of energy reflected from targets. The amount of reflected energy is dependent on the
surface properties (roughness) and the angle at which the energy strikes the target (Canadian Centre for Remote Sensing 2003).

RADAR is an acronym for **RAdio Detection And Ranging** (Connor 1972). Radar is essentially a ranging or distance-measuring device. It consists of a transmitter, a receiver, an antenna, and an electronics system to process and record the data (Connor 1972). The transmitter generates successive short bursts (or pulses) of microwave energy at regular intervals, which are focused by the antenna into a beam (Connor 1972).

In the case of terrain imaging radar, the radar beam is projected at right angles to the motion of the aircraft or satellite platform at an oblique angle to the terrain and reflects back to the source. This is similar to the flash of a camera. The antenna receives a portion of the reflected energy (or backscatter) from various objects within the illuminated beam (Sabins 1987, Drury 1998, Canadian Centre for Remote Sensing 2003). By measuring the time delay between the transmission of a pulse and the reception of the echo from different targets, their distance from the radar and thus their location in the resulting image can be determined (Sabins 1987, Drury 1998, Canadian Centre for Remote Sensing 2003).

One of the more useful features of radar is that the speed of moving objects can be determined with considerable accuracy. Doppler shift is the apparent change in wavelength (or frequency) of an electromagnetic or acoustic wave when there is relative movement between the transmitter and the receiver. This effect is commonly noticeable when a whistling train or police siren passes by. An observer in front of the moving car or train hears a higher pitch than a passenger in the vehicle. Similarly, the passenger hears a higher pitch than an observer behind the vehicle. Doppler can also affect the frequency of a radar carrier wave, the time between pulses of a radar signal, or even light waves causing an apparent shift of colour.

Ground penetrating radar (GPR) has been used for over twenty years at chemical and nuclear waste disposal sites as a non-invasive technique for site characterization. Standard GPR surveys are conducted from the surface of the ground providing geotechnical information from the surface to depths of 2 to 15 m, depending on GPR’s operating frequency and soil conductivity. Commercially available GPR systems operate over the frequency range from 50 MHz to 1,000 MHz.

Lower frequencies provide better penetration into the soil but poor resolution, while the higher frequencies give poor penetration but good resolution. There are many critical environmental monitoring situations where surface GPR does not provide the depth of penetration or necessary resolution. Borehole radar can place the sensor closer to the region of interest, overcoming the high signal attenuation near the surface.
3.3 Communication Systems

Agriculture is facing new and severe challenges due to the growing global population, which is expected to reach 9 billion by 2050. Feeding that population will require a 70 percent increase in food production (McNamara, et al. 2012). Modern production systems rely as much on good dissemination of information as they do on physical systems that directly contribute to production. Communication has always mattered in agriculture. Updated information allows farmers to: keep up to date with markets; maintain contact with family, colleagues and workers; automate many aspects of their production systems; and provide important knowledge about new production systems.

The arrival of information communication technology (ICT) is well timed (McNamara, et al. 2012). The benefits of the green revolution greatly improved agricultural productivity; however, there is a demonstrable need for a new revolution that will contribute to “smart” agriculture that can increase production (McNamara, et al. 2012) and potentially ward off Malthus’ predicted catastrophe (Malthus 1798). Available technology has allowed access to unprecedented amounts of agricultural and scientific data and mobile telephony, wireless data transmission, and the Internet have found a foothold, even in poor small farms (McNamara, et al. 2012).

3.4 Conclusion

Microwave and radio frequency energy has many potential applications in the agricultural and forestry industries. This chapter has discussed a few of these, but there are many more that have not been included. The purpose of this chapter was to encourage practitioners within the microwave engineering and agricultural and forestry industries to explore the many possibilities of applying radio frequency and microwave energy to address many problems and opportunities within primary industries. Clearly, the interaction between electromagnetic fields and materials is critical. The next chapter will explore these interactions more thoroughly.

References


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