Determination of best pine wilt disease treatment using irradiation

Jongsoon Kim\(^a\), Rosana G. Moreira\(^b\) and M. Elena Castell-Perez\(^a,b\)

\(^a\)Department of Bio-industrial Machinery Engineering, Pusan National University, Miryang, South Korea; \(^b\)Department of Biological & Agricultural Engineering, Texas A&M University, College Station, TX, USA

**ABSTRACT**

Although fumigation of affected trees is the common control method of the pinewood nematode, a causal agent of pine wilt disease, the treatment causes environmental problems and is expensive. This study assessed the effectiveness of irradiation technology. The physical properties and atomic composition of pinewood were obtained from the literature as input to a radiation transport code (MCNP5). Radiation energies were 10 MeV electron beam and 1.25 MeV gamma rays. For 10 MeV e-beams, penetration depth was 13.4 cm at one-directional irradiation. When the pinewood diameter was less than 17.5 cm, double-beam irradiation sufficed to exterminate the larva. When pinewood diameter was slightly less than 42 cm, a half-cut sample was sufficient to achieve the dose required under double-beam irradiation. For 1.25 MeV gamma rays, the whole sample absorbed the dose. APVC pipe improved dose absorption at the bark region. A pallet irradiator was also evaluated. The double-beam configuration was effective (lower DURs). Although the pine Sawyer beetle, a vector of the nematode, penetrates from the bark and moves into the stem, treatment with 1.25 MeV gamma rays could easily control them. Irradiation technology is an effective alternative to treat nematode-infested pinewood without unwanted environmental problems.

**1. Introduction**

Pinewoods in North America, East Asia, and Portugal are very susceptible to pine wilt disease (Mota & Vieira, 2008; Sutherland, 2008; Zhao, 2008). A beetle in the genus Monochamus serves as a vector of the pinewood nematode (PWN) Bursaphelenchus xylophilus, (Lint, 1988) which are the cause of the disease as the beetles move to young branches of healthy trees making feeding wounds on them. Next, the PWN leaves the beetles’ body and then moves on the wounded surface of the trees. The PWNs feed on the contents of living cells during the migration. Because the partial blockage of the sap ascent occurs in the xylem and the transport of water from the roots to the shoot becomes dysfunctional, the trees die (Kuroda, 2008). In addition, the female beetles deposit eggs under the bark of dying trees infected by PWN. Adult beetles acquire the PWNs when they emerge from such dead trees, beginning another cycle of disease.

In Korea, this pine wilt disease was first reported in Busan in 1988, and since then it has been a serious threat to Korea’s pine forest. From 1988 to 2005, the infested area has increased from 72 ha to 7,811 ha (KOSTAT, 2017). In 2005, a special law was passed to control pine wilt disease, and along with intensive management, the spread of the disease slowed until 2012 (5,286 ha). However, in 2013, the infested area increased drastically due to high temperatures associated with drought and human transporting pine logs infested with PWN. A total of 7.82 million trees have been withered and the costs of the disease have reached up to 490 million dollars (Korea Forest Service, 2016).

Fumigation and chipping are used to dispose of dead pine trees infested with the PWN. At fumigation, infested trees are felled down and cut into 1–2 m\(^3\) sections. These tree sections are treated with the chemical (Metham sodium) and the pile is covered with a PVC sheet (Lee et al, 2003). Even though the mortality of the beetle and the PWN is very high, this chemical treatment is expensive and it is restricted to tree trunks, obviously not applying to whole trees and twigs more than 2 cm in diameter. Moreover, a PVC sheet is likely to be scratched so that the surviving beetles can emerge and spread the disease (Shin, 2008). Usually, a mobile chipper is used to grind the infested trees into sawdust or chips smaller than 1.5 cm, preventing the survival of the beetle larvae (Kamata, 2008). However, it is a labor-intensive procedure and the machines must be transported into the forest. Another approach for controlling the beetles is the use of aerial spraying of insecticide, a highly efficient approach because it can be applied over a wide area (Ugawa & Fukuda, 2008). However, the harmful effects of insecticide on non-target organisms are a great concern. Thus, it is necessary to develop more efficient and environment-friendly control methods.
Irradiation has been applied to fruits and vegetables as a phytosanitary treatment to solve pest management problems (Heather & Hallman, 2008). Irradiation uses the energy of electron beams, X-rays, or gamma rays to break the chemical bonds of organisms like insects or eggs at a certain depth of target. Dose levels that are acutely lethal act on cell systems which maintain mitotic activity. This phytosanitary irradiation treatment was not commercially available until 1995, and currently, a total amount of 19,000 tons of fruits and vegetables is irradiated each year for phytosanitary purposes (Hallman, 2011).

The control dose for beetles in a number of horticultural species is in the range of 120 to 150 Gy (Johnson, Soderstrom, Brandl, Houck, & Wofford, 1990; Hayashi, Imamura, Todoriki, Miyanoshita, & Nakakita, 2004; Ignatowicz, 2004; Tuncbilek, 1997). The gray (Gy) is the amount of energy imparted to a given material; 1 Gy is defined as 1 J of energy absorbed in 1 kg of material (ICRU, 1980). The lethal dose for pinewood nematodes (Bursaphelenchus xylophilus) is 6–8 kGy (Eichholz, Bogdan, & Dwinell, 1991), which is much higher than the dose for the beetles. A simple structural organism is generally more radioresistant than the complex ones (Casarett, 1968). Conventionally, the beetles, the insect vector of the pinewood nematode, have been regarded as the main target in pinewood disease control, because the nematode itself is difficult to control directly. Thus, a dose of 1 kGy, the control dose for insects in wood (OEPP/EPPO, 2009), should be sufficient for pinewood disease control without causing any mutations or other changes to plant cells as it has been confirmed by the United States (Food and Drug Administration, 2008) and Hallman (2011). Higher radiation doses will cause depolymerization of hemicelluloses in wood, resulting in a significant decrease in wood strength (Despot et al., 2012; Hasan, Despot, Rapp, Brischke, & Welzbacher, 2006).

Irradiation treatment planning requires precise delivery of ionizing radiation (dose) to kill the target organism. Thus, accurate dose measurement is fundamental to any dose–response work. However, a large number of tests is required to determine dose experimentally and the dose measurement in some areas (e.g., just under the bark in wood or at a certain depth) is really challenging because of the limited access of commercial dosimeters to these areas. An alternative to dose measurement is to obtain the dose distribution within a target using computer simulation. The random nature of ionizing radiation makes Monte Carlo simulation the best tool for this purpose. The Monte Carlo simulation has been used to establish the irradiation treatments for fruits and vegetables such as apple (Kim, Rivadeneira, Castell-Perez, & Moreira, 2006), cantaloupe (Kim, Moreira, & Castell-Perez, 2010), and broccoli head (Kim, Moreira, & Castell-Perez, 2008). Recently, this simulation technique was applied to phytosanitary irradiation treatment for mango (Kim, Moreira, & Castell-Perez, 2015), mangosteen (Oh et al., 2014), and pineapple (Kim et al., 2013). Currently, there is nothing available in the scientific literature regarding the dose distribution in wood for phytosanitary treatment. The objective of this study was to obtain the dose distribution in pinewood using Monte Carlo simulation and then establish the proper irradiation treatment for pine wilt disease.

2. Material and methods

2.1. Chemical composition and density of pinewood

Wood is made up of three main constituents (cellulose, hemicelluloses, and lignin) and minor amounts of extraneous elements. The carbohydrate portion of wood comprises cellulose and hemicellulose. Cellulose, 40–50% of wood by weight, is an important structural component of the wood cell wall. Hemicellulose, 20–35% of wood, is a polymer built from different kinds of sugar monomers, but fewer complexes and easily decomposed by reacting with water. Lignin, 15–35% of wood, is a three-dimensional phenylpropane polymer and holds the cellulose fibers together (CIBSE, 2014). These three main constituents are composed of carbon, hydrogen, and oxygen, and each ratio differs between tree species. However, there tends to be a little variation in the overall quantities of the individual elements because these three constituents are all comprised of carbon, hydrogen, and oxygen. Thus, the overall elements composition of wood is 50% carbon, 6% hydrogen, and 44% oxygen (Pettersen, 1984). This composition was used in the pinewood radiation simulation carried out in the present study.

Wood is composed mostly of the outer bark and the inner wood (sapwood and heartwood). The bark is the outer, corky, dead part of a tree, and the inner wood is a network of hollow cells, which trees use to transport sap. The densities of pinewood’s bark (0.24 g/cm$^3$) and its inner wood (0.43 g/cm$^3$) at 25°C were obtained from the literature (ASHRAE, 2017; Yaws, 2014).

2.2. Geometry setup of pinewood

The pinewood geometry was established as cylindrical in shape. The outer diameter was set to 26.5 cm (Figure 1), which has been reported as the average diameter of breast height of infected trees (Cho, 2007); its age is about 39 years. Diameter at breast height is standard for measuring tress, representing the tree diameter at 137 cm above the ground (Matthews & Mackie, 2006). The geometry’s height was also set to 30 cm. The bark thickness, 1.18 cm, was calculated by subtracting the wood area from the basal area of pinewood (Pinus densiflora) (Lee, 2004). The inner wood region was divided by 20 concentric cylinders, and each cylinder was also divided into slices by 10 degrees angle increment. In addition,
the smaller diameter (17.5 cm) with its bark thickness of 0.78 cm and the larger diameter (35 cm) with its bark thickness of 1.56 cm were simulated, respectively, in order to obtain the dose distribution over the ranges of infected pinewood.

2.3. Monte Carlo simulation

Radiation interactions were simulated with the MCNP5 (Monte Carlo N-Particle, Version 5) program developed in Los Alamos National Laboratory (Brown, 2003). Most commercial radiation treatments use 10 MeV electrons or gamma rays (1.25 MeV) from a Co-60 source. In the present study, it was assumed that infected pinewoods are moved to the radiation facilities and exposed to the radiation sources. In the simulation, each source particle was emitted in a plane, distributed evenly, and entered the target perpendicularly. In 10 MeV electrons, the target conveyed under the electron scan horn is exposed to the electron beam. The distance between the scan horn and the target was 90 cm, which has been widely configured in commercial accelerators. In gamma rays, the target load moved by some type of conveyor system past the source plaque in a direction that is parallel to the plane of the source. To increase the utilization of the radiation energy and ensure the target moving safely, the distance between the source and the target was set to 30 cm. The energy deposition in a cell was scored when an electron or photon was entering or leaving the cell; added when the particles enter into a cell and subtracted when they exit a cell. The simulation was run on a Window PC (3.20 GHz CPU, 32.0 GB RAM) with Cygwin platform. For independent simulated histories (N), the dose calculated using the Monte Carlo method is subject to statistical uncertainty, which is proportional to a reciprocal of the square root of N (1/√N). The simulation result can be reliable when the statistical uncertainty is less than 5% (Brown, 2003); 10⁷ histories were run to achieve statistical precision and its CPU time was approximately 18 h.

3. Results and discussion

3.1. Dose distribution in pinewood sample at 10 MeV electron beam

For irradiation with 10 MeV electrons, the maximum penetration depth in water is 5.5 cm (Miller, 2005). Considering the density and thickness of both bark and wood (0.24 g/cm³ and 1.18 cm for bark, 0.43 g/cm³ and 12.07 cm for wood), the penetration depth at the center of the pinewood was 13.40 cm under upper beam direction (Figure 2(a)). Since the larva mostly bore tunnels into the xylem (wood), substantial irradiation dose in the wooded section is required to ensure the effective control of larvae. Assuming that the entrance dose at the wood is 1.0 kGy which has been suggested for controlling dose to insects in wood (OEPP/EPPO, 2009), as electrons move deeper and undergo collisions with atomic electrons and
nuclei, the dose increases with depth up to a maximum value (1.05 kGy), followed by an approximately linear decrease. However, the depth of the maximum dose along the beam direction becomes shorter, as electrons are away from its center. As the incident beam angle increases, the backscattering yield increases, resulting in decreasing the dose build-up region (Rosenstein, Eisen, & Silverman, 1972). Thus, at both edges in the bark, the maximum dose (around 1.2 kGy) occurs.

Results from the single e-beam treatment show that about 8.3% of the wood area did not get any dose and 74.9% received less than the target dose (1.0 kGy). This dose distribution can be improved by applying a double beam (upper and lower beam almost simultaneously) irradiation. Figure 2(b) shows that only 43.6% of the wood area received less than 1.0 kGy. However, significantly low doses (0.08 ± 0.04 kGy) were delivered in the pith of wood and near around. Thus, 10 MeV electrons would not efficiently control the larva in wood samples with a diameter of 26.5 cm, because of their limited penetration capability.

Figure 3 shows the dose distribution in pinewood samples with a small diameter (17.5 cm). Unlike the 26.5 cm samples, the penetration depth now exceeded the radius of the pinewood; thus, 60.5% of the wood area received less than 1.0 kGy (Figure 3(a)). However, in double beam irradiation, the entire wood region received larger than 1.0 kGy (Figure 3(b)). Its dose uniformity ratio (DUR, Dmax/Dmin) was 2.24, which is larger from the irradiation processing perspective since DUR should be closer to 1.0. The maximum dose was 2.24 kGy. It is desirable to limit the maximum delivered dose in order to minimize possible negative effects in the target. When a wood sample is exposed to high-energy irradiation sources, such as electron beams or gamma rays, cellulose chains are destroyed, resulting in changes in chemical structure and physical properties of the wood (Fengel & Wegener, 1983). However, an average increase of 25 kGy only causes a 1% loss of cellulose (Despot, Hasan, Rapp, Brishke, & Welzbacher, 2008). Thus, a dose of 2.24 kGy may only induce negligible changes in the material.

Figure 4 shows the dose distribution in pinewood with a large diameter (35.0 cm). Clearly, no dose is delivered around the pith (Figure 4(a)). In fact, for single beam irradiation, only 16.4% of the wood area received doses greater than 1.0 kGy while 25.8% of the wood area did not get any dose at all. On the other hand, for double beam irradiation, the dose distribution at the wood region was significantly improved; the dose area greater than 1.0 kGy was 36.1% and no dose area was 4.6%. Still, the lesser dose was delivered to the pith area, mainly due to the limited penetration power of electron particles.

To improve the dose distribution in the wood material, the pinewood sample was cut by half and the largest distance, from the outer surface of the bark to the pith, decreased to 17.5 cm. The half-cut woods could be loaded on a conveyor and then exposed to the electron beam. Figure 5(a) shows the dose distribution at the downward beam direction. Only 33.0% of the wood area received a dose greater than 1.0 kGy and 3.7% did not get any dose at all. Similar results were obtained for the upward beam direction (Figure 5(b)). However, when the half-cut wood was exposed to double beam (Figure 5(c)), 93.4% of the wood area received a dose greater than 1.0 kGy.

Figure 6 shows the depth–dose curve at the center of the wood (horizontal distance of 0 in Figure 5). The penetration depth, including the bark, was almost 14.0 cm for single beam irradiation. When a double
beam was used, a dose peak was observed in the center of the wood with a DUR of 1.69 and a minimum dose of 1.0 kGy, which indicates that the treatment allows for dose to be effectively absorbed by the pinewood. When the radius of the half-cut wood was greater than 17.5 cm, the two-sided irradiation treatment can extend the processable thickness due to the overlapping of dose distributions. Increasing the radius up to 21 cm causes uniform dose distribution and an acceptable minimum dose (Figure 7). A steep increase in uniformity ratio is observed as soon as the radius exceeds the optimal range (21 cm); increasing the thickness further causes severe underexposure in the wood.

In general, the dose distribution throughout the product strongly depends on the geometric constraints. If 10 MeV electron beams are used to irradiate the material, the double beam configuration of a pinewood sample of small diameter (17.5 cm) is necessary to ensure the control of larvae. For larger targets, the uniform dose is expected to occur when the radius of half-cut woods is less than the optimal thickness (21 cm).

3.2. Dose distribution of pinewood exposed to gamma rays

For one-sided gamma-ray simulation (Figure 8), the DURs (excluding bark region) were 1.48, 1.79, and 1.99 for small, average, and large diameter, respectively; the small diameter had better uniformity ratio and the overall bark region had 27.2% lower dose than the wood region. These values are quite acceptable for irradiation treatment of pinewood for whole sizes because those DURs are relatively close to 1. To ensure the control of the larva, the minimum dose should be increased to 1.0
Figure 5. Dose distribution in half-cut pinewood (d = 35.0 cm) with 10 MeV electrons: (a) in downward beam direction, (b) in upward beam direction, and (c) in double beam direction.
kGy. Then, the maximum dose at the large diameter will be 2.0 kGy, a level that would not have a negative impact on the quality of pinewood (Despot et al., 2008).

The female vector lays eggs in the inner bark of the pinewood and later larvae grow by feeding on the inner bark (Nakamura-Matori, 2008). Therefore, the bark region should be fully exposed to the radiation as well. Gamma-ray photons first transfer their kinetic energy to electrons in the matter and those electrons deliver their energy to the matter directly (Attix, 1986). Thus, the absorbed dose curve of pinewood increases with increasing depth near the bark area (Figure 9). The dose buildup region, mostly bark region, is shown clearly with only 71.4% of the dose at the wood area in average diameter.

To improve the dose at the bark area, a PVC pipe ($\rho = 1.3$ g/cm$^3$, outer diameter = 26.5 cm, thickness = 1.0 cm) was used as a radiation energy absorber (Figure 10). When a target is irradiated with one direction, a radiation energy absorber can be placed on the front and back surfaces of the target to minimize the buildup region (ASTM, 2006; Kim et al., 2015). The dose at the bark region with the PVC pipe significantly improved from 71.4% to 86.2% (Figure 11). Similar improvement occurred at the small diameter (from 65.2% to 85.7%).

Pallet gamma irradiators have been used for phytosanitary irradiation purposes (Craven, Schlecht, & Stein, 2018). The irradiator accepts pallets whose dimensions of 120 cm long x 100 cm wide x 220 cm high. Let us see what happens when one of these
Figure 8. Dose distribution in pinewood at 1.25 MeV gamma rays; (a) at small diameter, (b) at average diameter, and (c) at large diameter.

Figure 9. Dose distribution at the center of the average-diameter pinewood along the vertical direction.
pallets is filled with 3, 4, and 6 pinewoods along the length for large, average, and small diameter, respectively. Figure 12(a) shows gamma radiation treatment of small diameter pinewood (its diameter of 17.5 cm) at the pallet irradiator. Pinewoods were placed on the pallet and their doses decreased as treatment proceeded. At two-side treatment, the DUR was significantly improved from 4.76 (one-side) to 1.34 (two-side). The dose uniformity ratios at average and large diameter for a two-side process were 1.26 and 1.24, respectively. Thus, the pallet irradiator would be very effective in controlling larva in pinewood. However,
for better treatment, the detailed dose distribution of pinewood should be obtained to ensure the radiation effects.

4. Conclusions

The dose distribution within the sample is strongly dependent on the size of the wood when applying 10 MeV electrons for treatment of pinewood. Treatment of the pinewood using the double beam configuration is sufficient to control the larvae when the sample diameter is less than 17.5 cm. When the diameter is between 17.5 cm and 42.0 cm, it is recommended that the pinewood be cut in half and then exposed to the double beam for uniform dose distribution. Unlike electron beam treatment, one-side radiation is sufficient to control larvae for all sizes of pinewoods when using gamma rays. In addition, a PVC pipe may improve the absorbed dose at the bark region.

For practical applications, a pallet irradiator with two-sided radiation may be quite effective with DURs of 1.34, 1.24, and 1.26 for small, average, and large diameter, respectively. This study shows that exposure to gamma rays can control pine wilt disease more effectively than electron beams. However, a critical factor in the selection of an irradiator is not only the uniformity of the absorbed dose in the irradiated target (e.g., DUR), but also the minimization of the capital and operating costs. Thus, before choosing a technology for irradiation treatment, the throughput, operating costs, and availability should also be carefully taken into account.

Currently, pine wilt disease is a widespread threat to forests over the world, especially eastern Asian countries. Irradiation treatment of insect-infected pinewood would be a good alternative to treatment with chemicals because if pallet irradiators become available to the wood processors, the treatment would be more cost-effective than the labor-consuming chipping.

Figure 12. Pinewood (radius of 8.75 cm) in the pallet irradiator; (a) a schematic drawing of pinewood on the pallet, (b) their average doses at one-side and two-side treatment.
fumigation method and less harmful to workers and other individuals than when treating the wood using aerial spraying fumigation methods.

Acknowledgments

This work was partially supported by a 2-Year Research Grant of Pusan National University.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

M. Elena Castell-Perez http://orcid.org/0000-0002-3936-7606

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