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Analysis and modeling of agricultural processing with regard to grain post-harvest handling and winemaking

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Analysis and modeling of agricultural processing with regard to grain post-harvest handling and winemaking

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DEDICATION

I would like to dedicate this thesis to my mother Ji, Wenge and my father Zhang, Minqi without whose unconditional moral and financial support I would not have been able to complete this work.

TABLE OF CONTENTS

NOMENCLATURE

ASABE	American Society of Agricultural and Biological Engineers
FAO	Food and Agriculture Organization of the United Nations
LCA	Life Cycle Assessment
RH	Relative humidity
TEA	Techno-Economic Analysis
USDA	United States Department of Agriculture

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ABSTRACT

With increasing human population, urbanization and modernization, the shortage of food and energy as well as environmental impacts have become serious problems threatening the existence of humankind. The optimization of agricultural processing could be a valid way to relieve these problems by producing more high-quality agricultural products with fewer resources and less impacts on the environment. Agricultural processing has been defined as an activity which is performed to maintain or improve the quality of an agricultural product or to change its form or characteristics. This includes drying, storage, milling, packaging, brewage, etc. A critical step to optimize agricultural processing is to characterize, understand and predict it by analysis and modeling. The purpose of this research is to discuss it by conducting analysis, assessment and modeling for a complex grain farm including a vineyard with grain and red wine as product. Specific applications including analysis and modeling of grain hermetic storage reduce the impacts of pest infestation, analysis and assessment of the efficiency of a closed circuit grain drying system, and systemic economic analysis plus life-cycle assessment with respect to winemaking were discussed.

In the first study, a time-dependent model was developed to determine the effect of hermetic storage conditions on red flour beetle *(Tribolium castaneum)* and maize weevil *(Sitophilus zeamais)*. The counts of live and dead insects were examined over time in storage of wheat and maize, using both hermetic and non-hermetic conditions. It was found that 100% mortality for red flour beetle was obtained after 12 days for wheat under hermetic conditions. It was also found 100% mortality of maize weevils after 6 days of

hermetic storage of corn. The results have demonstrated that hermetic treatment is a valid and efficient way to kill red flour beetle (*Tribolium castaneum*) and maize weevil (*Sitophilus zeamais*). Data collected and model developed could be further used for scale up design of full-scale storage systems for grain.

The efficiency of a closed circuit grain drying system named the DOROTHY cyclone moisture removal system was analyzed and assessed in the second study. The system was designed and manufactured by the Loebach brothers (David R. Loebach and Joseph E. Loebach, Loebach Brothers Inc., sailboatcw@gmail.co), and consisted of a wagon to hold the grain and a drying apparatus composed of a compressor, an evaporation-condensation-system and a fan. Two trials were operated separately in fall and winter, using corn to evaluate drying efficiency. Power and moisture content were analyzed during experiment. Energy consumption and moisture removal could be utilized to calculate drying efficiency. The effect on germination was also evaluated after the drying process. Results showed that the drying system in the fall trial was very efficient compared to common drying systems on the market and did not decrease germination. While in the winter trial, the efficiency of the drying system decreased by half compared to the fall trial but was still comparable to the common drying systems used in industry. Additionally, germination performance was not affected.

In the last study, TEA (Techno-economic analysis) and LCA (Life cycle assessment) for the production of red wine was conducted for providing information with regard to economy and environment to help to make decision when establishing a winery. For LCA, the consumption of water, energy, greenhouse gas emissions, and solid waste generation were considered for environmental impacts. For TEA, small, medium and large-scale winemaking processes were chosen for analysis and a spreadsheet-based economic model was developed. The results of the LCA showed that bottle manufacturing, vine planting and winemaking processes contributed the greatest environmental impacts. While for the TEA, the relationship between cost and profit among all three scales fitted an exponential model, and fitted a liner model better.

Overall, this thesis has shown several specific applications of analyzing, assessing and modeling of agricultural processing to indicate, predict and optimize it. The author believes such applications could be conducted not only for the specific practices mentioned in this thesis, but also could be conducted for all kinds of agricultural processing, therefore reducing the problems associated with food, energy and impacts on environment caused by the increase of human population.

CHAPTER 1. GENERAL INTRODUCTION AND OBJECTIVES

Along with the increase of the world's population and the development of human society, the shortage of food and energy as well as environmental impacts become serious problems threating the existence of humankind. In 2012-2014, about 805 million people in the world were chronically undernourished (FAO, 2014), and 11 million children under the age of five die from hunger or hunger-related diseases every year until 1990 (Lean et al., 1990). Food shortage could be more severe and less predictable upon drought, war, or the loss due to insects or disease (Campbell and Trechter, 1982). In 2000, severe drought occurred in Kenya and undermined the food security of nearly 4.4 million people (FAO, 2001). Energy is required in almost all aspects of daily life (Sayigh, 2004). The demand for energy throughout the world is rapidly increasing with increasing human population, urbanization and modernization (Asif and Muneer, 2007). With the demand increasing, the shortage of energy became a serious problem. In 2007, it was estimated that 2 billion people in developing countries lacked grid-based electricity service (Nfah et al., 2007). In 1978, the insufficient supplies of natural gas caused price increases for irrigation fuel in Texas and therefore affected the irrigated crop production by increasing costs of pumping irrigation water (Lacewell et al., 1978). For the environmental impacts, by the end of twentieth century, atmospheric carbon dioxide concentrations have been increased to about 40% above preindustrial levels (Schlesinger, 2013), and the natural rates of phosphorus liberation and nitrogen addition to terrestrial ecosystems have been doubled (Tilman and Lehman, 2001; Vitousek, 1994; Vitousek et al., 1997; Carpenter et al., 1998). In the same period, 35% of the productivity of the oceanic shelf were consumed (Pauly and Christensen, 1995) while 60% of freshwater run-off were used by humankind (Postel et al. 1996). The fire suppression or increased use of fire to clear or manage land could change fire frequency thus affect structuring communities and ecosystems (Tilman and Lehman, 2001; Bird and Cali, 1998; Tilman et al., 2000; Clark, 1990).

The optimization of agricultural processing could be a valid way to relieve the problems of shortage of food and energy as well as the destructive impacts on environment. Agricultural processing is defined as an activity which is performed to maintain or improve the quality of an agricultural product or to change its form or characteristics. This includes drying, storage, milling, packaging, brewage, vinification, etc. (Sahay and Singh, 2004). With optimized agricultural processing, the resources needed such as energy and water could be reduced while the output of products such as high quality cereals, beer and wine could be increased. Therefore, the situation of shortage of food and energy could be improved, and the impacts on environment due to land reclamation and energy consumption, such as greenhouse gas emissions, destruction of natural vegetation, habitat destruction, etc., could be relieved.

A critical step to optimize agricultural processing is to characterize, understand and predict it by analysis and modeling. With that useful data like cost, energy consumption, efficiency, pest mortality, and profit could be obtained, and models regarding input and output, environment and output, plus scale and impacts could be established. Many efforts have been made through this approach with respect to agricultural processing. Cantos et al. (2001) developed an induction modeling method to predict and characterize the increase of resveratrol content within table grapes by applying UV irradiation pulses, and a study has been conducted to establish the basis for a potential usefulness of UV-C-irradiated grapes to develop a stilbene-enriched red wine (Cantos et al., 2003). A combined respiration rate model for predicting and optimizing the shelf life of apples has been developed and verified based on the principles of enzyme kinetics, for dependence of oxygen and carbon dioxide and also based on the Arrhenius equation, for dependence on storage temperature (Mahajan and Goswami, 2001). For the specific agricultural processing such as drying, Jain and Pathare (2004) have developed a model to describe infrared radiative and convective drying characteristics of onion slices for optimum management of operation parameters and prediction of performance of a thin layer drying system. Sabarez and Price (1999) have tested a model which is a numerical solution based on Fick's law. With the model high quality drying data was obtained for the dehydration of d'Agen plums as a function of temperature. Other research has been conducted to study the drying kinetics of apples in a tunnel dryer as affected by various pretreatments, and to predict drying rates of apple by evaluating a time-dependent model of drying process (Goyal and Bhargava, 2008). Additionally, a simplified plate drying model has been used to simulate the intermittent drying of Maitake mushroom and to determine the optimum tempering duration for the drying process (Cao et al., 2004). For storage and packaging, by utilizing the relationship between the rate of oxygen uptake and oxygen concentration for tomato fruit at different stages of ripening, which was described as a continuous mathematical function, novel prediction models for optimization of oxygen concentration in the package have been developed (Cameron et al., 1989). Talasila and Cameron (1997) have developed a mathematical model to predict the influence of packaging and storage variables on the rate of free volume change. The model predictions were used to suggest methods for controlling the rate of free-volume change of a flexible, hermetic storage and packaging system. Other study has been conducted to predict the effect of temperature fluctuations on oxygen and carbon dioxide levels in passive and active modified atmosphere packaging (Charles et al., 2005).

The main motivation of this thesis is to conduct analysis, assessment and modeling with regard to agricultural processing which could help to optimize it and thus relieve the problems of shortage of food, shortage of energy and negative impacts on environment. By discussing specific applications including analysis and modeling of grain hermetic storage to reduce the impacts of pest infestation, analysis and assessment of the efficiency of a closed circuit grain drying system, and systemic economic analysis plus life-cycle assessment with respect to winemaking, agricultural processing including storage, drying and processing regarding changing the form and characteristics of agricultural products would be spanned in this thesis.

Thesis Objectives

The general objective of the present thesis was to discuss analysis and modeling as critical steps to optimizing agricultural processing. By studying several specific applications with regard to grain hermetic storage, grain on-farm drying and red wine production, the methods of analysis and modeling to characterize, understand and predict agricultural processing was developed.

The objective of Chapter 2 was to develop a model to determine the effect of hermetic storage conditions on red flour beetle *(Tribolium castaneum)* and maize weevil *(Sitophilus zeamais),* and to hopefully reduce infestation during storage.

The objective of Chapter 3 was to analyze and assess the efficiency of a closed circuit grain drying system named the DOROTHY cyclone moisture removal system which was designed and manufactured by the Loebach brothers (David R. Loebach and Joseph E. Loebach, Loebach Brothers Inc., sailboatcw@gmail.co), and consisted of a wagon to hold the grain and a drying apparatus composed of a compressor, an evaporation-condensation-system and a fan.

The objective of Chapter 4 was to provide information with regard to economy and environment to help to make decision when establishing a winery, by conducting TEA (Techno-economic analysis) and LCA (Life cycle assessment) for the particular red wine production processes.

Thesis Organization

Chapter 1 corresponds to the general introduction and organization for the thesis. In this chapter, thesis objectives were stated as well.

Chapter 2 corresponds to the research regarding grain hermetic storage against the infestation of the pest including red flour beetle (*Tribolium castaneum*) and maize weevil (*Sitophilus zeamais*). It details the research of laboratory scale experiment and the development of a time-dependent model to determine the effect of hermetic storage.

Chapter 3 corresponds to the research of analyzing and assessing the efficiency of a closed circuit grain drying system. Fall and winter trials were carried out by running the system with corn.

Chapter 4 corresponds to the TEA (Techno-economic analysis) and LCA (Life cycle assessment) for the production of red wine. For LCA, the consumption of water and energy, greenhouse gas emissions, and solid waste generation were considered for environmental impacts. For TEA, three different scales of winemaking processes were chosen for analysis and a spreadsheet-based economic model with regard to cost, revenue and profit was developed.

Chapter 5 corresponds to the overall conclusions for the thesis and the future work that could be done with regard to the specific applications of analysis and modeling of agricultural processing that mentioned in chapter 2, chapter 3 and chapter 4.

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CHAPTER 2. LABORATORY-SCALE HERMETIC STORAGE OF WHEAT AND MAIZE AGAINST THE INFESTATION OF RED FLOUR BEETLE *(TRIBOLIUM CASTANEUM)* AND MAIZE WEEVIL *(SITOPHILUS ZEAMAIS)*

Modified from a paper to be submitted as a poster presentation at the *2015 ASABE Annual International Meeting in New Orleans, Louisiana, USA*

C. Zhang, K. A. Rosentrater, and C. J. Bern

Abstract

Hermetic storage is a method to form the basis for suppressing and controlling insect infestations by isolating the storage ecosystem from the external environment while respiration within the storage ecosystem causes O_2 depletion and CO_2 accumulation. By applying hermetic conditions, insects in the grains could be killed and therefore the storage loss of wheat and maize could be reduced. The objective of this project was to develop a model to determine the effect of hermetic storage conditions on red flour beetle *(Tribolium castaneum)* and maize weevil *(Sitophilus zeamais)*, and to hopefully reduce infestation during storage. This project used 4 oz glass jars and vacuum grease to provide hermetic storage conditions. Red flour beetles *(Tribolium castaneum)* were placed in jars filled with wheat, and maize weevils *(Sitophilus zeamais)* were placed in jars containing corn. We examined counts of live and dead insects over time in both grains, using both hermetic and non-hermetic conditions. After 30 days, statistical analyses were conducted and a time-dependent model was developed to determine the

effects of hermetic vs. non-hermetic conditions for both grains. We found that 100% mortality for red flour beetle was obtained after 12 days for wheat under hermetic conditions. We also found 100% mortality of maize weevils after 6 days of hermetic storage of corn.

Introduction

Hunger is an enormous challenge for the modern world, especially for some of the developing regions. During 2010-2011, cereal production of developing countries was 1320 million Mg while the consumption of them was 1420 million Mg. Twenty-eight African countries required external assistance of food until 2013 (FAO, 2013). Wheat and maize are two of the most important food resources and they are beneficial to relieve the situation of hunger. However, the output is relatively low in developing regions. The output of wheat in 2011 was 700 million Mg all over the world but was 46.4 Mg in Near East, was 24.7 Mg in Latin America and was 2.3 million Mg in Africa (FAO, 2013), only accounted for 6.6 percent, 3.5 percent and 0.3 percent separately of world wheat output. And the output of maize in 2011 was 836 million Mg all over the world (USDA, 2014) but was 22.7 million Mg in southern Africa (FAO, 2012), was 4.9 million Mg in Ethiopia, and was 6.8 million Mg in Indonesia (USDA 2014), only accounted for 2.7 percent, 0.6 percent, and 0.8 percent separately of world maize output. The output of wheat and maize in some of the developing regions is too low to satisfy the consuming requirement. Take Indonesia as an example, the output of maize in 2011 was 6.8 million Mg while the consuming requirement of maize in that year was 9.8 million Mg (USDA, 2014). Therefore, Indonesia had to import 3 million Mg of maize.

It is no doubt the output of wheat and maize is not enough to satisfy the requirement; and the loss during storage period of them could make things worse. According to The World Bank's report (The World Bank, 2011), 17.5 percent weight loss was estimated due to poor storage condition of maize in Eastern and Southern Africa during 2005-2007, while 13 percent weight loss was estimated for wheat in same period. The major biotic factors that cause the storage loss are insects, molds, birds and rats (Baloch, 1999). For wheat, the average loss due to insect pests during post-harvest storage in two-year-old wheat was estimated at around 9 percent of total production, and in some individual cases, up to 15 percent. Additionally, this damage may result in the rejection of a large amount of potential food material at the cleaning and food preparation stage (Baloch, 1999). For maize, the storage loss caused by insect pests was generally estimated to range between 20-30 percent (Tefera et al., 2011), and the weight loss of 3 month storage could be up to 34-40 percent due to larger grain borer (*Prostephanus truncates*) pests and 10-20 percent due to maize weevil (*Sitophilus zeamais*) pests (Boxall, 2002). Furthermore, the loss caused by maize weevil (*Sitophilus zeamais*) during post-harvest storage was 20 percent to 30 percent in Ethiopia while 100 percent damage has been found in maize stored for 6-8 months in the Bako region of this country (Demissie et al., 2008), and 18 percent of stored maize was infected and destroyed by maize weevil in Tanzania (Mulungu et al., 2007).

Red flour beetle (*Tribolium castaneum*) is one of the major insect species that could infect wheat (Baloch, 1999). It is a cosmopolitan pest for wheat (Hamed and Khattak, 1985). With destroying the kernels of wheat by gnawing holes through them (Atanasov, 1978), red flour beetle (*Tribolium castaneum*) damages wheat and results in losses of weight and quality of it. Thus, it becomes the most serious pest for wheat. Maize weevil (*Sitophilus zeamais*) is a major pest of maize and is one of the major insect species known to infect maize in storage in tropic regions (Longstaff, 1981; Jacobs and Calvin, 2001). It damages maize by attacking the kernels and lays eggs into the kernels (Throne, 1994). Within kernels, its larvae could feed and develop (Storey, 1987). The infection of maize weevil (*Sitophilus zeamais)* could cause the reduction of percent germination, weight and nutritional values of maize (Keba and Sori, 2013).

Many efforts have been made to prevent the infection of red flour beetle (*Tribolium castaneum*) and maize weevil (*Sitophilus zeamais)*. Chemical application is one of the most valid methods and a lot of research relates to it. Haliscak and Beeman (1983) found that both red flour beetle (*Tribolium castaneum*) and maize weevil (*Sitophilus zeamais)* have Malathion resistance but this resistance could be suppressed by triphenylphosphate and therefore achieve a good result of killing the insects. However, the chemical insecticide application could result in environmental pollution, adverse effect on non-target organisms and food contamination with toxic residues (Niber, 1994; Asawalam et al., 2006; Dhuyo and Ahmed, 2007; Kumar et al., 2007; Muluken and Ketema, 2014). Additionally, the cost of the chemical insecticides is difficult for the farmers of developing regions to afford (Mendesil et al., 2007). Another effective method to protect stored wheat and maize from attacked by red flour beetle (*Tribolium castaneum*) and maize weevil (*Sitophilus zeamais)* is by temperature control (Maier et al., 1996). As the temperature condition could determine how fast the insects could develop into populations large enough threaten grain quality and value (Pedersen, 1992). This method has demonstrated that female maize weevil lays few eggs when the temperature drop below 20 °C (Throne, 1994), and temperatures below 17 °C are adequate to slow insect development enough to limit pest damage (Burges and Burrell, 1964). Though, the cost of establishing a temperature control system is too high to implement this method in developing regions.

To manage the pests properly and avoid their infestation on wheat and maize, hermetic storage is another valid method. Hermetic storage is a method to form the basis for suppressing and controlling insect infestations by isolating the storage ecosystem from the external environment while respiration within the storage ecosystem causes O_2 depletion and CO_2 accumulation (Navarro et al., 1994; Yakubu et al., 2011). Research was carried out with hermetic storage bag and 100% mortality was obtained within 4 weeks for lesser grain borer and cowpea weevil (Garcia-Lara et al., 2013). A study by Yakubu et al. (2011) utilized 350 g maize together with 30 maize weevils (*Sitophilus zeamais)* stored within 473 mL glass canning jars. The jars were stored at 27 °C and 10 °C, 6.3% and 16% moisture. For hermetic treatment, maize weevil mortality was recorded on days 2, 4, 6, 8, 10 while for non-hermetic treatment, the mortality was recorded on days 2, 6, 10. Based on the results of their experiment, the effects of temperature and maize moistures on the mortality of maize weevil (*Sitophilus zeamais)* have been measured, and weevil oxygen consumption has been quantified. Time to 100% mortality could be predicted by using the oxygen consumption value together with container and maize information, and they gave an example to illustrate the procedure: 162 kg of maize at 10% moisture content and 20 °C is in a 225 L barrel, and contains 100 maize weevils per kg. An oxygen utilization value of 0.114 cm^3 per weevil per day could be obtained by utilizing the figure that they developed (Figure 1), by interpolating between points in the figure. On average, maize weevils die when oxygen level reaches 4% and by using container and maize information, along with the calculated oxygen utilization value, in their example, the predicted time to 100% mortality is calculated to be nine days. Furthermore, in their study, for both the 6.3% and 16% moisture maize, maize weevil mortality reached 100% in six days with hermetic storage at 27 °C.

It was demonstrated that red flour beetle (*Tribolium castaneum*) also could be killed by hermetic conditions (Press and Harein, 1966) and 95% mortality was obtained by exposing the beetles in a pure carbon dioxide atmosphere for 11.9 hours. Another study showed that at 26.7 degree Celsius, 95% mortality of red flour beetle adults could be obtained by an exposure of 271 hours to 45% CO_2 and 55% air mixture; 58 hours to 62% CO_2 and 38% air mixture; 47.5 hours to 80% CO_2 and 20% air mixture (Aliniazee, 1971). Aliniazee (1971) also indicated that under hermetic conditions the adult red flour beetles depleted the oxygen from 20.9% to 1.7% while produced about 20% of carbon dioxide gas in 7 days.

However, as far as we know, the method of hermetic storage has not been applied to red flour beetle (*Tribolium castaneum*) so far. Although hermetic storage has been demonstrated as a valid way to prevent maize weevil infection, its effect on red flour beetle (*Tribolium castaneum*) has not been clear. The effect and efficiency of hermetic storage on red flour beetle (*Tribolium castaneum*) needs to be determined by characterizing the hermetic storage process. Meanwhile, same work need to be done for the hermetic storage on maize weevil (*Sitophilus zeamais)*.

The present study was undertaken to determine the effects of hermetic storage on controlling the infestation of red flour beetle (*Tribolium castaneum*) and maize weevil

(*Sitophilus zeamais)* during wheat and maize storage by determining the mortality of the insects under different conditions (hermetic or non-hermetic), and by developing a model to characterize the hermetic storage. Therefore provide basic information on feasibility of applying it in the control of red flour beetle (*Tribolium castaneum*) and maize weevil (*Sitophilus zeamais)* during wheat and maize storage.

Materials and Methods

Red flour beetle (*Tribolium castaneum*) in wheat

Adult red flour beetles (*Tribolium castaneum*) were obtained from laboratory cultures, reared on a food substrate consisting of rolled oats and wheat. The cultures were kept in an incubator and maintained at a constant temperature of 24± 0.8 °C.

Soft white wheat of fresh commercial variety was obtained from the local market (Ames, Iowa, USA). The wheat was produced by Honeyville during 2012 in northern USA. It was cleaned to remove broken wheat and foreign material and no pesticide was used. After purchase, the wheat was stored at 4 °C until used.

A laboratory scale hermetic storage model employing small glass jars was used. Treatment condition of temperature of 27 °C was chosen as typical wheat storage condition in Africa.

A chamber of model Fisher Scientific Isotemp Chromatography Refrigerator (Thermo Fisher Scientific Inc., Waltham, MA USA 02451) was used in the experiments, with heating and temperature controls, maintained at 27 °C.

Canning jars (4 oz, Ball Glass Mason Jars, Hearthmark, LLC dba Jarden Home Brands, Daleville, IN USA 47334) were utilized in present experiment. Each jar was loaded with wheat to nearly full and was weighed. The weight of wheat in each jar was recorded and the average value was computed and used for predicting time to 100% mortality (Yakubu et al., 2011). 10 adult red flour beetles (*Tribolium castaneum*) were put in each jar.

An experiment was conducted with maize weevil (*Sitophilus zeamais*) to test the effect of the hermetic treatment with and without vacuum grease on the lids (appendix). With one treatment, the jars were simply sealed with their lids for hermetic treatment. However, the results showed that the mortality after 6 days of storage is 100% but after 9 days of storage is 90%, after 12 days is 10%, and the mortality decreased after 6 days of storage. This may illustrate that the hermetic treatment was not effective. With the other treatment, vacuum grease (Dow Corning High Vacuum Grease, Dow Corning Corporation, Midland, MI USA 48686) was utilized by applying it to the edge of the lid to ensure the hermetic conditions, and no mortality decrease was observed in this improved handling during the experiment. Based on the results, vacuum grease was chosen for the hermetic treatment.

The hermetic group utilized canning jars with hermetic lids and vacuum grease (Dow Corning High Vacuum Grease, Dow Corning Corporation, Midland, MI USA 48686), while the non-hermetic group (control group), utilized jars with coffee filter (Hy-Vee 8-12 Cups Coffee Filter, Hy-Vee Inc., West Des Moines, IA USA 50266) as lids, which allowed air passage but not for red flour beetles to escape.

The experimental design for red flour beetle in wheat (Table 1) consisted of two factorials (days and hermetic conditions) and six replications, with the mortality being the dependent variable. Days had 5 levels (3rd, 6th, 9th, 12th, and 30th), while hermetic conditions had 2 levels (hermetic and non-hermetic). Total 6 replications were used for red flour beetle in wheat and each replication had a total of 10 treatments (a balanced design of 5 hermetic and 5 non-hermetic). The hermetic jars had five levels of days while the non-hermetic jars also had five levels of days. Each of the 60 jars contained 10 beetles.

To determine mortality, each jar from the 10 treatments was examined for dead bugs on the day to which it was randomly assigned. Based on a combination of observed rigor mortis features (Gullan and Cranston, 2000), by following the method that Yakubu et al. (2011) used in their study, insects were counted as dead if they were immobile or found lying on their side/back or unattached to wheat kernels or found to flow with kernels when jar was tilted or found to have any combination of these features. Both of the hermetic and non-hermetic treatments counts were done on days 3, 6, 9, 12, and 30. The number of dead bugs of each jar was recorded and divided by 10 to obtain the mortality. The mortality recorded was utilized in the statistical analyses, for testing the hypothesis of difference in mortality of bugs for different hermetic conditions.

The number of living beetles was obtained by subtracting the number of dead insects from 10 for each jar. The average value of the number of living beetles was calculated from the 6 replications for each level of days. The average value was used for the time-dependent model establishment.

Maize weevil (*Sitophilus zeamais*) in maize

Adult maize weevil (*Sitophilus zeamais*) was attained from laboratory cultures, cultivated on a food substrate of maize. The cultures were retained in an incubator and maintained at a constant temperature of 24± 0.8 °C.

Maize grain of fresh commercial hybrid Fontanelle 6T672 grown at the Agricultural Engineering-Agronomy farm 12 kilometers west of Ames, Iowa. It was harvested and dried without the addition of heat. It was cleaned to remove broken maize and foreign material and no pesticide was used. The maize was stored at 4 °C until used.

A laboratory scale hermetic storage model with small glass jars was used. Treatment condition of temperature of 27 °C was chosen.

A chamber of model Fisher Scientific Isotemp Chromatography Refrigerator (Thermo Fisher Scientific Inc., Waltham, MA USA 02451) was used in this experiments, with heating and temperature controls, maintained at 27 °C.

Canning jars (4 oz, Ball Glass Mason Jars, Hearthmark, LLC dba Jarden Home Brands, Daleville, IN USA 47334) were utilized. Each jar was loaded with maize to nearly full and was weighed. The weight of maize in each jar was recorded and the average value was computed and used for predicting time to 100% mortality (Yakubu et al., 2011). 10 adult maize weevils (*Sitophilus zeamais*) were put in each jar.

For hermetic group, based on the results of the appendix, utilized canning jars with hermetic lids and vacuum grease (Dow Corning High Vacuum Grease, Dow Corning Corporation, Midland, MI USA 48686), while for non-hermetic group (control group), utilized coffee filters (Hy-Vee 8-12 Cups Coffee Filter, Hy-Vee Inc., West Des

Moines, IA USA 50266) as lids with jars, which allowed air passage but not for weevils to escape.

The experimental design for maize weevil (*Sitophilus zeamais*) in maize (Table 2) consisting of two factorials (days and hermetic conditions) and six replications, with mortality being the dependent variable. Days had 5 levels (3rd, 6th, 9th, 12th, and 30th), while hermetic conditions had 2 levels (hermetic and non-hermetic). Total 6 replications were used for maize weevil in maize (*Sitophilus zeamais*) and each replication had a total of 10 treatments (a balanced design of 5 hermetic and 5 non-hermetic). The hermetic jars had five levels of days while the non-hermetic jars also had five levels of days. Each of the 60 jars contained 10 weevils.

To determine mortality, each jar from the 10 treatments was examined for dead insects on the day to which it was randomly assigned. Based on a combination of observed rigor mortis features (Gullan and Cranston, 2000), by following the method that Yakubu et al. (2011) used in their study, insects were counted as dead if they were curled up or had outstretched legs or immobile or found lying on their side/back or unattached to maize kernels or found to flow with kernels when jar was tilted or found to have any combination of these features. Both of the hermetic and non-hermetic treatments counts were done on days 3, 6, 9, 12, and 30. The number of dead bugs of each jar was recorded and divided by 10 to obtain the mortality. The mortality recorded was utilized in the statistical analyses, for testing the hypothesis of difference in mortality of bugs for different hermetic conditions.

The number of living weevils was obtained by subtracting the number of dead insects from 10 for each jar. The mean value of the number of living weevils was calculated from the 6 replications for each level of days. The mean value was utilized for developing the time-dependent model.

Results and Discussion

Red flour beetle (*Tribolium castaneum*) in wheat

For hermetic storage at 27 °C, red flour beetle mortality of all the six replications reached 100% in 12 days, while for the non-hermetic samples (control group), at 27 °C, compared to hermetic samples, beetles have much lower mortality for sixth to twelfth days (Figure 2 and Figure 3). The mortalities of non-hermetic treatment ranged from 10% to 60% for the samples of the12th day (Figure 2 and Table 3).

The reason of the red flour beetle mortality of hermetic group increased more rapidly than non-hermetic group over time could be the oxygen content within the jars of hermetic group was much lower and the CO_2 content within the jars of hermetic group was much higher than those within the jars of non-hermetic group. And the higher the CO_2 content, the more easily the red flour beetle (*Tribolium castaneum*) could be killed (Aliniazee, 1971).

By following the method that Yakubu et al. (2011) developed to predict time to 100% mortality of maize weevil (*Sitophilus zeamais*), with the information that with regard to the present study, including the average weight of wheat in one jar, which was 98.65 g (Table 3), the volume of each jar, which was 118.29 cm^3 (4 oz), the kernel density of the wheat, which was assumed to 1.37 g/ cm^3 based on the study that Chang (1988) conducted, the amount of insects in each jar, which was 10, the oxygen level that

100% mortality could be obtained, which was assumed to 4% based on the study of Yakubu et al. (2011), the moisture content of the wheat, which was estimated based on the basis of a sample which was retained in the lab, was 10.51%, the storage temperature, which was 27 °C, and the oxygen consumption, which could be estimated by using the figure of 'Average oxygen consumption of maize weevils in shelled maize' (Figure 1) in the study of Yakubu et al. (2011) with wheat moisture content (10.51%) and storage temperature (27 °C), was 0.187 cm^3 per insect per day (Interpolating the 10.51% point between points on the line 27 °C in the figure), the predicted time to 100% mortality of red flour beetle (*Tribolium castaneum*) was calculated to be 4 days. This somewhat achieved the same result compared to the outcome of the experiment of the present study, as two of the total six replications of hermetic treatment showed 100% mortality when samples were examined after 6 days storage (Table 3). However, if considering all of the six replications, the predicted time to 100% mortality calculated is different from the result that obtained in the experiment of the present study, which is 12 days, illustrated that the method of predicting time to 100% mortality for maize weevil (*Sitophilus zeamais*) that Yakubu et al. (2011) developed could not be completely applied to the hermetic storage of red flour beetle (*Tribolium castaneum*) in wheat.

For hermetic storage at 27°C, the number of living red flour beetles (*Tribolium castaneum*) reached 0 in 12 days, while for the non-hermetic samples (control group), at 27°C, compared to hermetic samples, beetles have much higher living numbers for zero to twelve days (Figure 4 and Figure 5). As the number of living beetles for non-hermetic samples was 4-9 for 12th day (Figure 4 and Table 3).

The reason that the numbers of living red flour beetles (*Tribolium castaneum*) of hermetic group decreased more rapidly than non-hermetic group over time could be the oxygen content within the jars of hermetic group was much lower and the CO_2 content within the jars of hermetic group was much higher than those within the jars of non-hermetic group, and the higher the CO_2 content, the more easily the red flour beetle (*Tribolium castaneum*) could be killed (Aliniazee, 1971).

From figure 6, the numbers of living red flour beetles (*Tribolium castaneum*) dropped along with time by following the exponential regression exactly for the treatment of non-hermetic (R^2=0.95), while with hermetic treatment applying, this exponential regression could be greatly affected (R^2=0.67, Figure 7), illustrated that hermetic treatment could affect the natural trend of the death of the insect. Furthermore, since all the red flour beetles (*Tribolium castaneum*) could be killed under hermetic condition within 12 days, if considering its decreasing trend until all the beetles were killed, from 0 to 12 days, the numbers of living red flour beetles dropped along with time by following the linear regression (R^2=0.93, Figure 8). A logistic regression fitting has been conducted as well, and results showed that the numbers of living red flour beetles (*Tribolium castaneum*) dropped along with time with R^2 equals to 0.77 for the treatment of non-hermetic, with R^2 equals to 0.82 for the treatment of hermetic. For the non-hermetic treatment, compared to the exponential regression, although the R^2 value is less, the logistic regression fits the overall data better by comparing the parameters (a, b, c and d) of the logistic regression (Table 4). For the hermetic treatment, the logistic regression fits the overall data well, from zero to thirty days (Table 5).

For statistical analysis, there was significant statistical evidence that there were differences in mortalities of red flour beetle (*Tribolium castaneum*) for different hermetic conditions for days 6, 9, and 12, but no differences for different hermetic conditions for days 0 and 3, illustrated that hermetic treatment became effective in killing red flour beetle (*Tribolium castaneum*) after 6 days storage (Table 6).

Maize weevil (*Sitophilus zeamais*) in maize

For hermetic storage at 27 °C, the mortality of maize weevil (*Sitophilus zeamais*) reached 100% in 12 days for all the replications, while for the non-hermetic samples (control group), at 27 °C, compared to hermetic samples, weevils have much lower mortalities for sixth and twelfth days (Figure 9 and Figure 10). The mortalities for non-hermetic treatment ranged from 20% to 50% for all the replications of the 12th day (Figure 9 and Table 7).

The reason that the maize weevil mortality of hermetic group increased more rapidly than non-hermetic group over time could be the oxygen content within the jars of hermetic group was much lower and the CO_2 content within the jars of hermetic group was much higher than those within the jars of non-hermetic group, and demonstrated that the hermetic condition could kill maize weevil effectively.

By following the method that Yakubu et al. (2011) developed to predict time to 100% mortality, with the information that with regard to the present study, including the average weight of maize in one jar, which was 88.49 g (Table 7), the volume of each jar, which was 118.29 cm^3 (4 oz), the kernel density of the maize, which was assumed to 1.24 g/ cm^3 based on the study that Yakubu et al. (2011) conducted, the amount of insects in each jar, which was 10, the oxygen level that 100% mortality could be obtained, which was assumed to 4% based on the study of Yakubu et al. (2011), the moisture content of the maize, which was estimated based on the basis of a sample which was retained in the lab, was 10.37%, the storage temperature, which was 27 °C, and the oxygen consumption, which could be estimated by using the figure of 'Average oxygen consumption of maize weevils in shelled maize' (Figure 1) in the study of Yakubu et al. (2011) with maize moisture content (10.37%) and storage temperature (27 °C), was 0.187 cm^3 per weevil per day (Interpolating the 10.37% point between points on the line 27 °C in the figure), the predicted time to 100% mortality was calculated to be 4 days. This somewhat achieved the same result compared to the outcome of the experiment of the present study, as 100% mortality was observed in one of the total six replications of hermetic treatment when samples were examined after 6 days (Table 7). However, if considering all of the six replications, the predicted time to 100% mortality calculated is different from the result that obtained in the experiment of the present study, which is 12 days.

For hermetic storage at 27 °C, the numbers of living maize weevil (*Sitophilus zeamais*) decreased to 0 in 12 days for all the replications, while for the non-hermetic samples (control group), at 27 °C, compared to hermetic samples, weevils had much higher living numbers for six to twelve days (Figure 11 and Figure 12). The numbers of living weevils for non-hermetic samples was 5-8 for all the replications of 12th day (Figure 11 and Table 7).

From figure 13, for the treatment of non-hermetic, the numbers of living maize weevils (*Sitophilus zeamais*) dropped along with time by following the exponential regression (R^2=0.97), while for the hermetic treatment, this regression was greatly affected (R^2=0.67, Figure 14). This illustrates that hermetic treatment could affect the natural trend of the death of the maize weevil. Furthermore, since all the maize weevils (*Sitophilus zeamais*) could be killed under hermetic condition within 12 days, if considering its decreasing trend until all the weevils were killed, from 0 to 12 days, the numbers of living maize weevils dropped along with time by following the linear regression (R^2=0.97, Figure 15). A logistic regression fitting has been conducted, and results showed that the numbers of living maize weevils (*Sitophilus zeamais*) dropped along with time with R^2 equals to 0.77 for the treatment of non-hermetic, with R^2 equals to 0.82 for the treatment of hermetic. For the non-hermetic treatment, compared to the exponential regression, although the R^2 value is less, the logistic regression fits the overall data better by comparing the parameters (a, b, c and d) of the logistic regression (Table 8). For the hermetic treatment, the logistic regression fits the overall data well, from zero to thirty days (Table 9).

For statistical analysis, there was significant statistical evidence that there were differences in mortalities of maize weevil (*Sitophilus zeamais*) for different hermetic conditions for days 9 and 12, but no differences for different hermetic conditions for days 0, 3, and 6. Which illustrated that hermetic treatment became effective in killing maize weevil (*Sitophilus zeamais*) after 9 days storage (Table 10).

Implications

The results of the present investigation have demonstrated that hermetic treatment is a valid and efficient way to kill red flour beetle (*Tribolium castaneum*) and maize weevil (*Sitophilus zeamais*). A model for characterizing the hermetic storage was developed to determine the effect of hermetic storage and basic information needed on the feasibility of applying it to control of red flour beetle (*Tribolium castaneum*) and maize weevil (*Sitophilus zeamais*) during wheat and maize storage has been collected. Data collected and model developed could be further used for scale up design of full-scale storage systems for grain. Hermetic storage could be a useful method for both wheat and maize storage and can prevent huge amounts of post-harvest loss and therefore is meaningful for relieving the food pressure.

Conclusions

Hermetic storage results and the time-dependent model developed from present investigation showed that hermetic storage is effective on controlling of the infestation of red flour beetle (*Tribolium castaneum*) and maize weevil (*Sitophilus zeamais*) during wheat and maize storage. 100% mortality of red flour beetle was obtained in 12 days under hermetic condition and hermetic treatment become effective on killing it after 6 days storage. 100% mortality of maize weevil was obtained in 12 days under hermetic condition and hermetic treatment become effective on killing it after 9 days storage.

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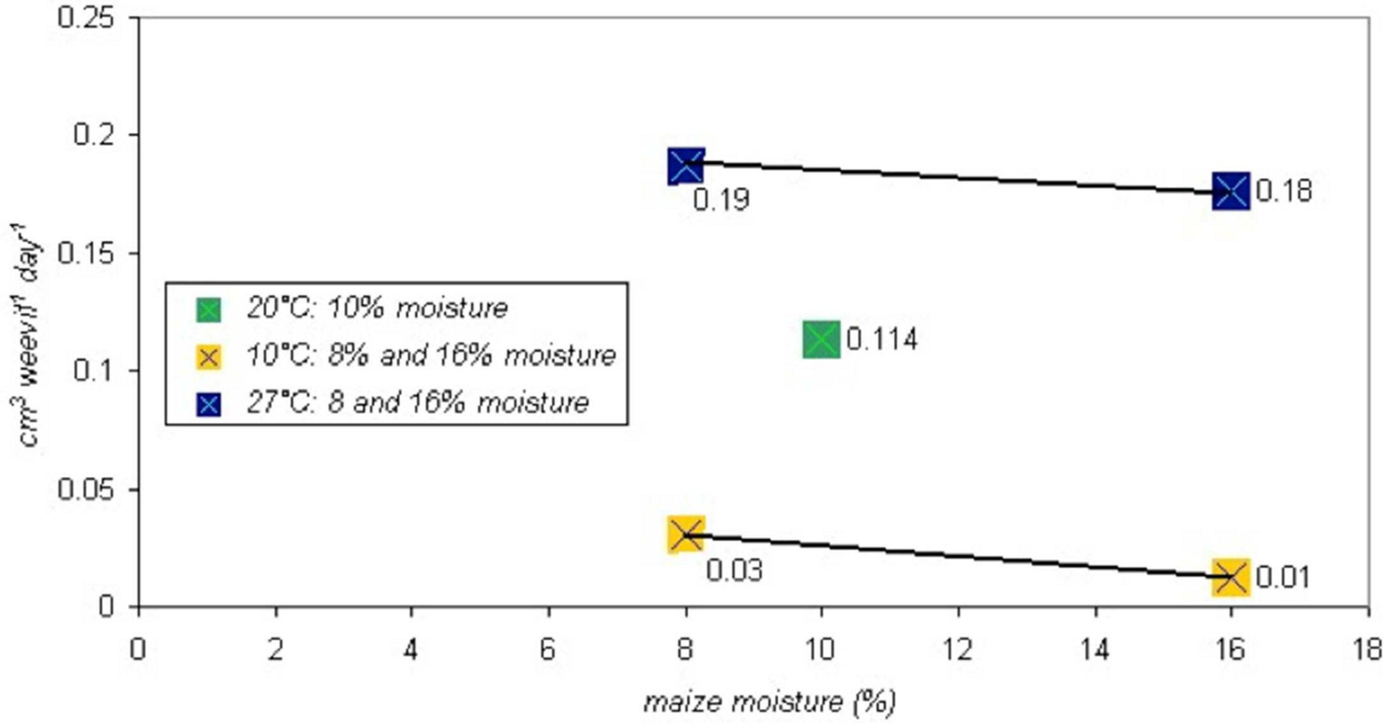

Figure 1. Average oxygen consumption of maize weevils in shelled maize (cited from Yakubu et al., 2011)

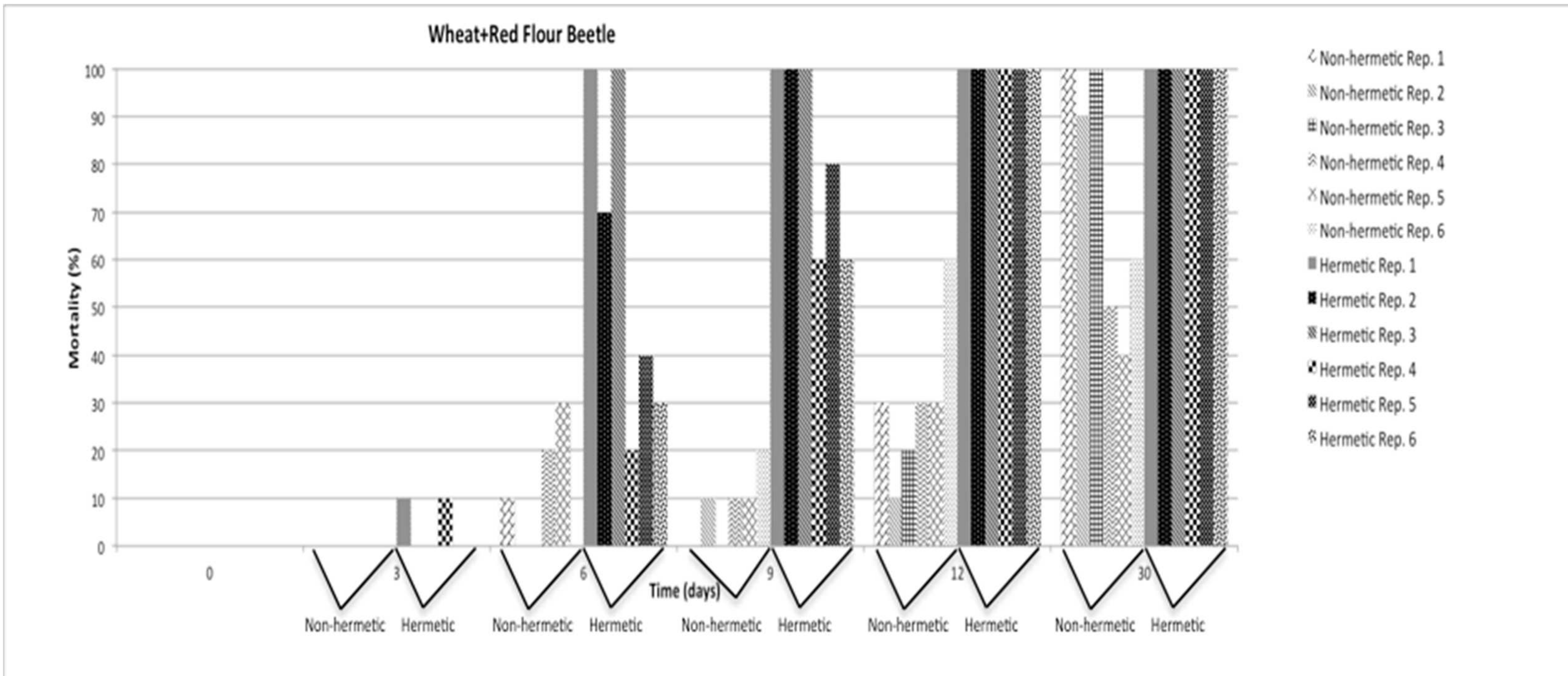

Figure 2. Mortality of red flour beetle

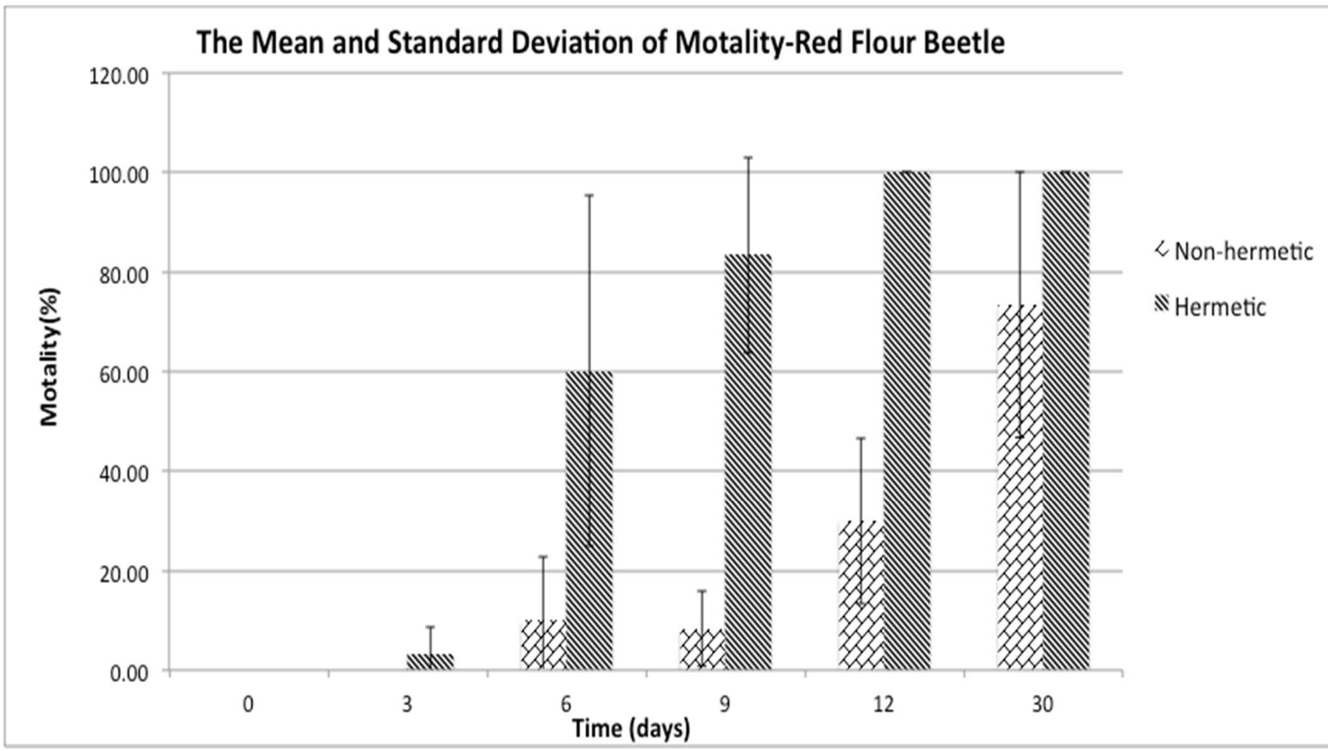

Figure 3. The mean and standard deviation of mortality - red flour beetle

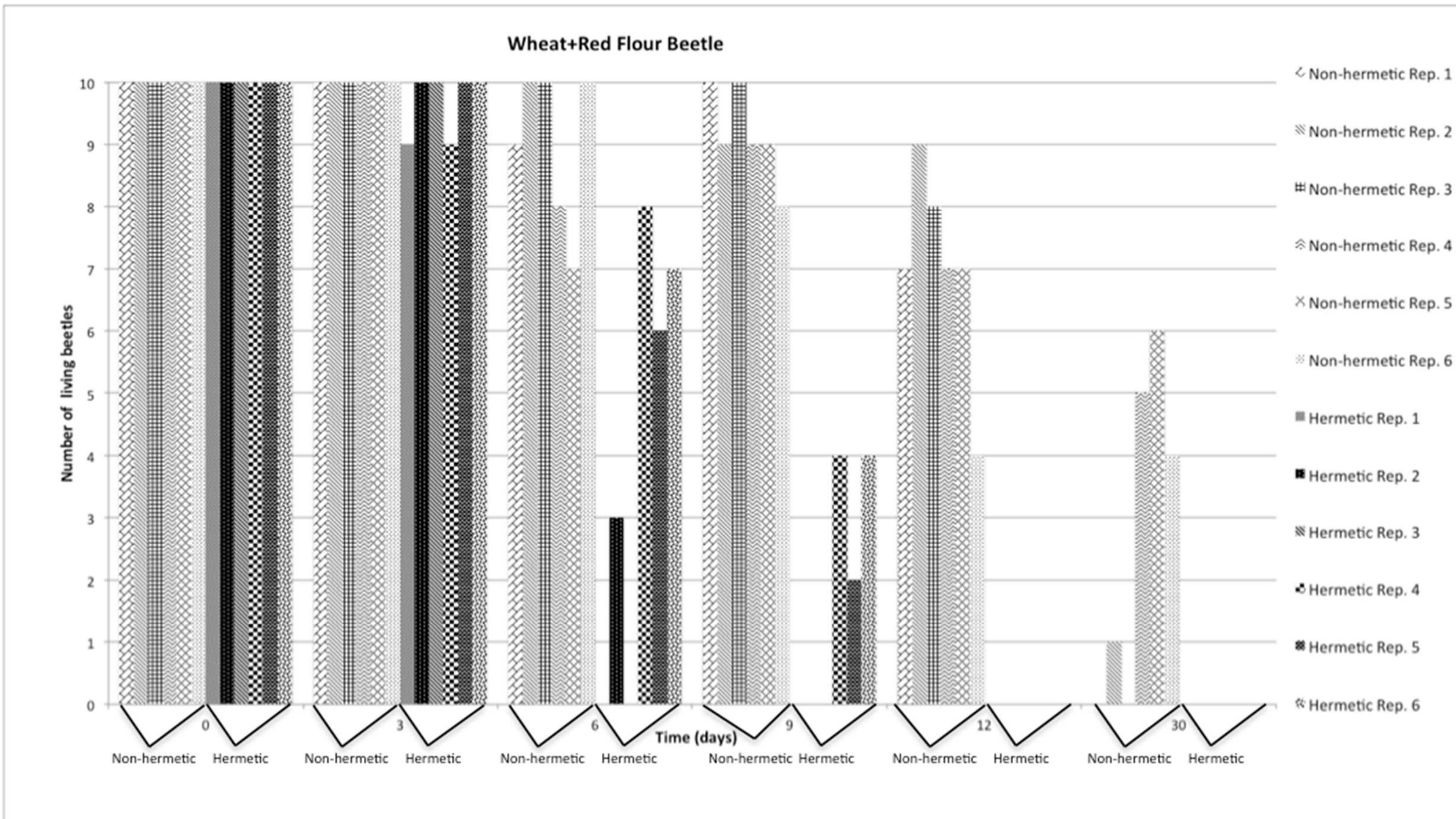

Figure 4. The number of living red flour beetle

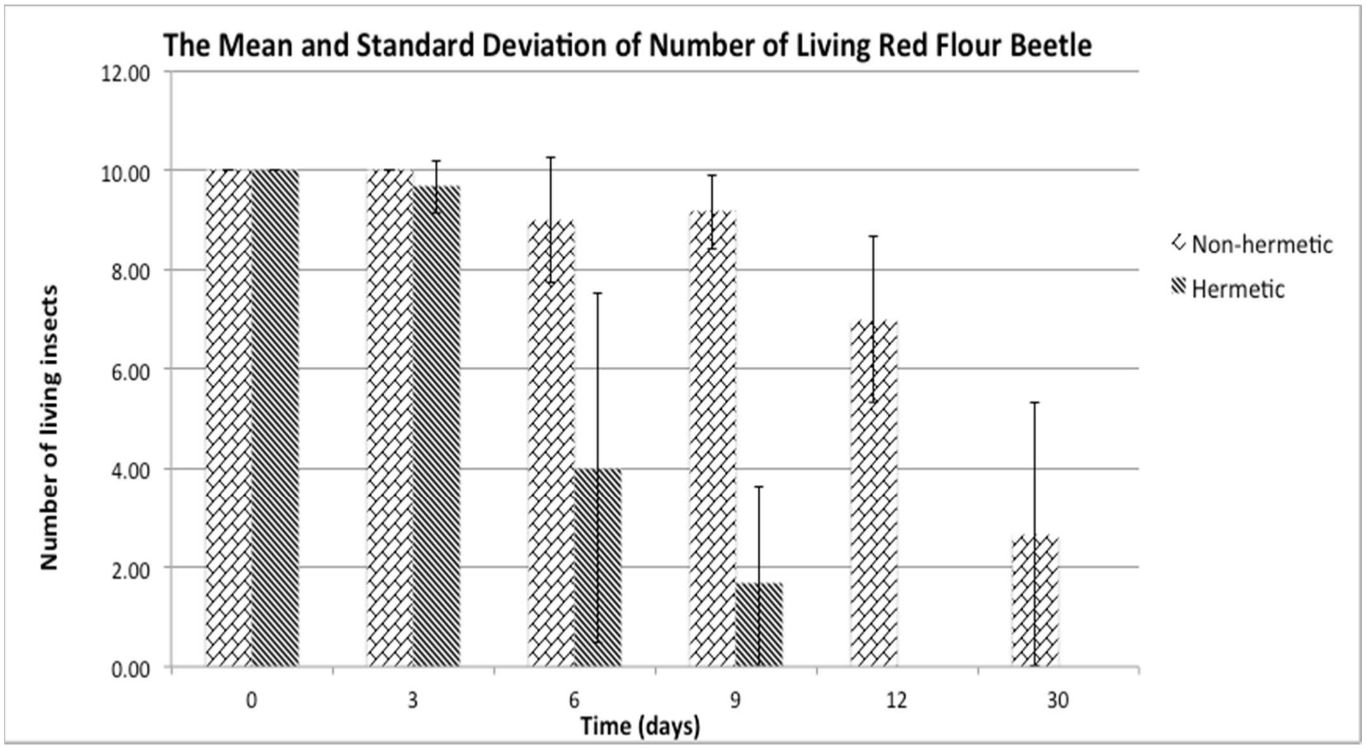

Figure 5. The mean and standard deviation of number of living red flour beetle

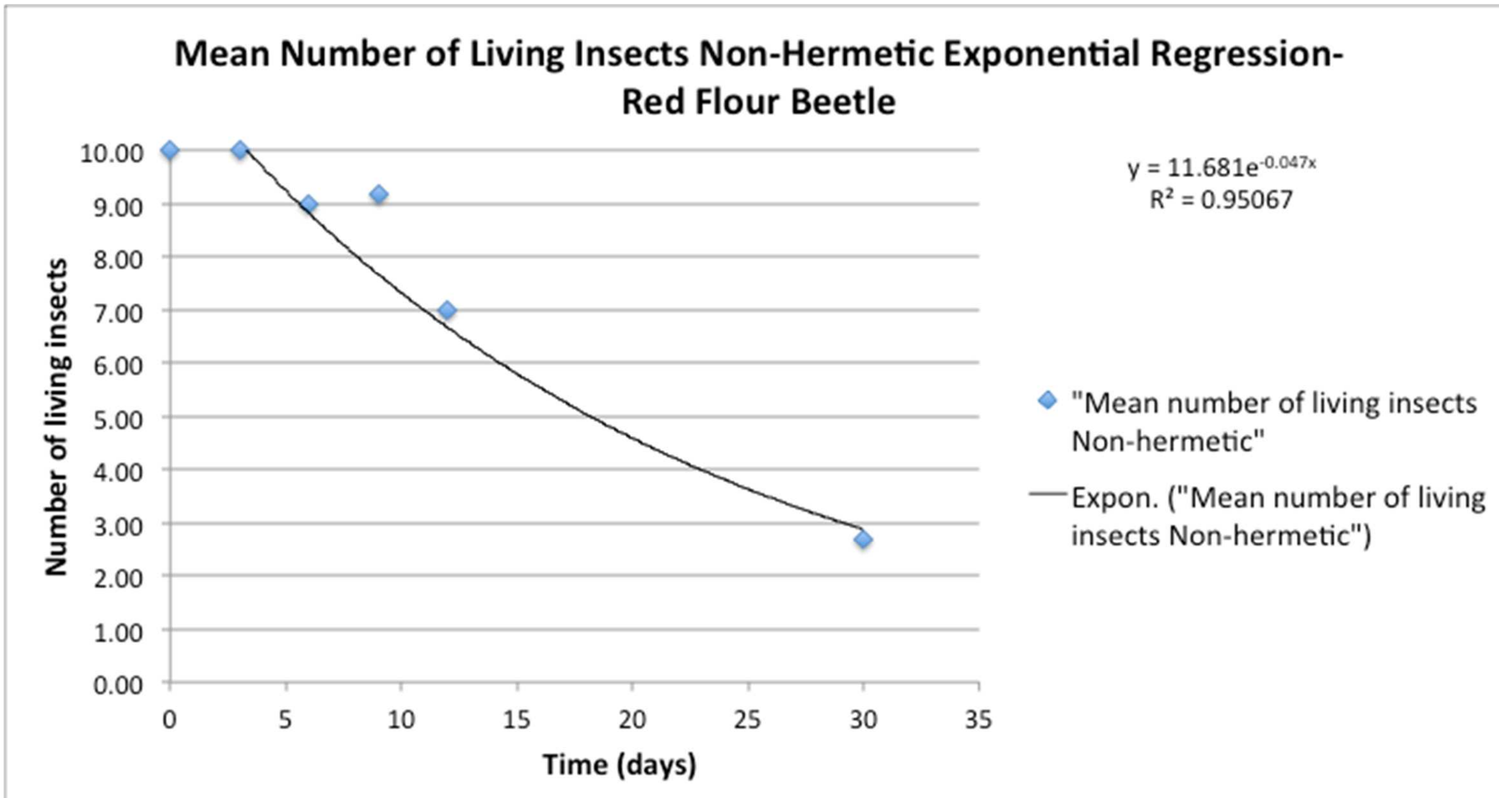

Figure 6. Exponential regression fitting of number of living red flour beetle (non-hermetic)

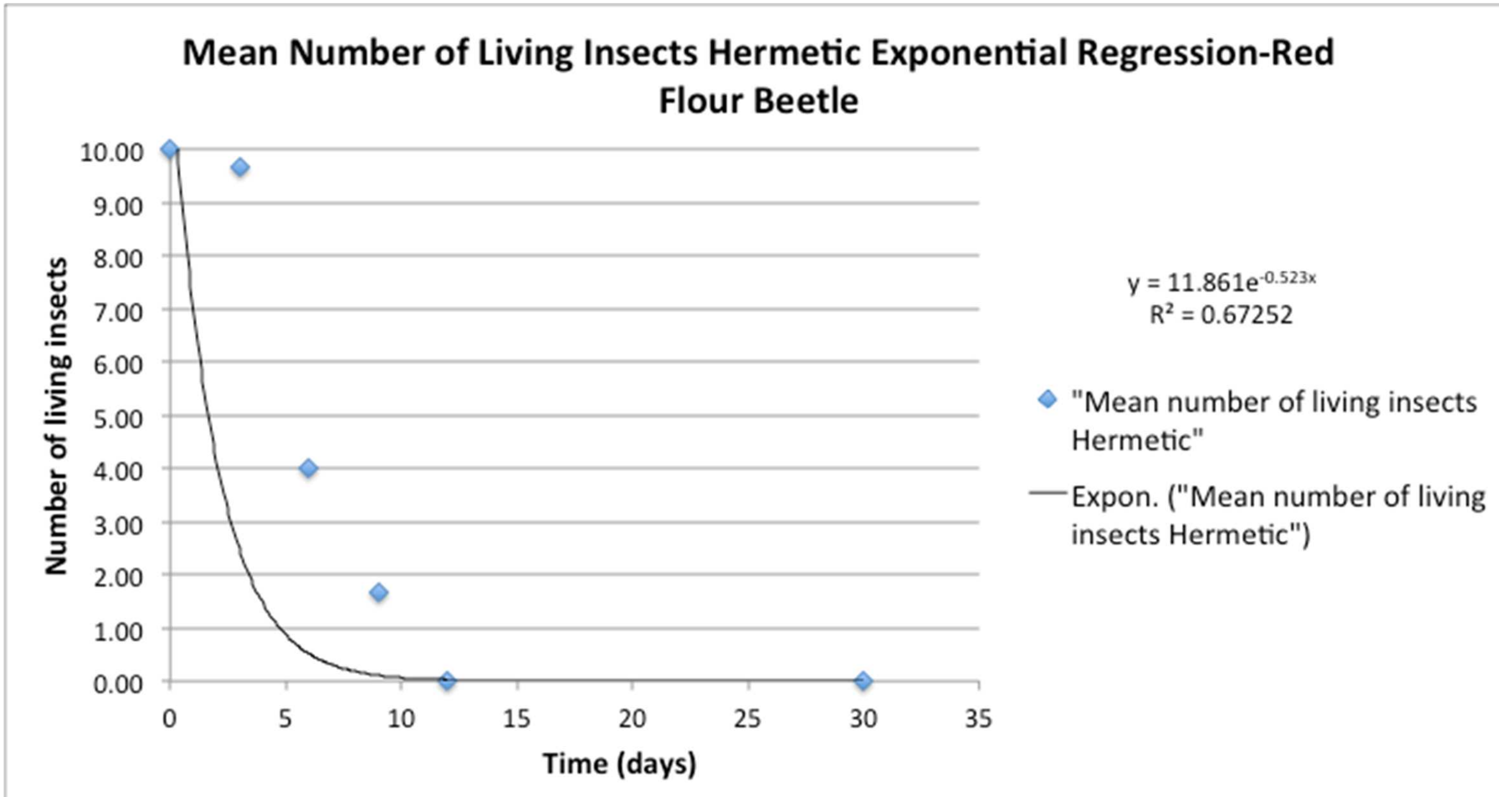

Figure 7. Exponential regression fitting of number of living red flour beetle (hermetic)

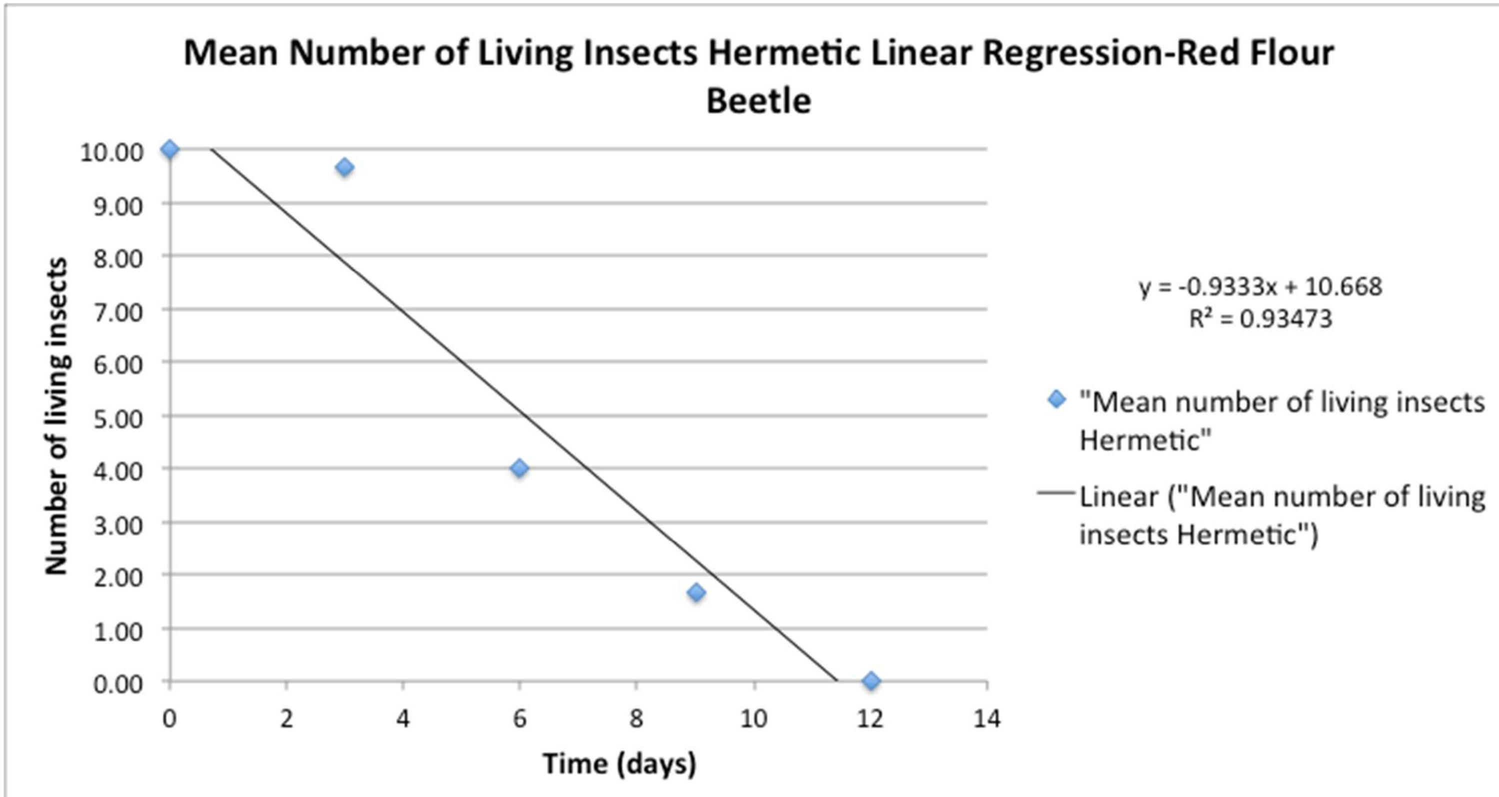

Figure 8. Linear regression fitting of number of living red flour beetle (hermetic)

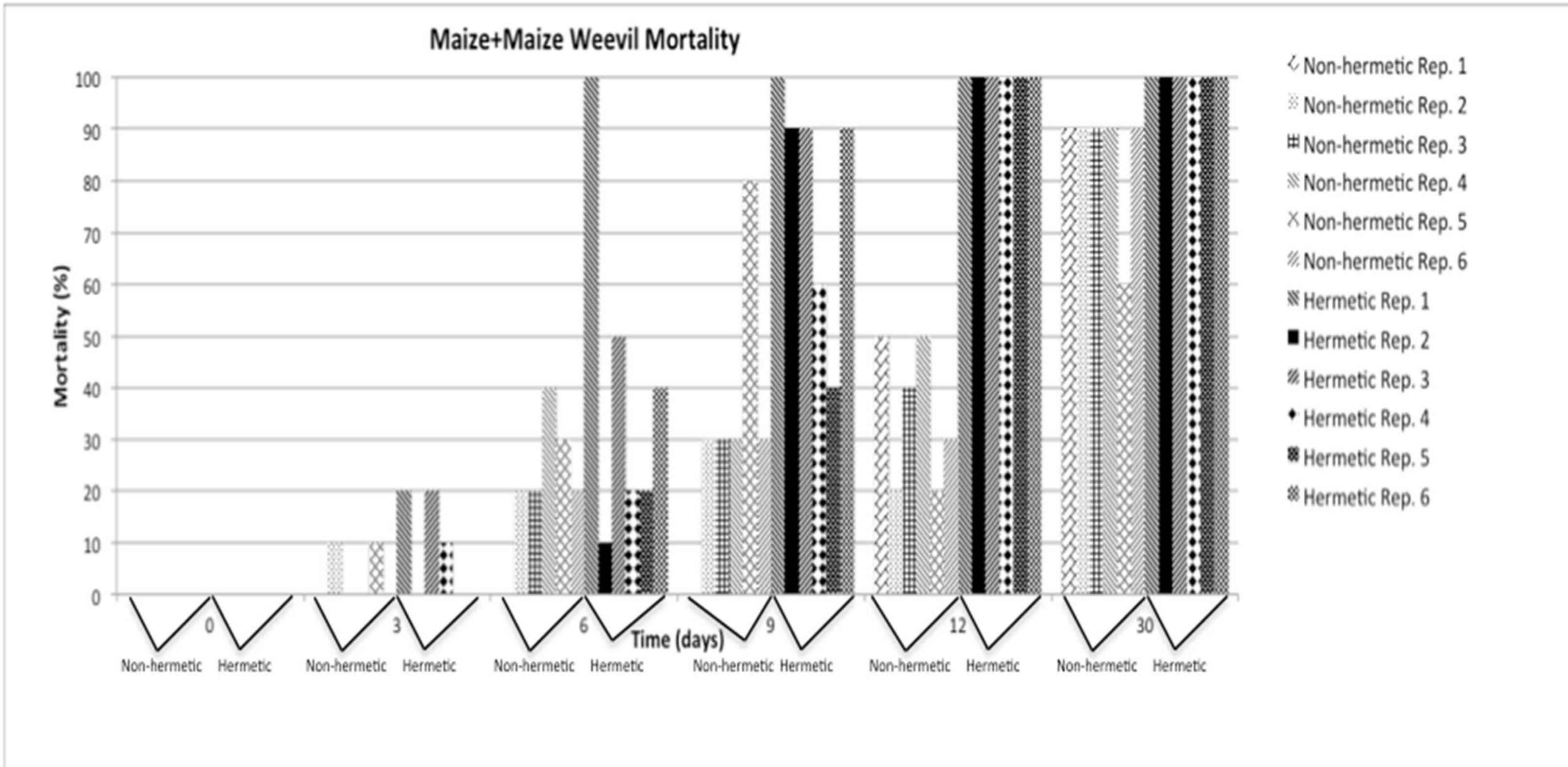

Figure 9. **Mortality of maize weevil**

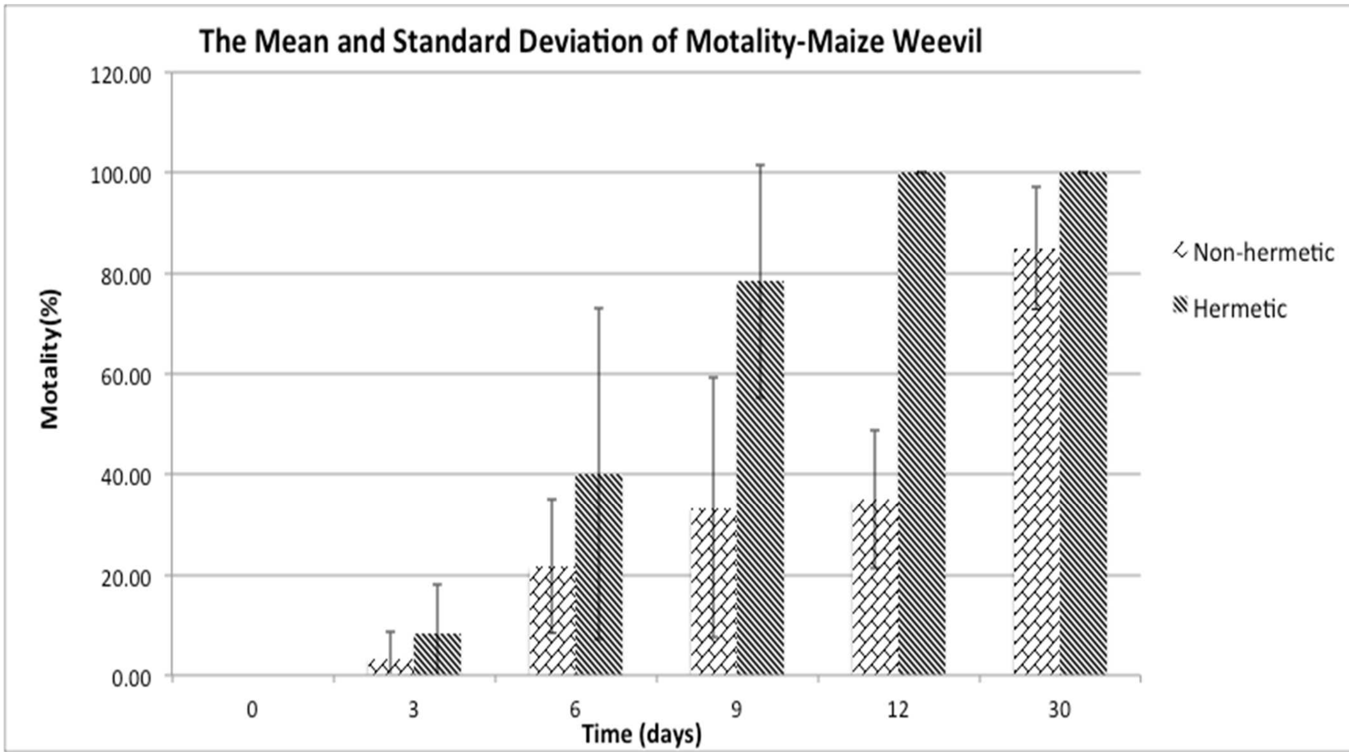

Figure 10. The mean and standard deviation of mortality – maize weevil

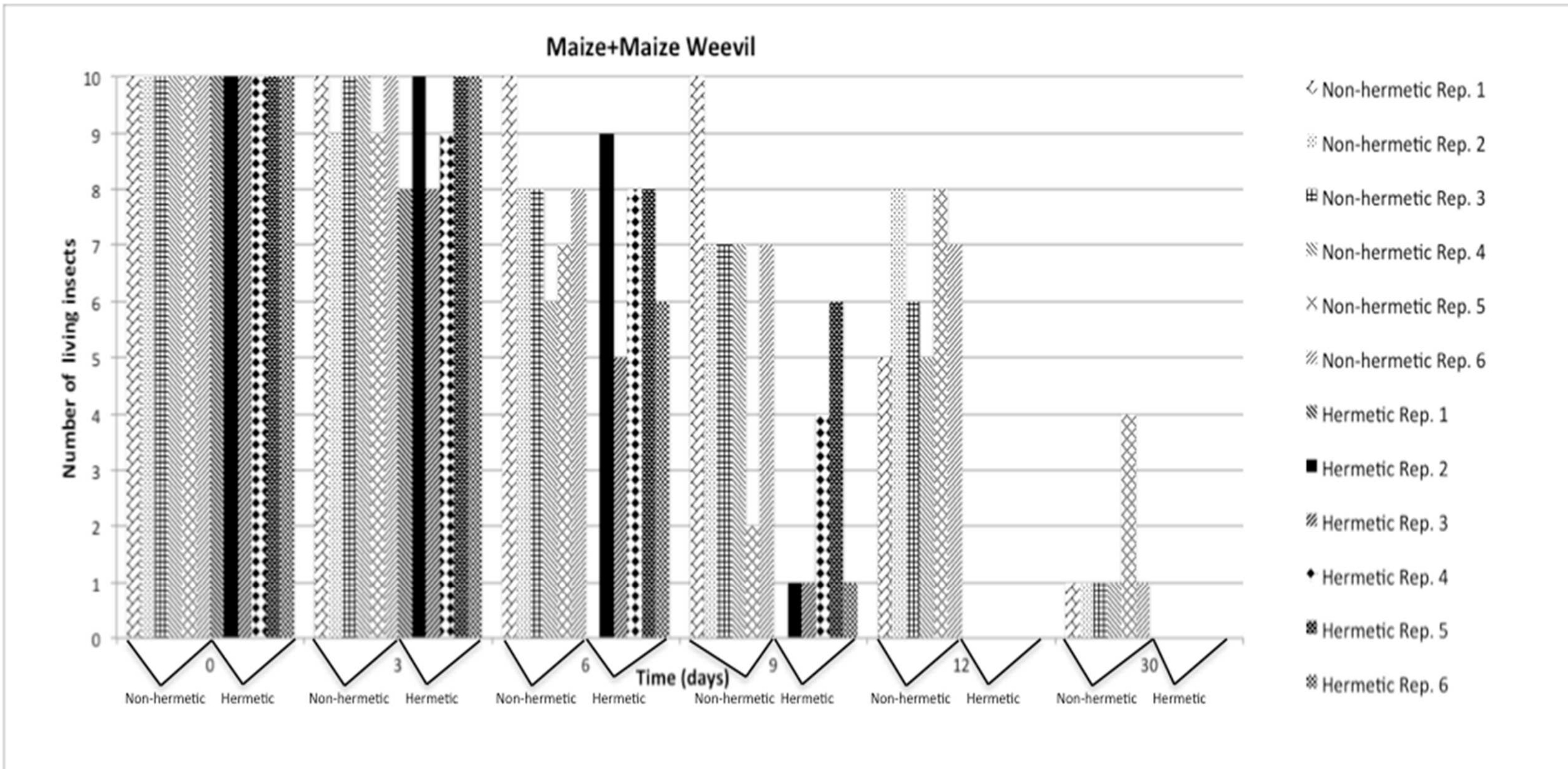

Figure 11. The number of living maize weevil

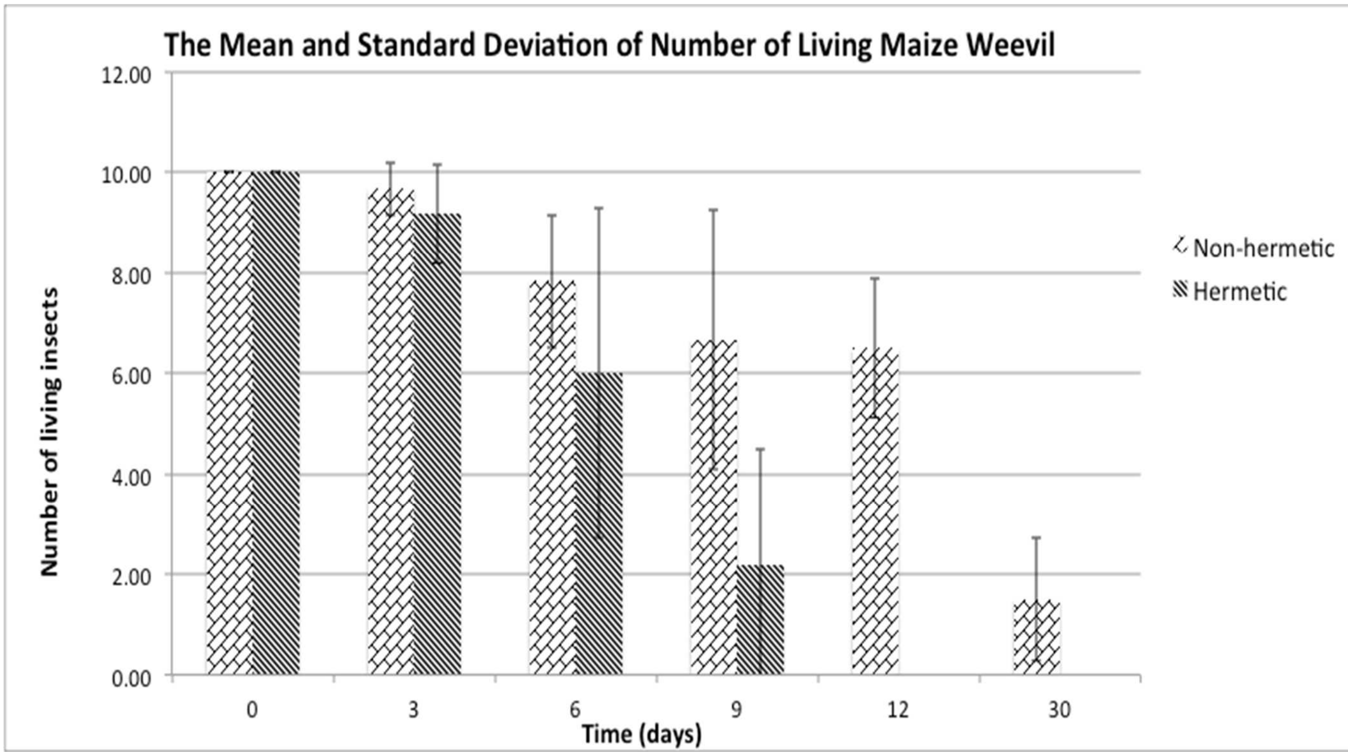

Figure 12. The mean and standard deviation of number of living maize weevil

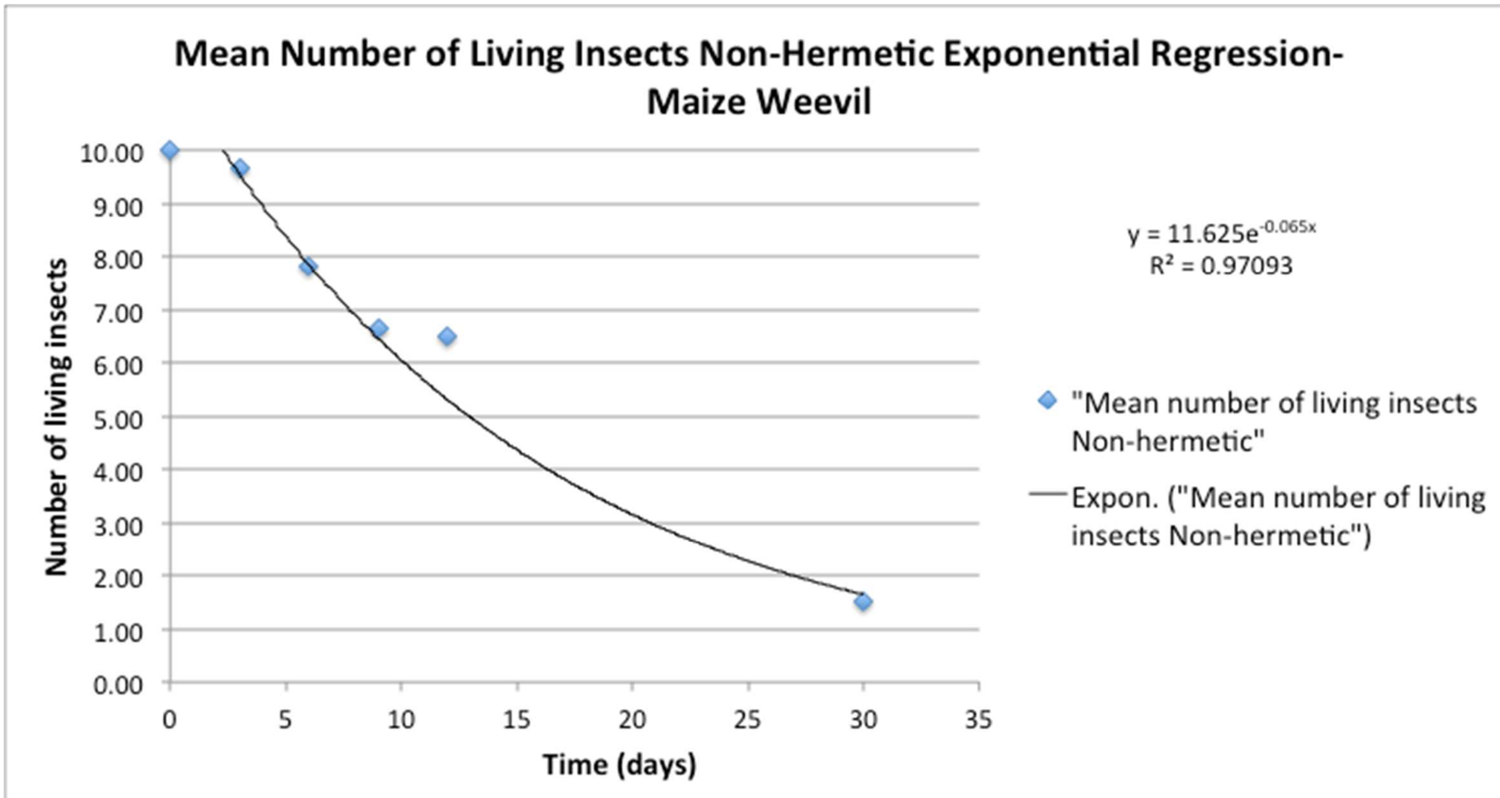

Figure 13. Exponential regression fitting of number of living maize weevil (non-hermetic)

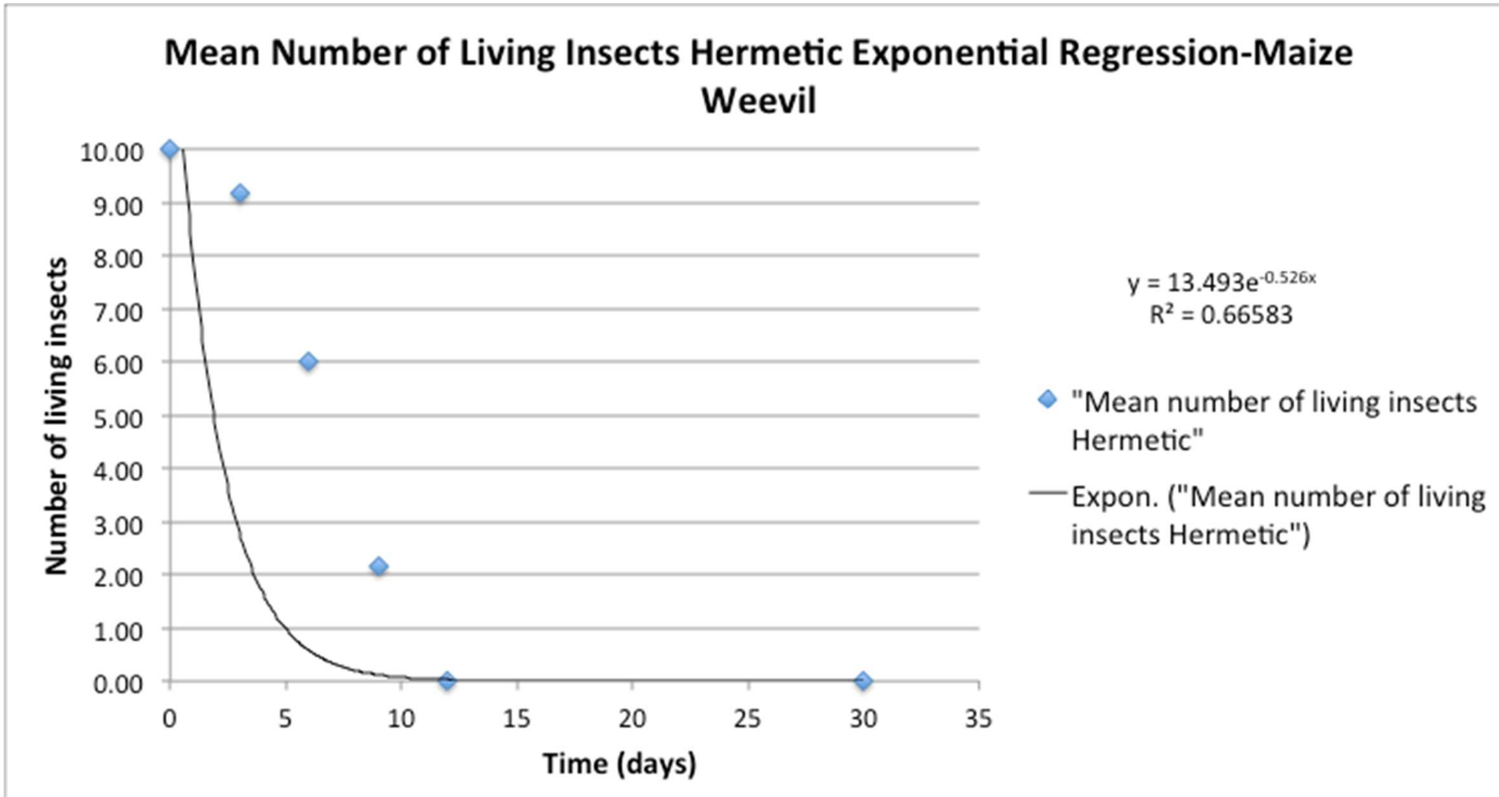

Figure 14. Exponential regression fitting of number of living maize weevil (hermetic)

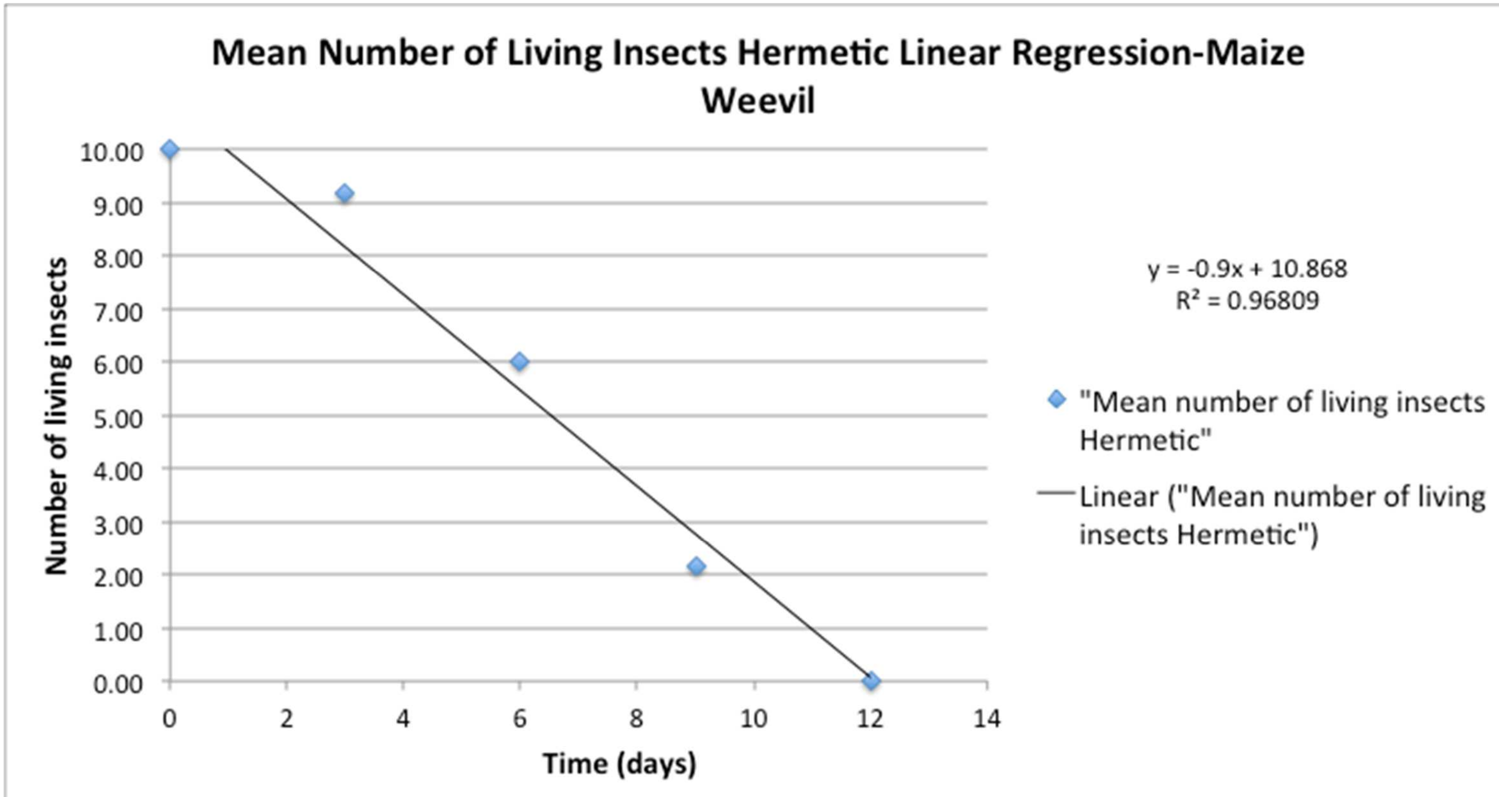

Figure 15. Linear regression fitting of number of living maize weevil (hermetic)

Table 1. Experimental design for red flour beetle

Days	Hermetic condition	Replications
3	Hermetic	1, 2, 3, 4, 5, 6
6	Hermetic	1, 2, 3, 4, 5, 6
9	Hermetic	1, 2, 3, 4, 5, 6
12	Hermetic	1, 2, 3, 4, 5, 6
30	Hermetic	1, 2, 3, 4, 5, 6
3	Non-hermetic	1, 2, 3, 4, 5, 6
6	Non-hermetic	1, 2, 3, 4, 5, 6
9	Non-hermetic	1, 2, 3, 4, 5, 6
12	Non-hermetic	1, 2, 3, 4, 5, 6
30	Non-hermetic	1, 2, 3, 4, 5, 6

Table 2. Experimental design for maize weevil

Days	Hermetic condition	Replications
3	Hermetic	1, 2, 3, 4, 5, 6
6	Hermetic	1, 2, 3, 4, 5, 6
9	Hermetic	1, 2, 3, 4, 5, 6
12	Hermetic	1, 2, 3, 4, 5, 6
30	Hermetic	1, 2, 3, 4, 5, 6
3	Non-hermetic	1, 2, 3, 4, 5, 6
6	Non-hermetic	1, 2, 3, 4, 5, 6
9	Non-hermetic	1, 2, 3, 4, 5, 6
12	Non-hermetic	1, 2, 3, 4, 5, 6
30	Non-hermetic	1, 2, 3, 4, 5, 6

Table 3. Raw data for red flour beetle

Time (days)		Red Flour Beetle Non-Hermetic							
		Rep. 1	Rep. 2	Rep. 3	Rep. 4	Rep. 5	Rep. 6	Mean	Std. dev.
3	Total insects	10.00	10.00	10.00	10.00	10.00	10.00		
	Weight of wheat (g)	101.4	98.6	98.2	95.5	98.4	94.2	97.72	
	Number of living beetles	10.00	10.00	10.00	10.00	10.00	10.00	10.00	0.00
	Mortality (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	Total insects	10.00	10.00	10.00	10.00	10.00	10.00		
	Weight of wheat (g)	100.4	97.3	100.3	98.9	100.1	96.3	98.88	
	Number of living beetles	9.00	10.00	10.00	8.00	7.00	10.00	9.00	1.26
	Mortality (%)	10.00	0.00	0.00	20.00	30.00	0.00	10.00	12.65
9	Total insects	10.00	10.00	10.00	10.00	10.00	10.00		
	Weight of wheat (g)	102.2	99.0	97.0	93.9	96.4	95.2	97.28	
	Number of living beetles	10.00	9.00	10.00	9.00	9.00	8.00	9.17	0.75
	Mortality (%)	0.00	10.00	0.00	10.00	10.00	20.00	8.33	7.53
12	Total insects	10.00	10.00	10.00	10.00	10.00	10.00		
	Weight of wheat (g))	104.6	97.8	99.8	100.1	96.6	95.4	99.05	
	Number of living beetles	7.00	9.00	8.00	7.00	7.00	4.00	7.00	1.67
	Mortality (%)	30.00	10.00	20.00	30.00	30.00	60.00	30.00	16.73
30	Total insects	10.00	10.00	10.00	10.00	10.00	10.00		
	Weight of wheat (g)	98.2	102.8	100.1	95.9	96.4	93.1	97.75	
	Number of living beetles	0.00	1.00	0.00	5.00	6.00	4.00	2.67	2.66
	Mortality (%)	100.00	90.00	100.00	50.00	40.00	60.00	73.33	26.58
Time (days)		Red Flour Beetle Hermetic							
		Rep. 1	Rep. 2	Rep. 3	Rep. 4	Rep. 5	Rep. 6	Mean	Std. dev.
3	Total insects	10.00	10.00	10.00	10.00	10.00	10.00		
	Weight of wheat (g)	101.8	97.9	101.1	98.6	95.4	98.9	98.95	
	Number of living beetles	9.00	10.00	10.00	9.00	10.00	10.00	9.67	0.52
	Mortality (%)	10.00	0.00	0.00	10.00	0.00	0.00	3.33	5.16

Table 3. Raw data for red flour beetle (continued)

Time (days)		Red Flour Beetle Hermetic							
		Rep. 1	Rep. 2	Rep. 3	Rep. 4	Rep. 5	Rep. 6	Mean	Std. dev.
6	Total insects	10.00	10.00	10.00	10.00	10.00	10.00		
	Weight of wheat (g)	98.4	99.5	99.2	100.4	100.4	99.5	99.57	
	Number of living beetles	0.00	3.00	0.00	8.00	6.00	7.00	4.00	3.52
	Mortality (%)	100.00	70.00	100.00	20.00	40.00	30.00	60.00	35.21
9	Total insects	10.00	10.00	10.00	10.00	10.00	10.00		
	Weight of wheat (g)	97.8	96.8	96.0	97.4	99.6	97.6	97.53	
	Number of living beetles	0.00	0.00	0.00	4.00	2.00	4.00	1.67	1.97
	Mortality (%)	100.00	100.00	100.00	60.00	80.00	60.00	83.33	19.66
12	Total insects	10.00	10.00	10.00	10.00	10.00	10.00		
	Weight of wheat (g)	103.2	97.2	97.7	103.5	96.2	101.6	99.90	
	Number of living beetles	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Mortality (%)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	0.00
30	Total insects	10.00	10.00	10.00	10.00	10.00	10.00		
	Weight of wheat (g)	102.0	98.4	98.5	101.5	100.0	98.8	99.87	
	Number of living beetles	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Mortality (%)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	0.00
Average weight of wheat (g)								98.65	

Table 4. Logistic regression fitting of number of living red flour beetle (non-hermetic)

R^2	0.77				
Logistic parameters	Value	Standard Error	t-value	95% Confidence Limits	P>|t|
a	2.65	0.65	4.1	1.32 -- 3.98	0.00036
b	6.89	0.83	8.30	5.18 -- 8.60	0.00000
c	12.91	1.17	11.06	10.51 -- 15.32	0.00000
d	7.40	6.53	1.13	-6.02 -- 20.81	0.26727

Table 5. Logistic regression fitting of number of living red flour beetle (hermetic)

R^2	0.82				
Logistic parameters	Value	Standard Error	t-value	95% Confidence Limits	P>|t|
a	-0.20	0.78	-0.26	-1.79 -- 1.40	0.80054
b	11.51	3.80	3.03	3.69 -- 19.33	0.00552
c	5.12	1.28	3.99	2.49 -- 7.76	0.00048
d	3.33	1.96	1.70	-0.70 -- 7.36	0.10103

Table 6. Statistical analysis results for red flour beetle

Days	Mean Hermetic Mortality (%)	Mean Non-hermetic Mortality (%)	Mean Mortality Difference (%)	P-Value
0	0.00	0.00	0.00	1.0
3	3.33	0.00	3.33	0.145
6	60.00	10.00	50.00	0.0084
9	83.33	8.33	75.00	<0.0001
12	100.00	30.00	70.00	<0.0001
30	100.00	73.33	26.67	0.0338

Table 7. Raw data for maize weevil

Time (days)		Maize weevil Non-hermetic							
		Rep. 1	Rep. 2	Rep. 3	Rep. 4	Rep. 5	Rep. 6	Mean	Std. dev.
3	Total insects	10.00	10.00	10.00	10.00	10.00	10.00		
	Weight of maize (g)	90.8	88.4	88.0	89.5	88.5	84.0	88.20	
	Number of living weevils	10.00	9.00	10.00	10.00	9.00	10.00	9.67	0.52
	Mortality (%)	0.00	10.00	0.00	0.00	10.00	0.00	3.33	5.16
6	Total insects	10.00	10.00	10.00	10.00	10.00	10.00		
	Weight of maize (g)	91.8	92.1	90.0	88.2	89.5	89.0	90.10	
	Number of living weevils	10.00	8.00	8.00	6.00	7.00	8.00	7.83	1.33
	Mortality (%)	0.00	20.00	20.00	40.00	30.00	20.00	21.67	13.29
9	Total insects	10.00	10.00	10.00	10.00	10.00	10.00		
	Weight of maize (g)	91.6	89.7	87.0	88.9	88.1	83.7	88.17	
	Number of living weevils	10.00	7.00	7.00	7.00	2.00	7.00	6.67	2.58
	Mortality (%)	0.00	30.00	30.00	30.00	80.00	30.00	33.33	25.82
12	Total insects	10.00	10.00	10.00	10.00	10.00	10.00		
	Weight of maize (g)	88	92.5	87.2	87.6	84.1	87.5	87.82	
	Number of living weevils	5.00	8.00	6.00	5.00	8.00	7.00	6.50	1.38
	Mortality (%)	50.00	20.00	40.00	50.00	20.00	30.00	35.00	13.78
30	Total insects	10.00	10.00	10.00	10.00	10.00	10.00		
	Weight of maize (g)	89.6	92.8	87.0	84.5	88.3	90.8	88.83	
	Number of living weevils	1.00	1.00	1.00	1.00	4.00	1.00	1.50	1.22
	Mortality (%)	90.00	90.00	90.00	90.00	60.00	90.00	85.00	12.25
Time (days)		Maize weevil Hermetic							
		Rep. 1	Rep. 2	Rep. 3	Rep. 4	Rep. 5	Rep. 6	Mean	Std. dev.
3	Total insects	10.00	10.00	10.00	10.00	10.00	10.00		
	Weight of maize (g)	92.0	89.2	89.2	89.0	88.5	87.3	89.20	
	Number of living weevils	8.00	10.00	8.00	9.00	10.00	10.00	9.17	0.98
	Mortality (%)	20.00	0.00	20.00	10.00	0.00	0.00	8.33	9.83

Table 7. Raw data for maize weevil (continued)

Time (days)		Maize weevil Hermetic							
		Rep. 1	Rep. 2	Rep. 3	Rep. 4	Rep. 5	Rep. 6	Mean	Std. dev.
6	Total insects	10.00	10.00	10.00	10.00	10.00	10.00		
	Weight of maize (g)	90.2	90.5	89.0	85.3	86.5	84.9	87.73	
	Number of living weevils	0.00	9.00	5.00	8.00	8.00	6.00	6.00	3.29
	Mortality (%)	100.00	10.00	50.00	20.00	20.00	40.00	40.00	32.86
9	Total insects	10.00	10.00	10.00	10.00	10.00	10.00		
	Weight of maize (g)	93.0	90.2	84.6	89.7	87.7	86.2	88.57	
	Number of living weevils	0.00	1.00	1.00	4.00	6.00	1.00	2.17	2.32
	Mortality (%)	100.00	90.00	90.00	60.00	40.00	90.00	78.33	23.17
12	Total insects	10.00	10.00	10.00	10.00	10.00	10.00		
	Weight of maize (g)	90.0	90.9	85.9	86.7	88.7	86.9	88.18	
	Number of living weevils	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Mortality (%)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	0.00
30	Total insects	10.00	10.00	10.00	10.00	10.00	10.00		
	Weight of maize (g)	90.6	87.5	86.9	87.7	87.5	88.1	88.05	
	Number of living weevils	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Mortality (%)	100.00	100.00	100.00	100.00	100.00	100.00	100.00	0.00
Average weight of maize (g)								88.49	

Table 8. Logistic regression fitting of number of living maize weevil (non-hermetic)

R^2	0.77				
Logistic parameters	Value	Standard Error	t-value	95% Confidence Limits	P>|t|
a	-34.31	786.49	-0.04	-1650.96 -- 1582.33	0.96553
b	45.91	797.78	0.06	-1593.96 -- 1685.78	0.95455
c	159.69	5577.60	0.03	-11305.23 -- 11624.61	0.97738
d	0.76	3.52	0.22	-6.46 -- 7.99	0.82993

Table 9. Logistic regression fitting of number of living maize weevil (hermetic)

R^2	0.82				
Logistic parameters	Value	Standard Error	t-value	95% Confidence Limits	P>|t|
a	-0.23	0.70	-0.32	-1.67 – 1.22	0.74949
b	9.54	1.22	7.84	7.04 – 12.05	0.00000
c	6.91	0.59	11.68	5.70 – 8.13	0.00000
d	4.74	1.62	2.93	1.42 – 8.06	0.00694

Table 10. Statistical analyses results for maize weevil

Days	Mean Hermetic Mortality (%)	Mean Non-hermetic Mortality (%)	Mean Mortality Difference (%)	P-Value
0	0.00	0.00	0.00	1.0
3	8.33	3.33	5.00	0.296
6	40.00	21.67	18.33	0.234
9	78.33	33.33	45.00	0.0099
12	100.00	35.00	65.00	<0.0001
30	100.00	85.00	15.00	0.013

CHAPTER 3. EFFICIENCY ANALYSIS AND ASSESSMENT OF A CLOSED CIRCUIT GRAIN DRYING SYSTEM

Abstract

Grain drying is an efficient way to reduce the internal moisture content of grain and thus keeping the quality of it. This work analyzed and assessed the efficiency of a closed circuit grain drying system named the DOROTHY cyclone moisture removal system. The DOROTHY system was designed and manufactured by the Loebach brothers (David R. Loebach and Joseph E. Loebach, Loebach Brothers Inc., sailboatcw@gmail.co), and consisted of a wagon to hold the grain and a drying apparatus composed of a compressor, an evaporation-condensation-system and a fan. We conducted fall and winter trials to measure energy consumption and moisture removal and thus calculated the drying efficiency by dividing the energy consuming by the amount of moisture removal for each trial. We also examined the effect of the drying process on germination by conducting germination tests. Results showed that in the fall trial, the drying system was very efficient and consumed 1480 Btu to remove a pound of water, and did not decrease germination. In the winter trial, the efficiency decreased by approximately half compared to the fall trial with 2760 Btu/lb water removal but was still comparable to the common drying systems used in industry, and germination performance was not affected.

Introduction

Grains play very important role in food supply for the majority of the population throughout the world, and they are the major sources of carbohydrates and proteins (Warchalewski et al., 2000).

Like any other hygroscopic material, grain could hold moisture (Shove and Oliver, 1967). The moisture within grain could be beneficial to the respiration of the grain and the grain quality (Brooker et al., 1992). Additionally, high moisture content of the grain could increase the chance of mold fungi infection. Hence, grain drying could be an efficient way to reduce the respiration rate and the probability of mold fungi infection by reducing the grain's internal moisture content and thus keeping the quality of the grains (Brooker et al., 1992).

Grain drying is process of moving moisture out of grain, it could be divided into on-farm drying and off-farm drying. On-farm drying includes drying with bin, non-bin, and combination dryers while Off-farm drying is the drying with elevator grain dryers including three categories of crossflow, concurrent flow and mixed flow (Brooker et al., 1992). The drying capacity and temperature could be different for each category of drying (Brooker et al., 1992). A number of studies have been conducted with respect to grain drying. Schulman et al. (1993) studied the head rice yield of two long-grain varieties dried at different air temperatures and relative humidities and observed that the head rice yield changed little when drying with air conditions corresponding to higher equilibrium moisture content but decreased significantly when drying with lower equilibrium moisture content. Fan et al., (2000) observed that drying condition and drying duration had significant interactive effects on the head rice yield and they found that a decrease of rice moisture content at the early drying stages did not affect the head rice yield until a certain moisture content level was reached. They also found that without affecting yield, the amount of moisture removal increased while the harvest moisture content increased. Watson and Hitara (1962) observed that the millability of corn could be reduced at drying temperatures above 82.2 °C, for which two-thirds of the original starch quantity were released by the dried corn and at 93 °C it produced very little starch. Mistry et al. (1993) evaluated the effect of high temperature and high humidity during drying in wet-milling characteristics of corn. The effect of drying condition on the corn starch recovered was investigated (Haros and Suarez, 1997). In their study, they indicated that starch recovery of corn decreased as both initial moisture content of the grains and drying air temperature increased. Malumba et al., observed that the starch yield from corn kernel wet-milling process dropped significantly and the salt-soluble protein solubility indexes decreased continuously while the drying temperature increases when corn kernels were dried between 54 °C and 130 °C. Furthermore, Gomes et al. (2003) found that when soybean were slow dried at 25 °C, the green pigments were almost degraded and chlorophyll could be removed effectively therefore enhance the quality of the grain.

Grain drying is a very energy-intensive process (Gunasekaran and Thompson, 1986). The energy required for drying is often more than the energy used from planting through harvesting for most grains (Enlow, 1982; Verma, 1982). A minimum of approximately 2.5 to 2.67 MJ/kg of water removed was required for grain drying (Fluck and Baird, 1979) yet in actual practice, in terms of different type and variety of grain, drying air temperature and air flow rate, moisture content of grain, and drying method, 3 to 8 MJ/kg of water removed was required (Kreyger, 1972; Rao and Pfost, 1980;

Stroshine et al., 1983; Bakker-Arkema et al., 1983). To obtain a good drying result and high drying efficiency, a good drying apparatus is essential. A high efficiency drying apparatus could reduce the dying cost and therefore increase the grain production profit by reducing the energy consumption while achieving a good drying performance. Research showed that as much as 10% increase in profits could be obtained by only improving energy efficiency by 1% (Beedie, 1995). In this regard, many studies have been undertaken to analyze efficiencies of drying systems. Lipper and Davis (1959) found that by using solar heated air, drying could be completed by consuming less electricity and in a shorter time than by natural air system. Syahrul et al. (2002) found that during fluidized bed drying of moist particles, energy efficiency decreased sharply with decreasing moisture content of the material. With respect to grain drying by using bin dryer, Kenyon and Shove (1969) and Shove (1973) have found that the drying efficiency could be enhanced by intermittent blowing of hot and cold air. Harnoy and Radajewski (1982) have conducted an experiment with corn, and in their study, they introduced blowing ratio to define the ratio of full cycle time and the period of time that the grain is exposed to the hot air, while the full cycle time includes the hot air blowing time and the resting time, during which the hot air supply is stopped. In their study, they found that most of the energy saving could be achieved up to the blowing ratio of around 8. A dryeration process was introduced by Foster (1964) and could save energy of up to 25% (Peterson, 1979) and improve grain quality by reducing stress cracks in grain kernels (McKenzie et al., 1967). In this process grain is first dried at approximately 60 °C to within 2% of desired final moisture and then is transferred the grain to a separate dryeration bin without cooling. In the dryeration bin, the grain is tempered 6 to 8 hours with no aeration and then is slow cooled using ambient air at about 0.6 m^3/min for 8 to 12 hours (Morrison, 1979). In 2013, Hanna et al., (2014) conducted energy measurement and analysis on farm of Ames and Nashua with 'batch-in-bin' drying systems and they presented that the energy needed to remove a pound of water from the grain ranged from 2010 to 3310 British thermal units. The 'batch-in-bin' drying systems is composed with vertical stirring augers inside each bin and a fan which blew heated air upward from the under-floor plenum.

Although the moisture removal rate with high-temperature drying (drying air temperature: approximately 60 °C) is much faster, drying grain with heated air may results in low quality grain in terms of higher amounts of stress-cracked kernels, lower breakage susceptibility, and lower test weight (Gunasekaran and Thompson, 1986). Thus, could affect germination performance. On the other hand, traditional low-temperature drying with ambient air could enhance grain quality but the grain dried with this process is highly susceptible to spoilage (Pierce, 1985). Therefore, a drying method that could maintain grain quality and avoid it from spoilage is needed. Meanwhile, the method should be energy efficient.

In order to enhance the drying efficiency by reducing energy consumption while maintaining good grain quality and making on-farm drying more convenient, a closed circuit drying system named the DOROTHY cyclone moisture removal system was designed and manufactured by the Loebach brothers (David R. Loebach and Joseph E. Loebach, Loebach Brothers Inc., sailboatcw@gmail.co). The system consisted of a wagon holding grain and a drying apparatus composed of a compressor, an evaporation-condensation-system including an evaporator and a condenser, and a fan. The present study was conducted to analyze and assess the efficiency of this drying system. Drying trials in fall and winter were run separately to measure energy consuming and moisture removal, thus the drying efficiency could be calculated.

Materials and Methods

The closed circuit grain drying system used in the present study was designed and manufactured by the Loebach brothers (David R. Loebach and Joseph E. Loebach, Loebach Brothers Inc., sailboatcw@gmail.co), named the DOROTHY cyclone moisture removal system (U.S. Patent No. 13-871,494, Moisture removal system, April 26th, 2013). The system consisted of a wagon holding grain and a drying apparatus composed of a compressor (Copeland CF06K6E-PFV-979, Emerson climate technologies incorporated, Sidney, OH 45365), an evaporation-condensation-system (assembled by David R. Loebach and Joseph E. Loebach, Loebach Brothers Inc., sailboatcw@gmail.co) including two evaporators and a condenser, and a household type centrifugal fan (GE motors GE5KCP39KGV804S, 0.5 hp, GE Energy Management, Atlanta, GA 30339) (Figure 1 and Figure 2). The air dried by the drying apparatus was blown into the wagon to dry the grain and the moist air out from the wagon was dried by the drying apparatus again, the water in the moist air was condensed and then exhausted (Figure 1). Electricity was used by the system as the only energy resource.

Corn with moisture content of 17% to 20% wet basis was used in the present study. It was obtained from local market (Ames, IA) and stored in BioCentury Research Farm (Iowa State University, 1327 U Avenue, Boone, IA) until used.

A power meter (Landis+Gyr MX-92-270-908, Landis+Gyr AG, Alpharetta, GA 30022) was assembled to the system to record the electric energy consumption. For the fall trial, there were 2 temperature probes (Omega OM-EL-USB-2-LCD, Omega Engineering, Inc., Stamford, CT 06907) were employed to capture the temperature and relative humidity, separately for moist air out from wagon with corn and dry air from drying apparatus (Figure 1). For the winter trial, as ambient temperature was very low, three temperature probes (Omega OM-EL-USB-2-LCD, Omega Engineering, Inc. Stamford, CT 06907) were used, separately for moist air out from wagon with corn, dry air from drying apparatus and ambient air.

For the fall trial, before the beginning of the drying process, total 2680 pounds of corn with average moisture content of 18.9% wet basis were loaded into the wagon. The drying process continued for more than 2 days and end at 50 hours after beginning based on the suggestion of the manufacturer (David R. Loebach and Joseph E. Loebach, Loebach Brothers Inc., sailboatcw@gmail.co). Samples were picked up before and after drying process for moisture content measurement and germination test.

For the winter trial, before the beginning of the drying process, total 2300 pounds of corn with average moisture content of 18.9% wet basis were loaded into the wagon. The drying process continued for approximately 2 days and end at 47 hours after beginning based on the suggestion of the manufacturer (David R. Loebach and Joseph E. Loebach, Loebach Brothers Inc., sailboatcw@gmail.co) and the drying results of the fall trial. Samples were picked up before and after drying process for moisture content measurement and germination test.

An oven (Thermo 6530, Thermo Fisher Scientific, Waltham, MA 02451) was employed for air oven moisture measurement. To determine moisture content (Bern and Rosentrater, 2014), 3 grams of corn was sampled and placed in the oven maintained at 103 °C. At the end of 72h, sample was removed and reweighed quickly. The moisture content (wet basis) could be computed by:

(Total grain weight-sample weight after oven)/Total grain weight (1)

Moisture measurement was conducted for samples before drying process and after drying process separately and the moisture change (wet basis) was calculated by subtracting the moisture content of sample after drying process from that before drying process. Total 3 samples were tested for each treatment for each fall and winter trial and the average was reported.

An incubator (Fisher Scientific Isotemp incubator 650D, Thermo Fisher Scientific, Waltham, MA 02451) was used in germination test. The germination test followed the process that conducted by Williams et al. (2014) which sampled 50 kernels of corn and put them between two pieces of wet, sterile filter paper (Hy-Vee 8-12 Cups Coffee Filter, Hy-Vee Inc., West Des Moines, IA 50266). The paper together with kernel was rolled and sealed into a plastic bag. After incubation at 30 °C for 7 days, the number of germinated kernel was accounted and the germination ratio was computed. One replication of germination test was conducted for each fall and winter trial.

The water content (lb) of the corn before drying process was calculated by multiplying the total weight of corn in the wagon before drying process and its moisture content (wet basis). The water content (lb) of the corn after drying process was calculated by multiplying the total weight of corn in the wagon after drying process and its moisture content (wet basis). The water removal (lb) was calculated by subtracting the water content after drying process from water content before drying process.

The drying efficiency in Btu/lb water removal were calculated by dividing the energy consumption (Btu) by water removal (lb).

Results and Discussion

Fall trial

In total 399000 Btu of electric energy was consumed for fall trial. System efficiency was calculated as 1480 Btu/lb water removal (Table 1).

Compared to the drying method (bin dryer, combination of bin and fan) that Hanna et al. (2014) used, the efficiency of which was 2010-3310 Btu/lb water removal, the present system was more efficient, compared to drying efficiency of the Centrifugal dryers (Sukup, TC series), which was 2380-2520 Btu/lb water removal (Sukup, 2013), the present system was more efficient.

For temperature, both the moist air after drying the corn and the dry air from the drying apparatus (captured by probe, Figure 1) were following the trend of environment temperature. However, in a same time period, the temperature of the moist air was lower than the temperature of the dry air (Figure 3 and Figure 4).

For relative humidity (RH), the moist air followed the trend of decreasing, gradually from 85% to 40% (Figure 3). This illustrates that the moisture content of the air after drying the corn was decreasing while the moisture content of the corn was decreasing during the drying process. The RH of the dry air from the drying apparatus (Figure 1) was changing from 55% to 35%, showed that the drying apparatus could effectively change the relative humidity of the air from 85% to 55% at the start point of the drying process and could change it from 40% to 35% at the end point (Figure 3 and Figure 4).

From the germination test, 86% of the corn before drying process successfully germinated while 96% of the corn after drying process successfully germinated. This illustrates that the drying process was not harmful to the germination performance of the corn.

Winter trial

In total 359000 Btu of electric energy was consumed for winter trial. System efficiency was calculated as 2760 Btu/lb water removal (Table 2).

Compared to the drying method (bin dryer, combination of bin and fan) that Hanna et al. (2014) used, the efficiency of which was 2010-3310 Btu/lb water removal, the efficiency of present system working in winter was approximately the same. Compared to drying efficiency of the Centrifugal dryers (Sukup, TC series), which was 2380-2520 Btu/lb water removal (Sukup, 2013), the efficiency of present system working in winter was a little lower. Compared to the efficiency of fall trial, which was 1480 Btu/lb water removal, the winter trial was less efficient. The lower working environmental temperature was one of the root causes of that. The working environmental temperature of fall trial was 15 to 25 degree Celsius, while the working environmental of winter trial was -3 to 10 degree Celsius (Figure 5).

For temperature, both the moist air after drying the corn and the dry air from the drying apparatus were following the trend of environment temperature (Figure 5, Figure 6 and Figure 7). However, in a same time period the temperature of the moist air was lower than the temperature of the dry air (Figure 6 and Figure 7).

For relative humidity (RH), the moist air followed the trend of decreasing, gradually from 85% to 55% (Figure 6). This illustrates that the moisture content of the air after drying the corn was decreasing while the moisture content of the corn was decreasing during the drying process. The RH of the dry air from the drying apparatus (Figure 1) was changing from 65% to 50%, which showed that the drying apparatus could effectively change the relative humidity of the air from 85% to 65% at the start point of the drying process and could change it from 55% to 50% at the end point (Figure 6 and Figure 7).

For germination test, 86% of the corn before drying process successfully germinated while 84% of the corn after drying process successfully germinated. This illustrates that the drying process was not harmful to the germination performance of the corn.

Conclusions

The efficiency of the present system operating in winter was comparable to the common drying systems in the market. This illustrates that the present system could work well under winter condition and its efficiency was acceptable. However, compare to the fall trial, the efficiency of the winter trial was approximately half (1480 Btu/lb water removal to 2760 Btu/lb water removal). As conclusion, the present system could work well in winter but could work with high efficiency in fall. The environmental temperature is important to achieve the high efficiency of the present drying system.

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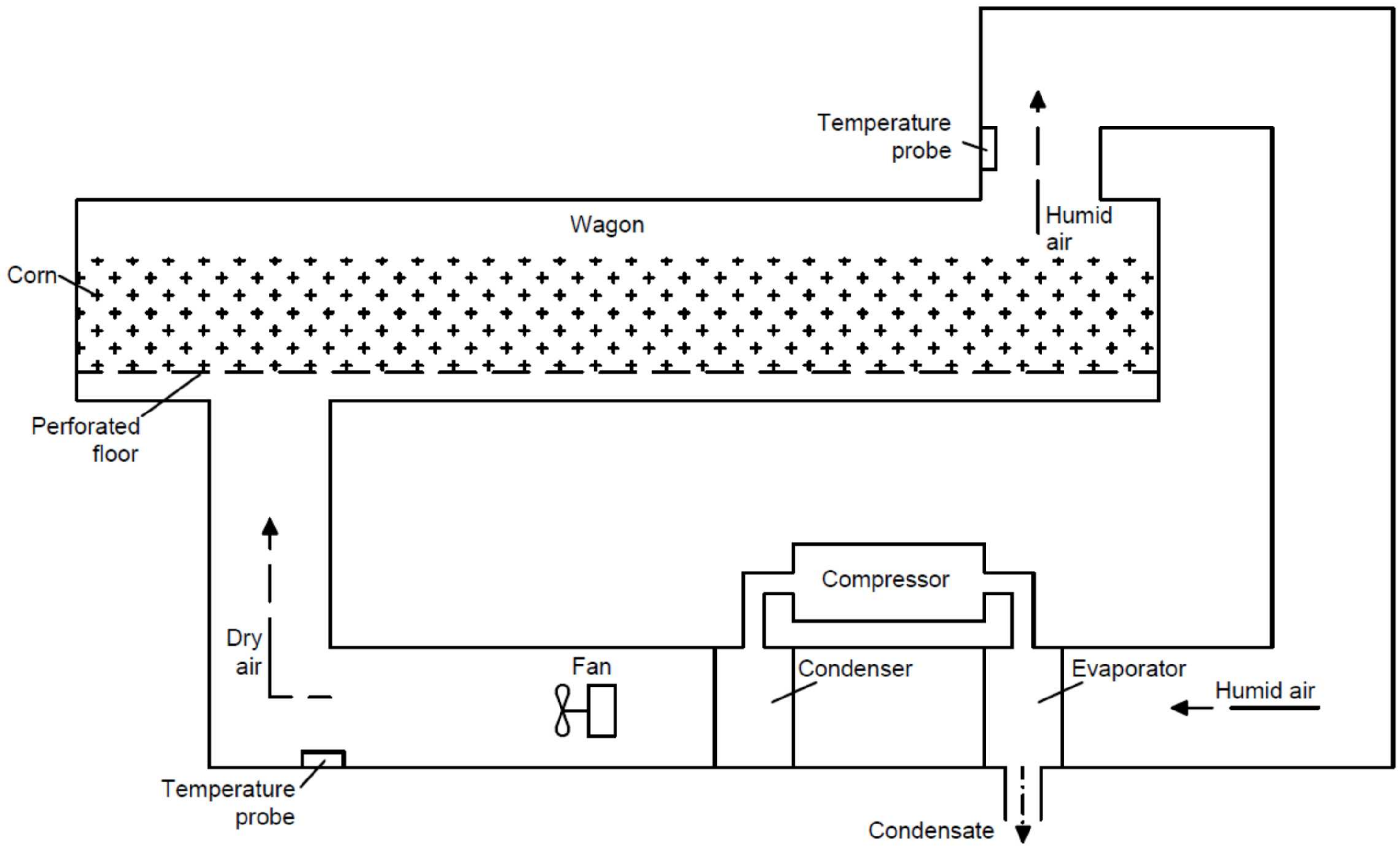

Figure 1. Grain drying system

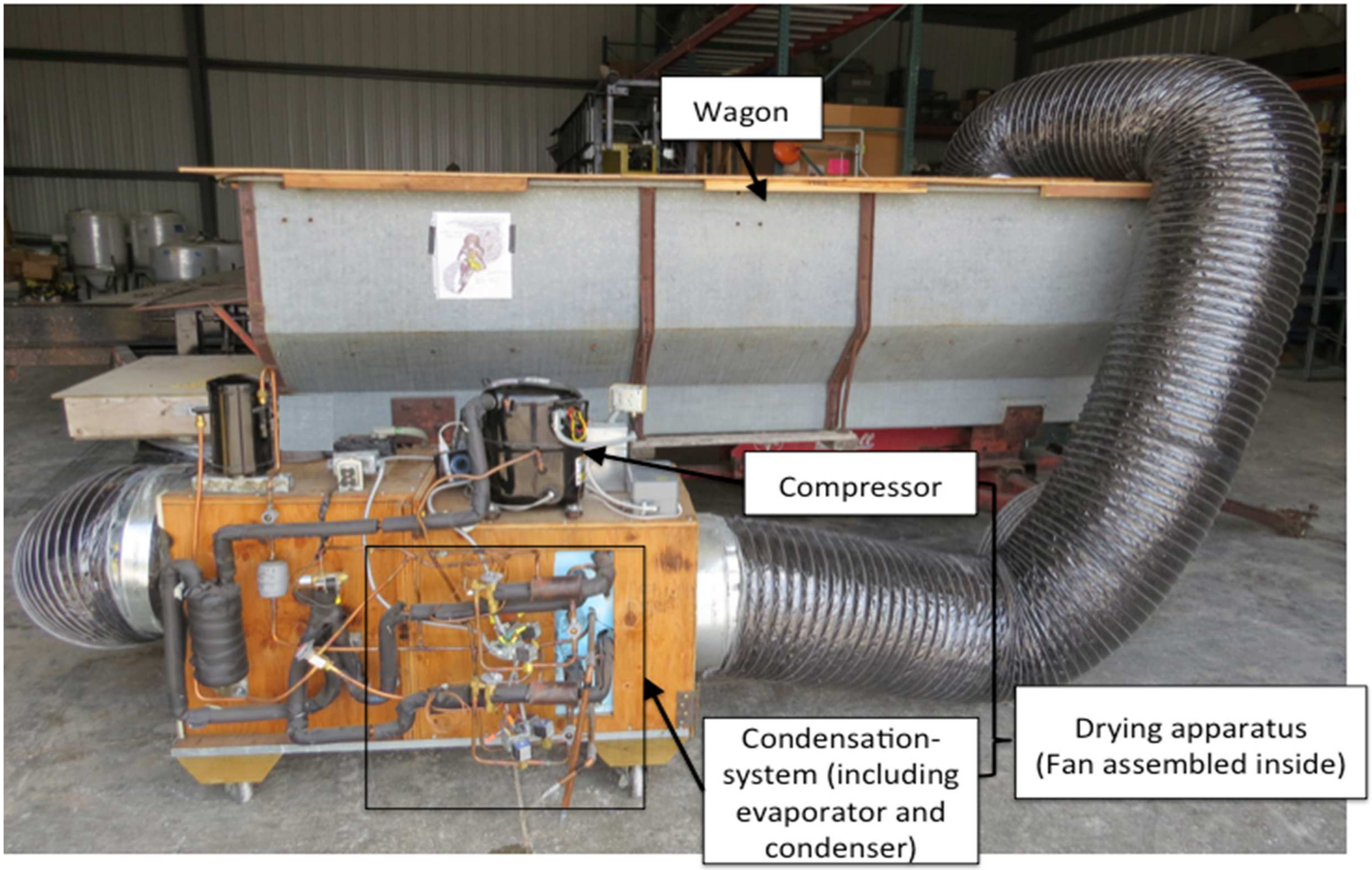

Figure 2. Picture of the grain drying system

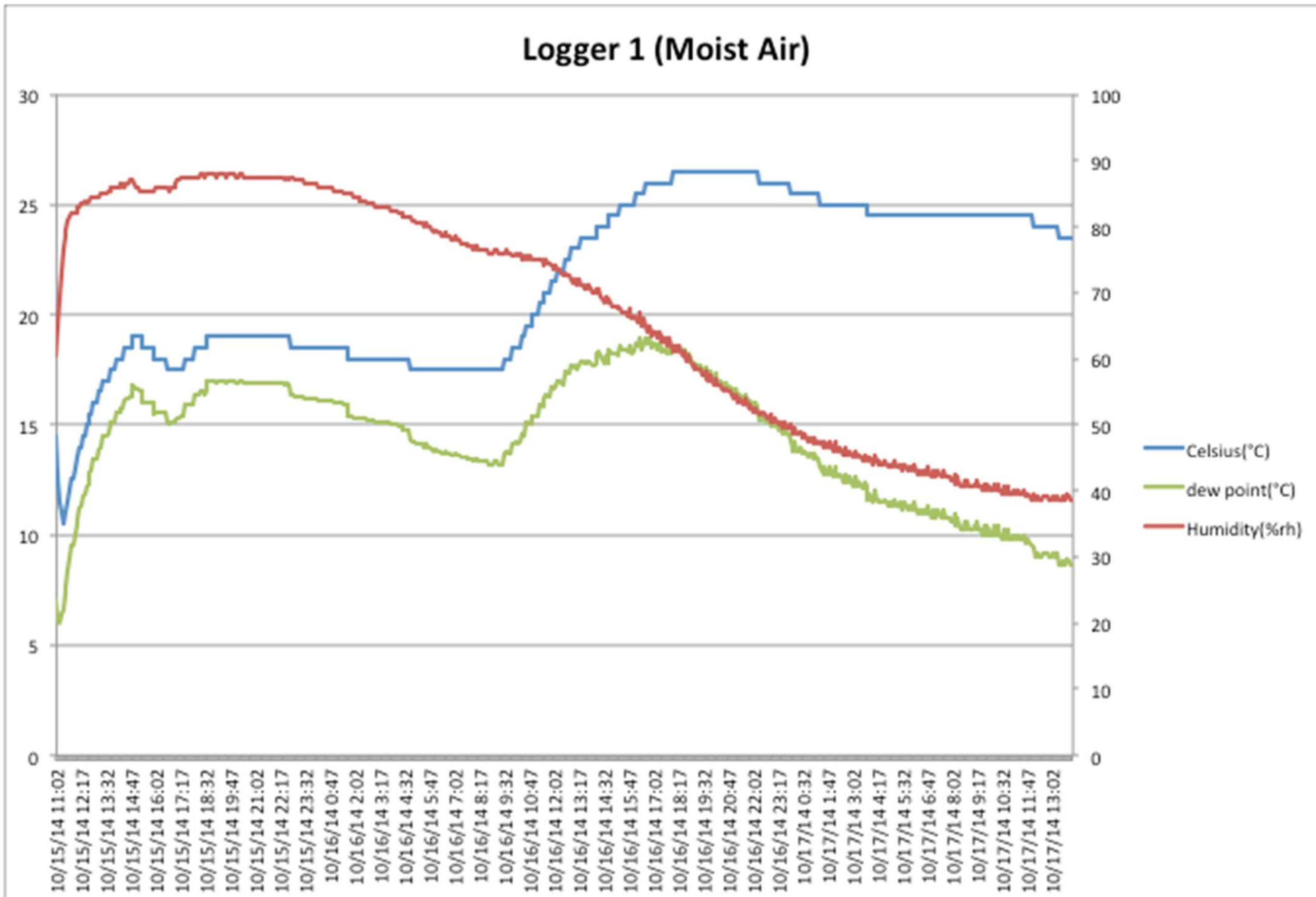

Figure 3. Temperature and relative humidity record of the air after drying the corn (fall trial)

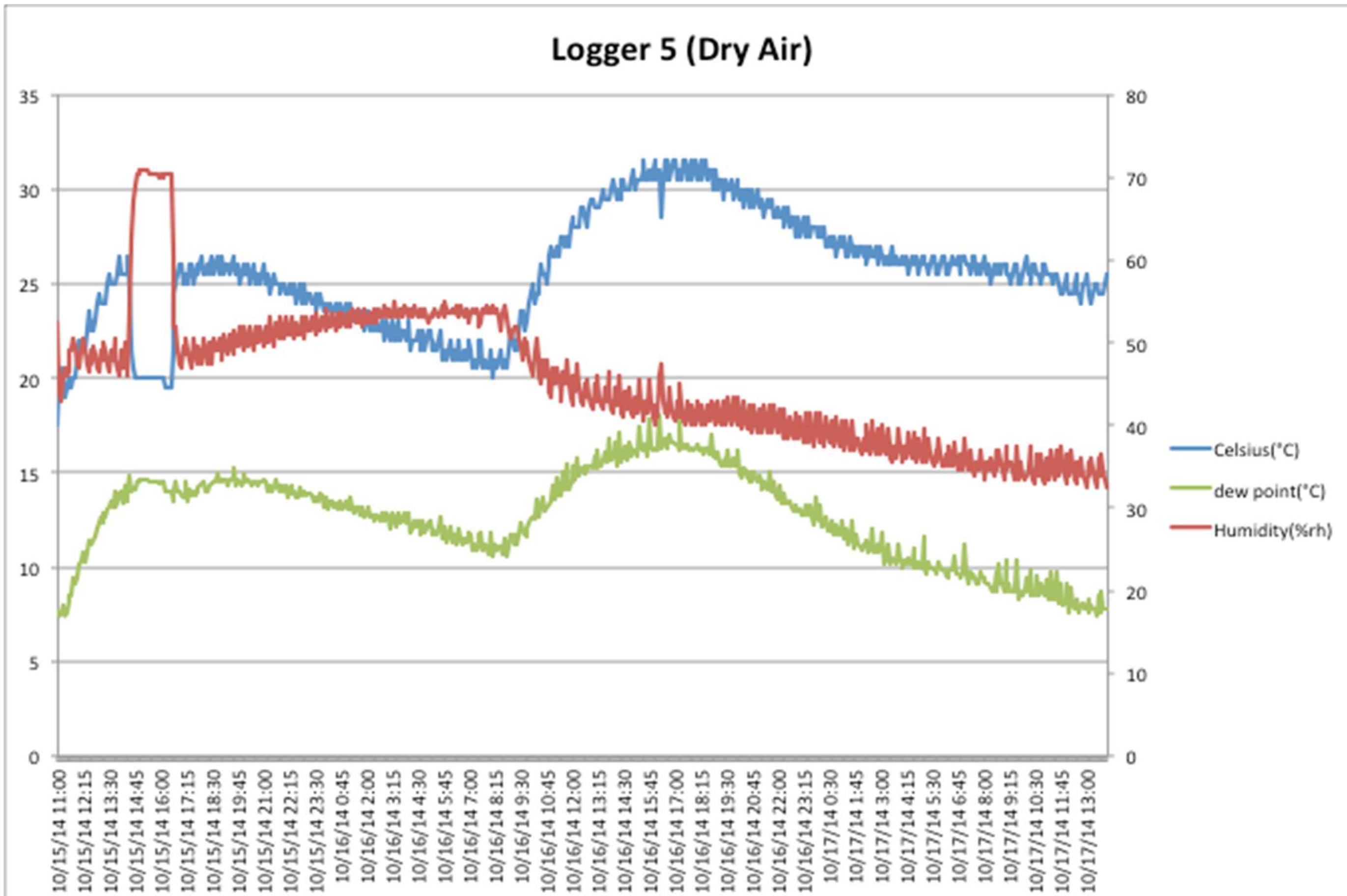

Figure 4. Temperature and relative humidity record of the air from drying apparatus (fall trial)

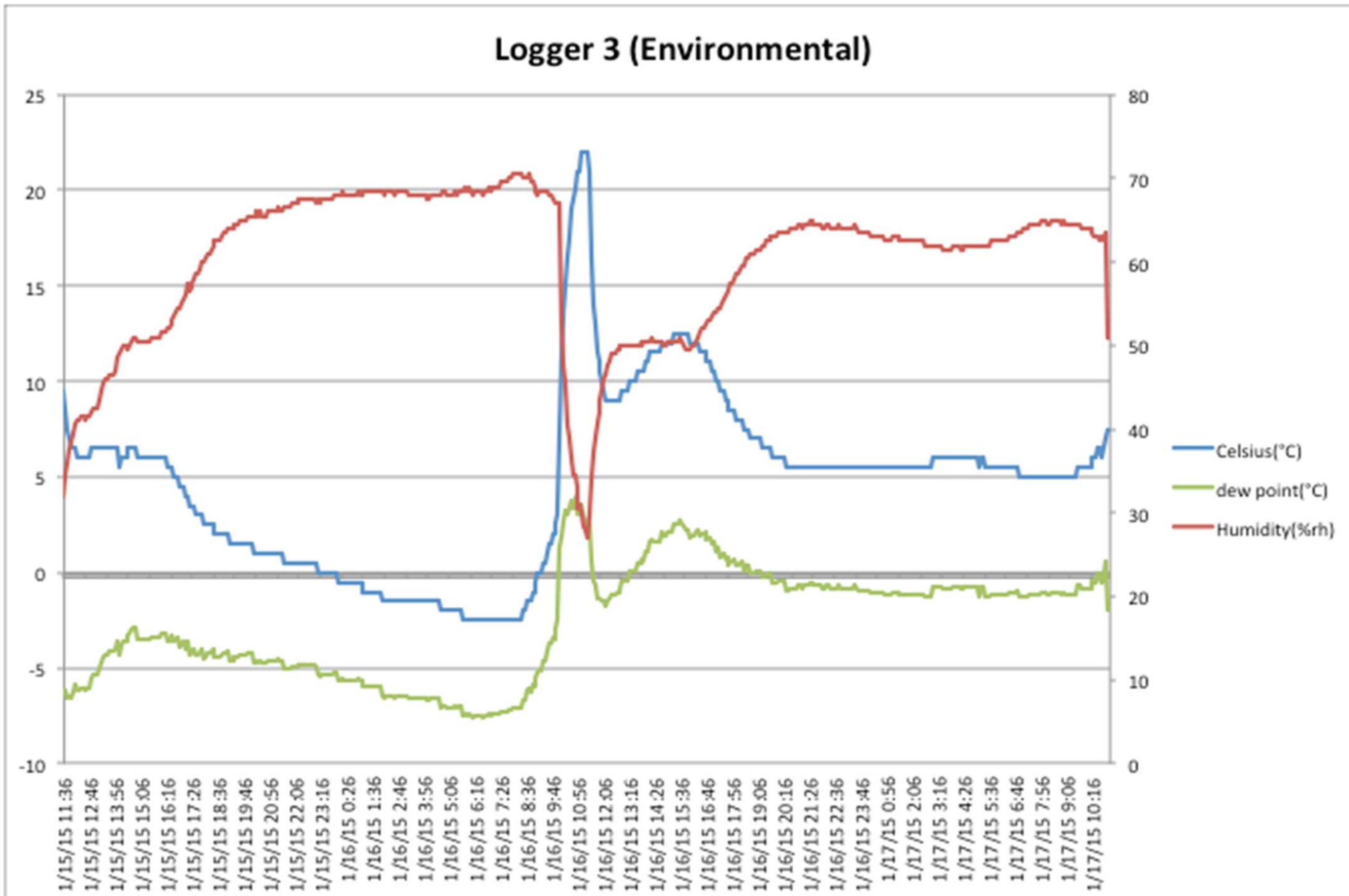

Figure 5. Temperature and relative humidity record of the ambient air (winter trial)

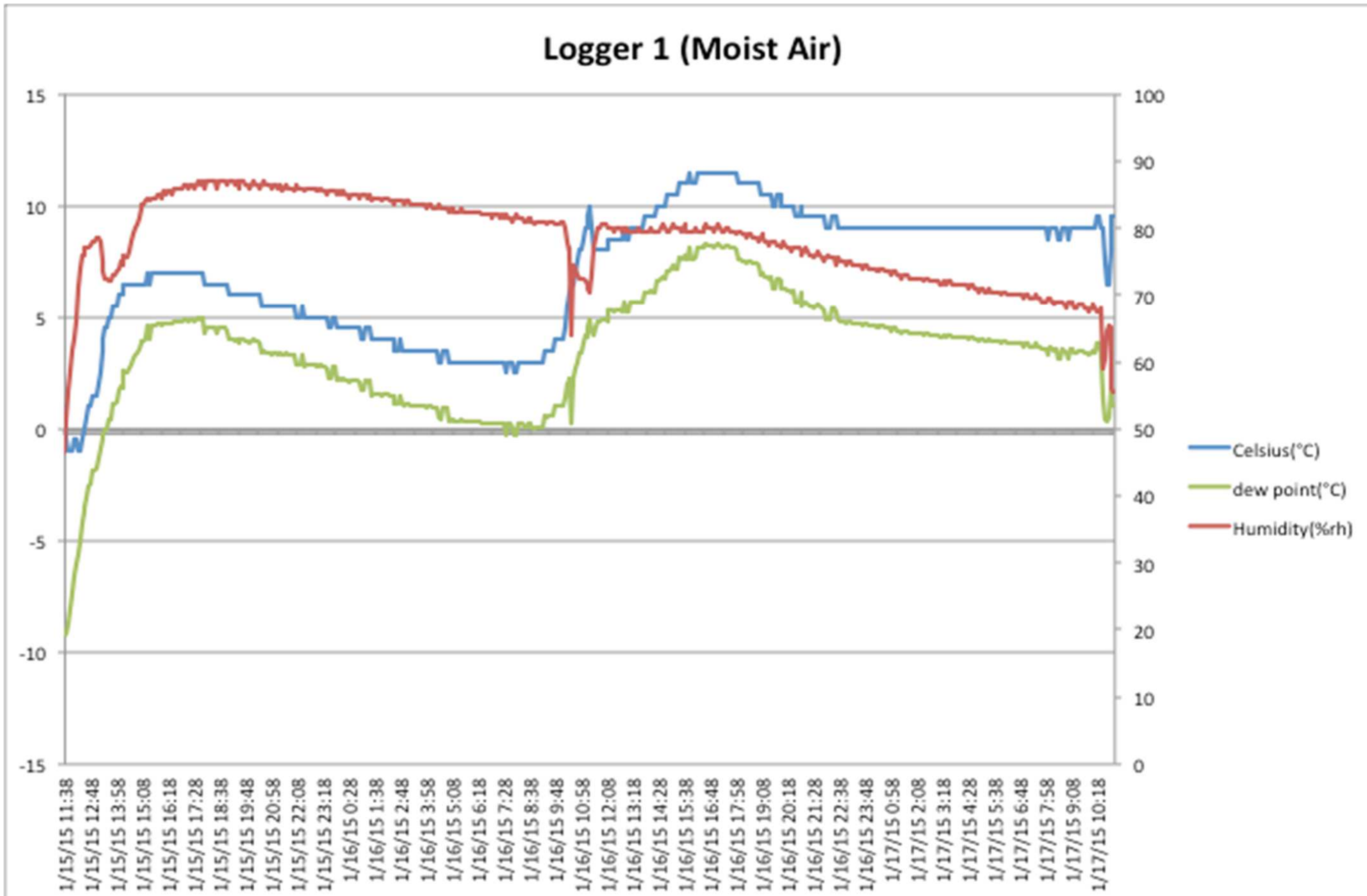

Figure 6. Temperature and relative humidity record of the air after drying the corn (winter trial)

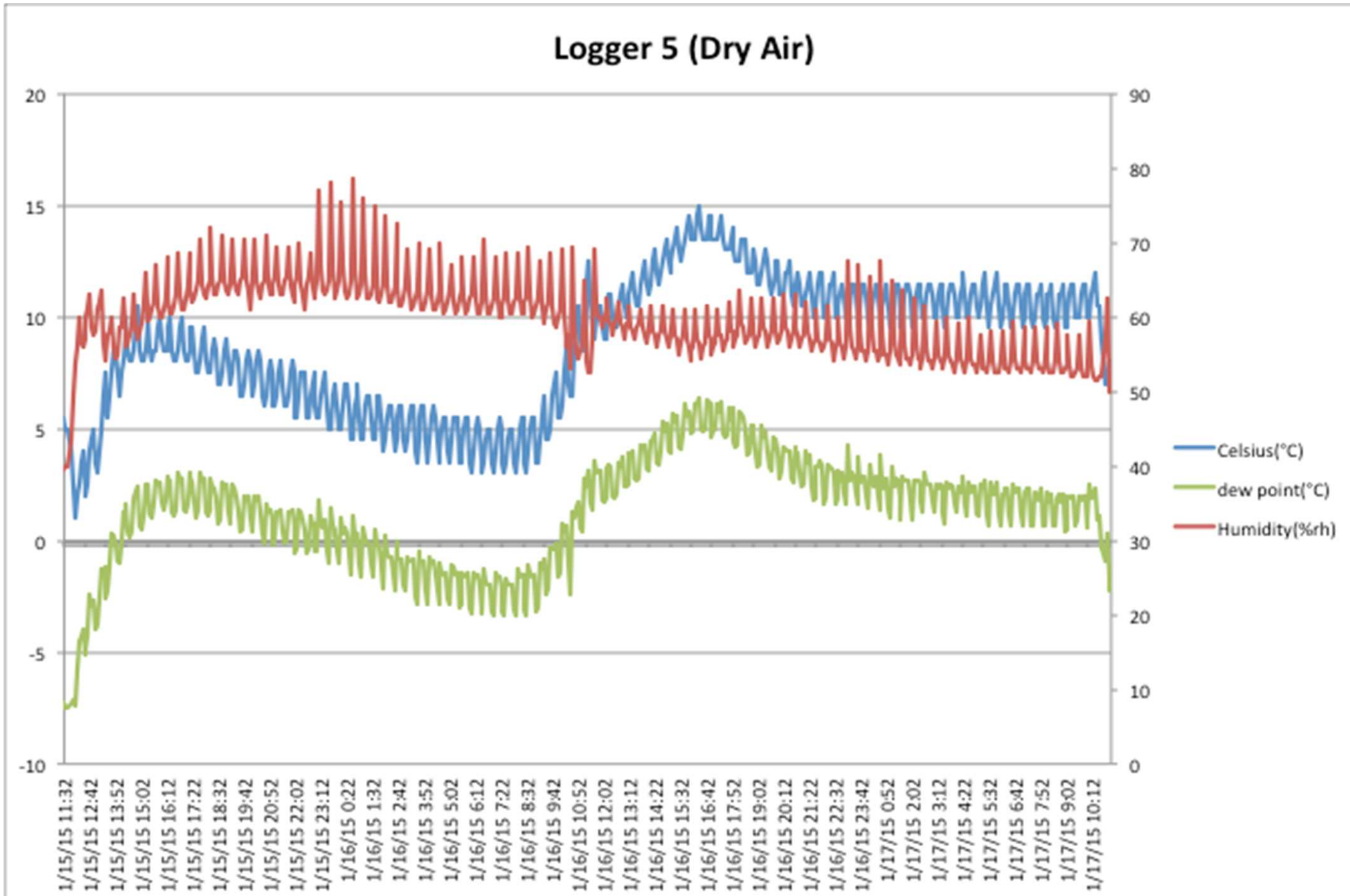

Figure 7. Temperature and relative humidity record of the air from drying apparatus (winter trial)

Table 1. Data collection and calculation (fall trial)

	Before drying				After drying				
	Rep. 1	Rep. 2	Rep. 3	Average	Rep. 1	Rep. 2	Rep. 3	Average	
Total grain weight (g)	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
Dry matter weight (g)	2.39	2.44	2.47	2.43	2.67	2.70	2.74	2.70	
Moisture content (%, wet basis)	20.3	18.7	17.7	18.9	11.0	10.0	8.67	9.89	
Corn weight in wagon (lb)	2680	2680	2680	2680	2400	2400	2400	2400	
Water content (lb)	545	500	473	506	263	240	208	237	
Germination (%)	86			86	96			96	
Water removal (lb)									269
Power consumption (Btu)									399000
Efficiency (Btu/lb water removal)									1480

Table 2. Data collection and calculation (winter trial)

	Before drying				After drying				
	Rep. 1	Rep. 2	Rep. 3	Average	Rep. 1	Rep. 2	Rep. 3	Average	
Total grain weight (g)	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
Dry matter weight (g)	2.45	2.45	2.42	2.44	2.56	2.58	2.56	2.57	
Moisture content (%, wet basis)	18.6	18.9	19.3	18.9	14.1	14.0	14.1	14.1	
Corn weight in wagon (lb)	2300	2300	2300	2300	2180	2180	2180	2180	
Water content (lb)	428	435	445	436	307	305	307	307	
Germination (%)	86			86	84			84	
Water removal (lb)									130
Power consumption (Btu)									359000
Efficiency (Btu/lb water removal)									2760

CHAPTER 4. TEA (TECHNO-ECONOMIC ANALYSIS) AND LCA (LIFE CYCLE ASSESSMENT) OF SMALL, MEDIUM, AND LARGE SCALE WINEMAKING PROCESSES

Modified from a paper to be submitted as a poster presentation at the *2015 ASABE Annual International Meeting in New Orleans, Louisiana, USA*

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Abstract

Life cycle assessment (LCA) is the assessment of all environmental burdens regarding a product, a service or a process from raw material to waste removal while TEA (Techno-economic analysis) is one of the economic analysis-methods that is widely used in food industry. The objective of the present study was to provide information with regard to economy and environment to help to make decision when establishing a winery, by conducting TEA and LCA for the particular red wine production processes. For LCA, the consumption of water, energy, greenhouse gas emissions, and solid waste generation were considered for environmental impacts. For TEA, small, medium and large-scale winemaking processes were chosen for analysis and a spreadsheet-based economic model was developed. The results of the LCA showed that bottle manufacturing, vine planting and winemaking processes contributed the greatest environmental impacts, while for TEA, the relationship between cost and profit among all three scales fitted an exponential model, and fitted a liner model better.

Introduction

Wine is one of the most important and most popular alcoholic beverages in the world. In 2005, the consumption of wine accounted for 8.6% of the total alcoholic beverage consumption all over the world, preceded only by spirits and beer (WHO, 2011). Wine is made from fermented grapes or other fruits. Grapes could ferment without the addition of acids, sugars, enzymes, water or other nutrients because of their natural chemical balance (Johnson, 1989). Under the action of yeast, the sugars in the grapes are converted into alcohol and carbon dioxide and thereby make wine. Besides its role as a popular beverage due to its distinctive flavor and aroma, wine could be a psychoactive drug, as are all alcoholic beverages (ISCD, 2013), and could be used for its intoxicating effects. The history of wine is rich; the earliest traces discovered so far having occurred Christian era 6000 B.C. in Georgia, and Christian era 5000 B.C. in Iran (Keys, 2003; Berkowitz, 1996), the first recovered crushed grapes of Christian era 4500 B.C. were discovered at Grecian Macedonia (Viegas, 2007), and the first winery dated to Christian era 4100 B.C was discovered in Armenia (Owen, 2011).

Wine making is the process with the input of grape and output of wine. It starts with selection of grape and ends with bottling of wine. In terms of final product, winemaking could be divided into still wine production, which produces wine without carbonation and sparkling wine production, which produces wine with carbonation. The still wine production could be further divided into red wine production and white wine production (Considine and Frankish, 2013). Different wine products were produced due to different processes. For red wine, red grapes were harvested, de-stem, and crushed; all berry parts including skins, pulps and seeds were fermented. There is double fermentation for red wine: first sugar is converted to alcohol by using yeast, and then converted from malic acid to lactic acid with a bacterium. The purposes of the latter fermentation are to reduce acidity, to ensure the stability against secondary fermentation in the bottle, and to add flavors that enhance the wine, especially with the storage in ‘toasted’ oak barrels (Considine and Frankish, 2013).

According to Sacchi et al. (2005), red wine making is an extractive process of skins, seeds and even some stems. In terms of their research, with the presence of high levels of antioxidants such like tannins and anthocyanins that were extracted, red wine making was less prone to oxidation. The ‘cap’ formed by floating skins that was buoyed by carbon dioxide generated from fermentation should be mixed with the must regularly to effectively extract tannins and anthocyanins to prevent the growth of spoilage yeast (Sacchi et al., 2005). The secondary fermentation of red wines and some white wines are also beneficial for the stability of wine against spoilage and in-bottle fermentation because the malic acid as fermentation substance was used up due to its conversion to lactic acid by applying of a bacterium, *Lactobacillus oeni* (Considine and Frankish, 2013).

Different from red wine, white wine is only fermented by yeast and then chilled and stabilized. Only the juice or must pressed from the pulps of white grapes is fermented. Very careful filtration should be applied in order to remove all microorganisms thus prevent malic acid fermentation right after bottling. The whole process is done very quickly therefore could produce the wine with dry, crisp, and aromatic palate. Compared to red wine production, white production needs much greater control of oxygen status, hygiene, yeast nutrition and temperature, thus, it is possible to produce an acceptable red wine in just ‘backyard’ but hard to make a sound white in the same environment (Considine and Frankish, 2013). As white wine after fermentation is sensitive to oxidation, it is not extractive and sterile filtration must be applied to stabilize it. Chilling before bottling process is required for white wine to precipitate excess potassium bi-tartrate salts to prevent it from unsightly crystalline deposits in refrigerated bottle. Clay could be used to remove excess protein in the wine that might coagulate and form an unsightly haze when the wine gets too hot during storage or transportation. Copper sulfate could be also utilized to remove hydrogen sulfide which may be formed when starving yeast metabolize grape proteins. Other fining process such as the use of natural products like protein from eggs, fish or gelatin could be applied to remove bitter tannins, and the precipitate should be removed before bottling (Considine and Frankish, 2013).

Life cycle assessment (LCA) is the assessment of all environmental burdens regarding a product, a service or a process from raw material to waste removal (Klopffer, 1997). It was invented in the USA at the Midwest Research Institute around 1970 (Hunt and Franklin, 1996), and the structure applied nowadays of LCA was defined by ISO, including goal and scope definition, inventory analysis, impact assessment and interpretation (ISO, 2006). There are a lot of applications of LCA in winemaking process and winery operation. Fusi et al. (2014) conducted a ‘cradle to grave’ LCA (total LCA) to identify and assess the environmental burdens along the white wine life cycle stage, including grape planting, wine production, wine bottling, packaging, distribution and disposal of wine bottle. In their research, the glass bottle production was considered the most determinative to the environmental performance of production of a bottle of white wine. And in their analysis of agricultural phase including vine planting and grape production, vine planting was not negligible on environmental impact compared to the whole agricultural operation. Same as this research, Neto et al. (2013) and Point et al. (2012) also carried out ‘cradle to grave’ analysis that included distribution. The authors also indicated that the production of wine bottles plays a very important part in environmental effect of the life cycle of wine. Some research added vine planting into consideration (Bosco et al., 2011; Benedetto, 2013). From which the vine planting contributed a lot to the environmental impact. Several other studies only conducted ‘cradle to gate’ research (Vazquez-Rowe et al., 2012: Benedetto, 2013). They did not take distribution into consideration in their studies. However, from their conclusions, glass bottle production was still the most significant element to affect the environment.

TEA (Techno-economic analysis) is widely used in food industry. The usefulness of TEA on cost analysis, profit assessment and production strategy determination has already been demonstrated. Marouli and Maroulis (2005) developed a model that utilized existing food factory data by analyzing them systematically to indicate the particular characteristics that concerned operation of the food industry. Another TEA was applied to characterize and improve pastoral dairy goat systems in Andalusia (Ruiz et al., 2008), and with that TEA a profitable production strategy was made. For winery and winemaking, Dillon et al. (1992) conducted research which leads to the development of an economic decision making model for small to medium-sized wineries. From their model, the break-even prices were indicated from 3.50 dollars to 6.00 dollars per 750 mL bottle for winery sizes from 100,000 gallons per year to 5,000 gallons per year, the larger the winery size, the lower the break-even price. An economic model was developed to evaluate costs of raw materials such as grape, labels and bottles (Dillon et al., 1993), the cost of the raw materials was demonstrated to have a substantial effect on the annual net profit. In this research, winery profits could fluctuate more than 60% when the change of grape price approximately equal to 25%. Furthermore, Sellers-Rubio (2010) compared different approaches of traditional profitability and productivity measures and a non-parametric technique to estimate efficiency only. And found out that none of the methodologies could be said to be better than the rest on evaluations of winery economic performance. In spite of numerous researches of diverse economic analyses have been applied to winemaking and winery operation, to the author's knowledge, there is no genuine TEA that focus on winemaking processes.

In order to provide information with regard to economy and environment to help make decision when establishing a winery, the present study conducted TEA and LCA for the particular red wine production processes. The LCA was carried out from vine planting to wine bottle disposal, while the TEA was conducted for small (5,000 gallons per year), medium (50,000 gallons per year), and large (500,000 gallons per year) size production.

Materials and Methods

Life cycle assessment (LCA)

The boundary of LCA was chosen from vine planting to wine bottle disposal, including vine planting, wine making, wine distribution and wine bottle disposal. The energy consumption and water consumption within this boundary were considered as input impacts while the greenhouse gas emission and solid waste disposal were considered as output impacts (Figure 1). The unit of energy consumption was the kilojoule (kJ), of water consumption was gallon, of greenhouse gas emission was gram carbon dioxide equivalents (g CO_2 eq.), and of solid waste disposal was gram (g).

We assumed 70% of glass was recycled for wine bottle production. We assumed the impacts occurred during energy production was not considered. The chosen functional unit (FU) was a 750 mL bottle of red wine.

Data regarding energy consumption and greenhouse gas emission were collected via EioLCA (2014) (Table 1 and Table 2). When collecting data from EioLCA, utilizing producer price model and assuming the producer price is 1 dollar per 750 mL bottle. Data with respect to water consumption and solid waste disposal were referred to Fusi et al. (2014) (Table 1 and Table 3). The processes within boundary were separated into four parts, including vine planting, wine making, bottle manufacture and wine distribution. All the impact data of these four parts were analyzed and the contribution to total impact of each part was calculated. For energy and water consumption, data collected were directly used for calculating the contribution (Table 1). For greenhouse gas emission and solid waste disposal, the summations were used for calculating the contribution. (Table 2 and Table 3).

Techno-economic analysis (TEA)

The TEA was conducted for wine production processes, including vine planting and wine making. Assuming land cost was not considerate, part time labor cost was 10 dollars per hour per person, full time labor cost was 40,000 dollars per year per person, grape vine was 100 percent recycle so no cost for it, and grape output was 6 Mg per acre per year. Assuming wine output was 120 gallon per Mg of grape, the useful life of all the equipment was 15 years, the diesel price was 3 dollars per gallon, no pesticide was applied during vine planting and the ex-factory price of wine was 10 dollars per 750 mL bottle.

All the relevant data of the wine production processes were collected based on three scales, which were small (5,000 gallons per year), medium (50,000 gallons per year), and large (500,000 gallons per year), the data were obtained from Alibaba (2014), the vintner's vault (2014), Novak and Burg (2013) and Dillon et al. (1992), cost of each unit within the red wine production process was calculated and assessed based on the assumptions mentioned above and the data collected (Table 4).

The TEA was conducted for annual base of those three scales of production. Annual cost of each scale was calculated by converting and summing the cost of each unit that calculated before, and then was divided into three parts, which were labor cost, equipment and material cost and cost for purchasing wine bottle (Table 5). The contribution to total annual cost of each part was assessed, while the relationship of each cost of each production scale was analyzed. Annual revenue of each scale was calculated by multiplying the ex-factory price with the production, and the relationship among three scales was assessed (Table 5). Annual net profit of each scale was calculated by subtracting the annual cost from the annual revenue, while the analysis of relationship among three sales was carried out (Table 5). The break-even unit price was calculated based on the annual total cost and the output, in the condition of the price of wine is not assumed:

Break-even unit price (dollars/750 mL bottle)

= Annual cost (dollars/year) /Annual output (mL/year) × 750 mL (1)

Results and Discussion

Life cycle assessment (LCA)

For the energy consumption, the bottle manufacture and the wine making contributed the most impact, which account to 35 percent and 31 percent separately (Figure 2). Since compared to vine planting and wine distribution, the process of bottle manufacture and wine making were much more complex and the units of energy consuming within them were more than vine planting and wine distribution, it is no doubt that the bottle manufacture and the wine making contributed the most energy consumption impact.

For the water consumption, vine planting contributed the most impact, account to 95 percent (Figure 2). It could be estimate that in the wine production, water is mainly used for vine planting.

For the output aspect, vine planting and bottle manufacture contributed the most greenhouse gas emission impact, which account to 38 percent and 25 percent separately (Figure 2). While bottle manufacture and wine making contribute the most solid waste disposal impact, which account to 32 percent and 59 percent separately (Figure 2).

Compared to the research conducted by Fusi et al. (2014), which was a 'cradle to grave' LCA (total LCA) to identify and assess the environmental burdens along the white wine life cycle stage, including grape planting, wine production, wine bottling, packaging, distribution and disposal of wine bottle, had the conclusion that the glass bottle production was the most determinative to the environmental performance of production of a bottle of white wine, the present study achieved the same conclusion. Additionally, from the LCA, the vine planting and wine making also plays a very important part on impacting the environment.

Techno-economic analysis (TEA)

For the annual cost, the cost increases while the production increases (Figure 3). The annual cost was 114,587 dollars per year, 341,839 dollars per year, and 2,816,280 dollars per year separately for small (5,000 gallons per year), medium (50,000 gallons per year), and large (500,000 gallons per year) scales. The relationship of annual cost of these three scales fits the exponential increase well with R square value equals to 0.93 (Figure 4). However, it fits the liner increase better with R square equals to 0.99 (Figure 5). While the production scale increases, the contribution of labor cost decreases and the contribution of cost of purchasing wine bottle increases (Figure 6).

For the annual revenue, same as the annual cost, increases while the production scale increases (Figure 7). The annual revenue was 252,360 dollars per year, 2,523,600 dollars per year, and 25,236,000 dollars per year separately for small (5,000 gallons per year), medium (50,000 gallons per year), and large (500,000 gallons per year) scales. The relationship of annual revenue of small, medium, and large scales production also fits the exponential increase well with R square value equals to 0.82 (Figure 8). However, from figure 9, the increase of annual revenue fits linear increase perfectly and the R square value equals to 1. This is because the revenue was calculated purely based on production scale.

For the annual profit, same as the annual cost and annual revenue, increases while the production scale increases (Figure 10). The annual profit was 137,773 dollars per year, 2,181,761 dollars per year, and 22,419,720 dollars per year separately for small (5,000 gallons per year), medium (50,000 gallons per year), and large (500,000 gallons per year) scales. The relationship of annual revenue of small, medium, and large scales production also fits the exponential increase well with R square value equals to 0.78 (Figure 11). Compared to exponential increase, from figure 12, the increase of annual profit fits linear increase better and the R square value equaled to 1. This is because the annual profit is affected more by annual revenue than by annual cost, as the amount of annual revenue is much more than that of annual cost.

For the break-even price, based on the total cost and output of each scale, the relationship between net profit and unit price could be calculated (Figure 13). The break-even price is 4.55 dollars per 750 mL bottle for 5,000 gallons per year production, is 1.36 dollars per 750 mL bottle for 50,000 gallons per year production, and is 1.12 dollars per 750 mL bottle for 500,000 gallons per year production. It showed that the larger the winery production size, the lower the break-even price. The relationship of break-even price of small, medium, and large scales production fits the power decrease well with the R square value equals to 0.85 (Figure 14)

Compared to the research conducted by Dillon et al. (1992), which led to the development of an economic decision making model for small to medium-sized wineries, had the conclusion that the larger the winery size, the lower the break-even price, the present study achieved roughly the same result. However, different from the result that Dillon et al. (1993) found, which was the cost of the raw materials was demonstrated to have substantial effect on the annual net profit, the present study found that the cost of labor and bottle purchasing contribute the most to the total cost (Figure 6).

Implications

Life cycle assessment (LCA)

Improving bottle manufacture, vine planting and wine making process could be efficient to reduce impact of energy and water consumption, as well as reduce impact on solid waste disposal. Improving vine planting and bottle manufacture process could be efficient to reduce impact of greenhouse gas emission.

Techno-economic analysis (TEA)

Since the annual cost of purchasing wine bottles contributed the most to the annual cost of the large-scale winery, it could build glass bottle factory to reduce the cost of purchasing bottle when establishing a winery with the output around 500,000 gallons per year, therefore increase the profit. Further economic analysis is needed to clarify this.

Conclusions

Life cycle assessment (LCA)

The information with regard to environment to help to make decision when establishing a winery have been provided by conducting the LCA for the particular red wine production processes. For the input impact, bottle manufacture and wine making contributed the most impact on energy consumption while vine planting contributed the most impact on water consumption. For the output impact, vine planting and bottle manufacture contributed the most impact on greenhouse gas emission while bottle manufacture and wine making contributed the most impact on solid waste disposal. In general, glass bottle production, vine planting and wine making was the most determinative to the environmental performance of production of a bottle of red wine and attention to them should be paid when establishing a winery.

Techno-economic analysis (TEA)

The information with regard to economy to help to make decision when establishing a winery have been provided by conducting the TEA for the particular red wine production processes. The annual cost was 114,587 dollars per year, 341,839 dollars per year, and 2,816,280 dollars per year separately for small (5,000 gallons per year), medium (50,000 gallons per year), and large (500,000 gallons per year) scales, and the relationship among the three sizes production fitted the exponential increase well but fitted the linear increase better. The labor cost contribution to total cost decreased while production size increased, and the bottle cost contribution to total cost increased while production size increased. The annual revenue was 252,360 dollars per year, 2,523,600 dollars per year, and 25,236,000 dollars per year separately for small, medium, and large scales, and the relationship among the three scales production followed the exponential increase well but it fitted linear increase perfectly as it was calculated purely based on production scale. The annual profit was 137,773 dollars per year, 2,181,761 dollars per year, and 22,419,720 dollars per year separately for small, medium, and large scales, and the relationship of the annual net profit among the three scales followed the exponential increase well but due to the effect of the annual revenue, it fitted linear increase better. The break-even prices were 4.55 dollars, 1.36 dollars and 1.12 dollars per 750 mL bottle separately for winery sizes of 5,000, 50,000 and 500,000 gallons per year, the larger the winery size, the lower the break-even price, and fits power decrease well.

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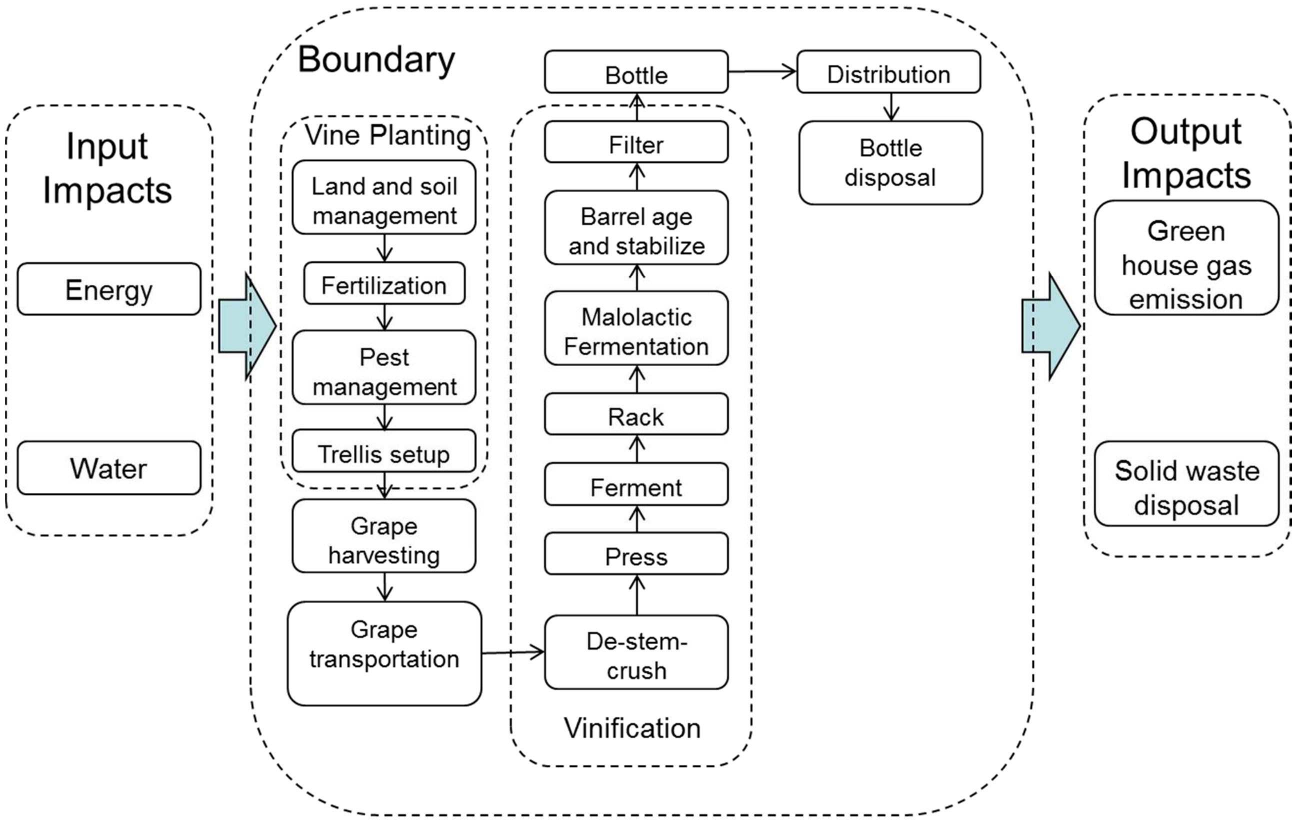

Figure 1. The boundary of LCA

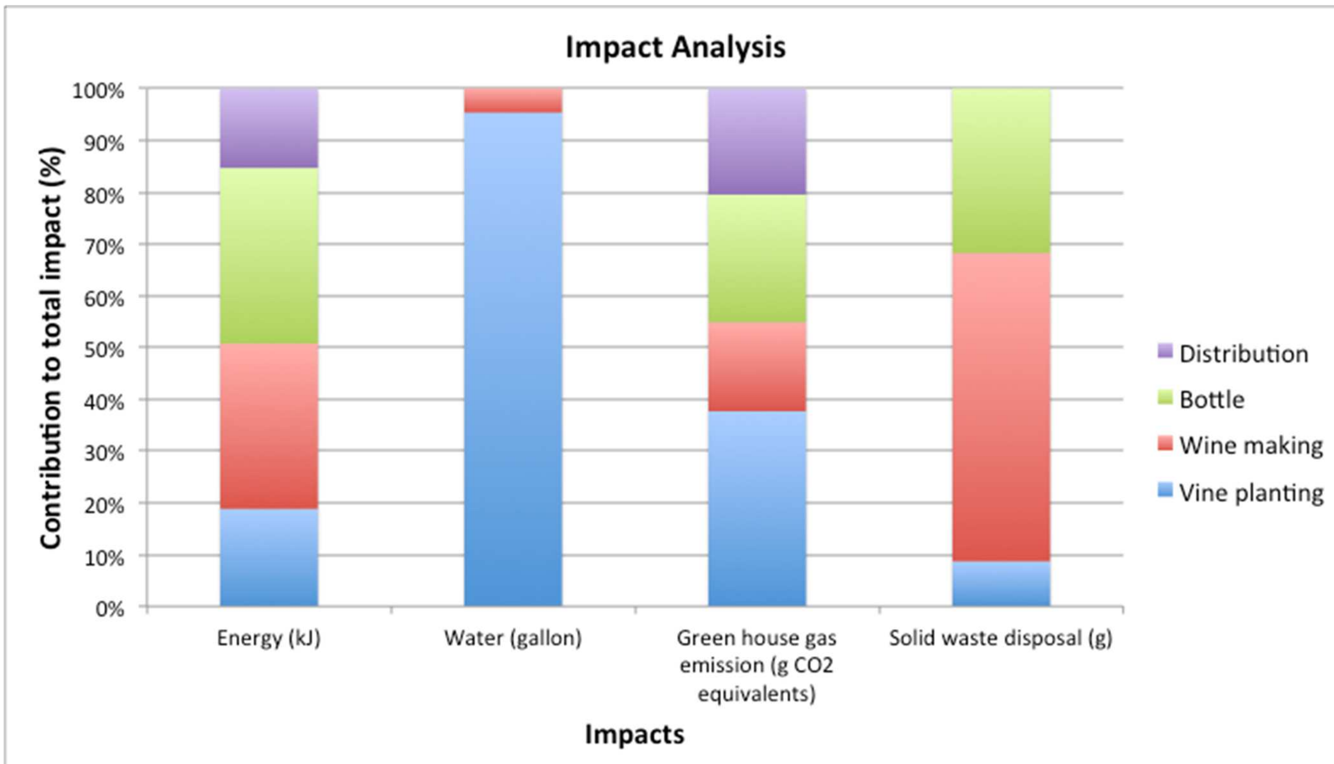

Figure 2. The impact contribution on environmental burdens

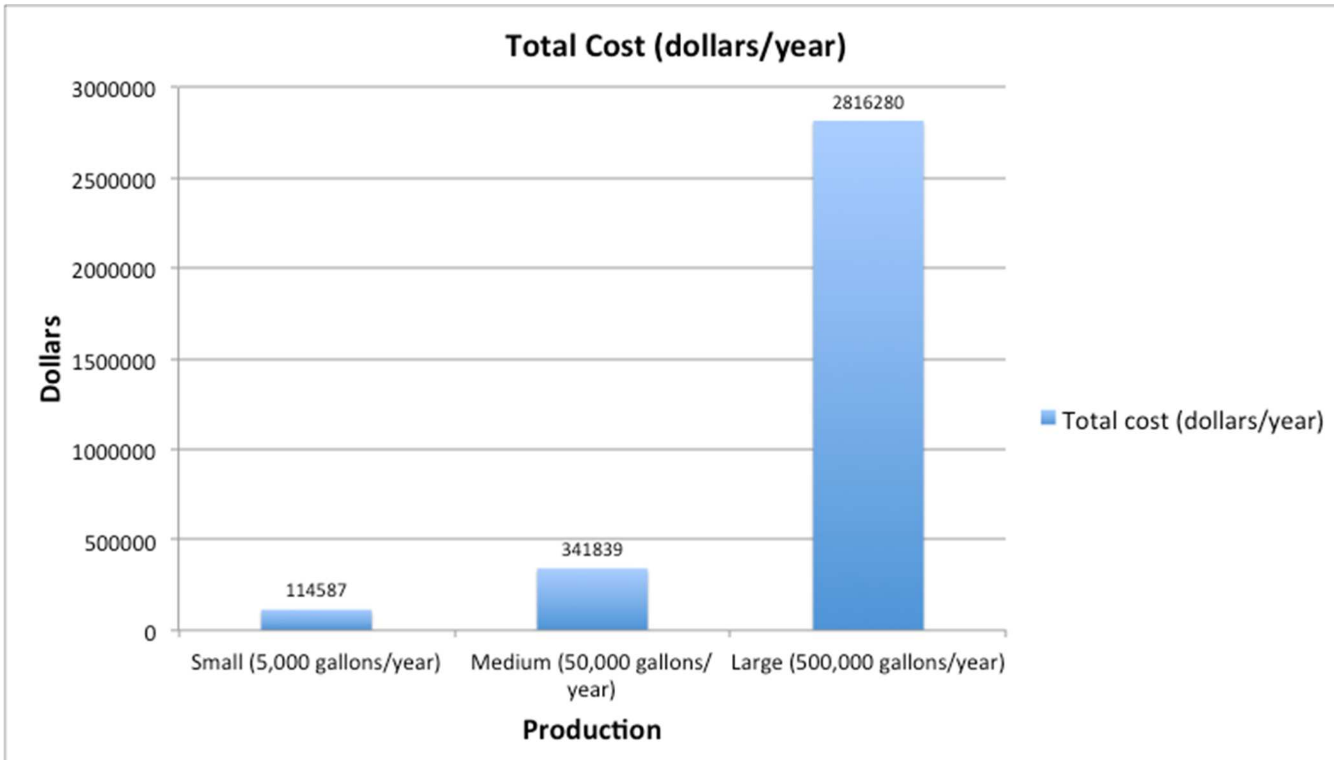

Figure 3. Total annual cost

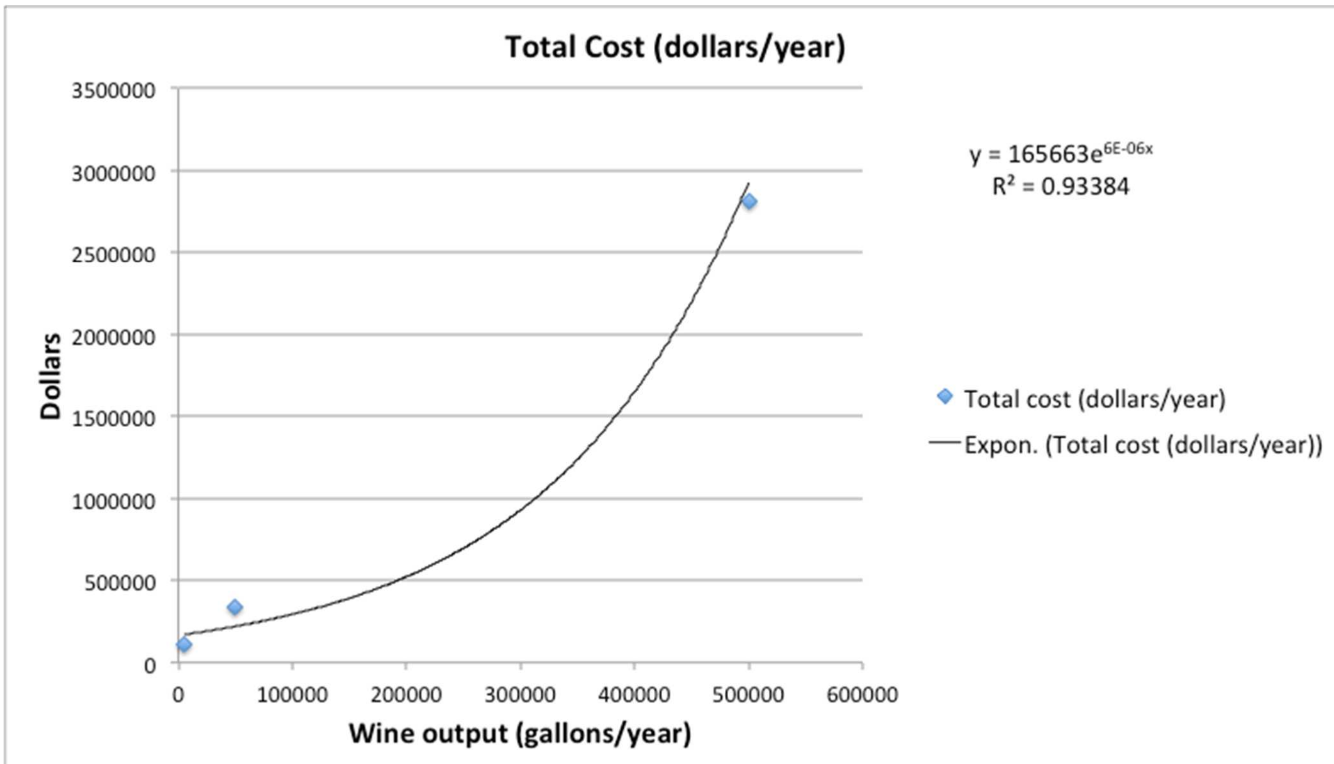

Figure 4. Annual cost relationship among three scales (exp.)

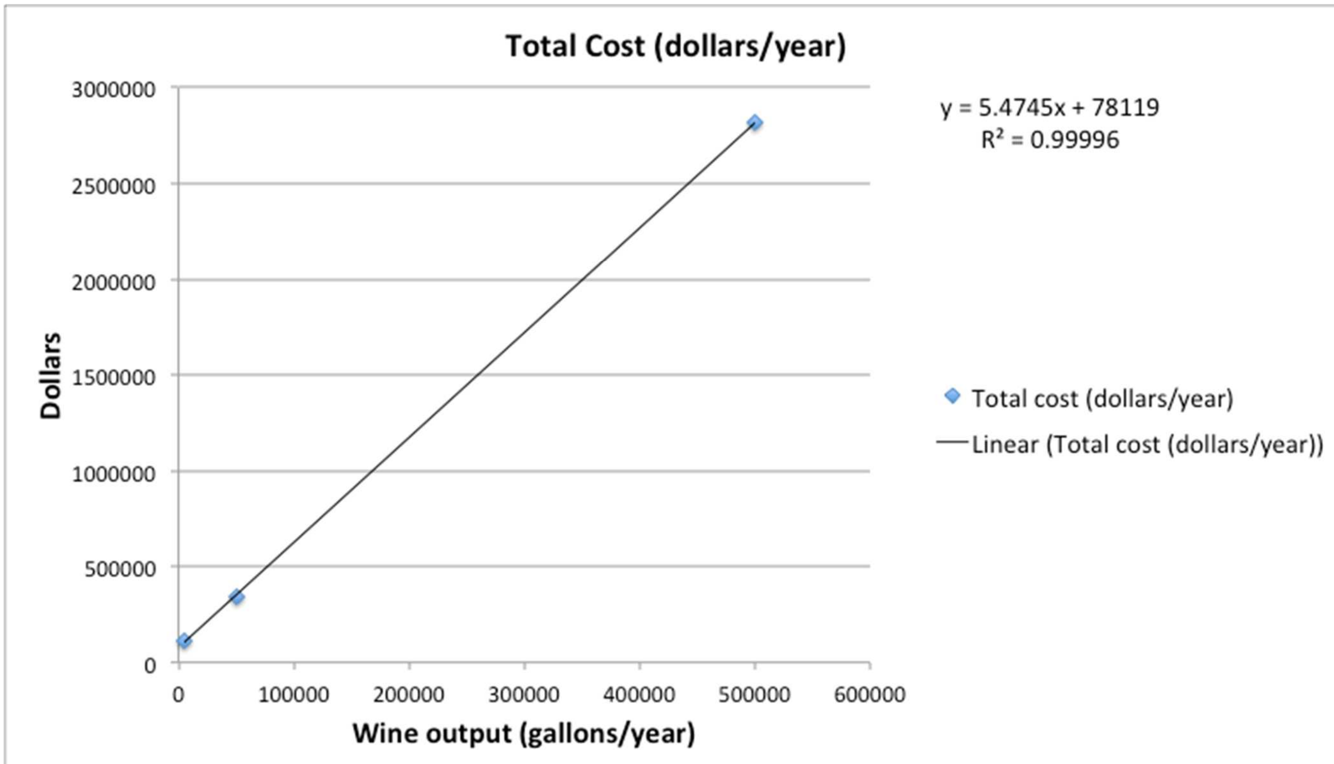

Figure 5. Annual cost relationship among three scales (linear)

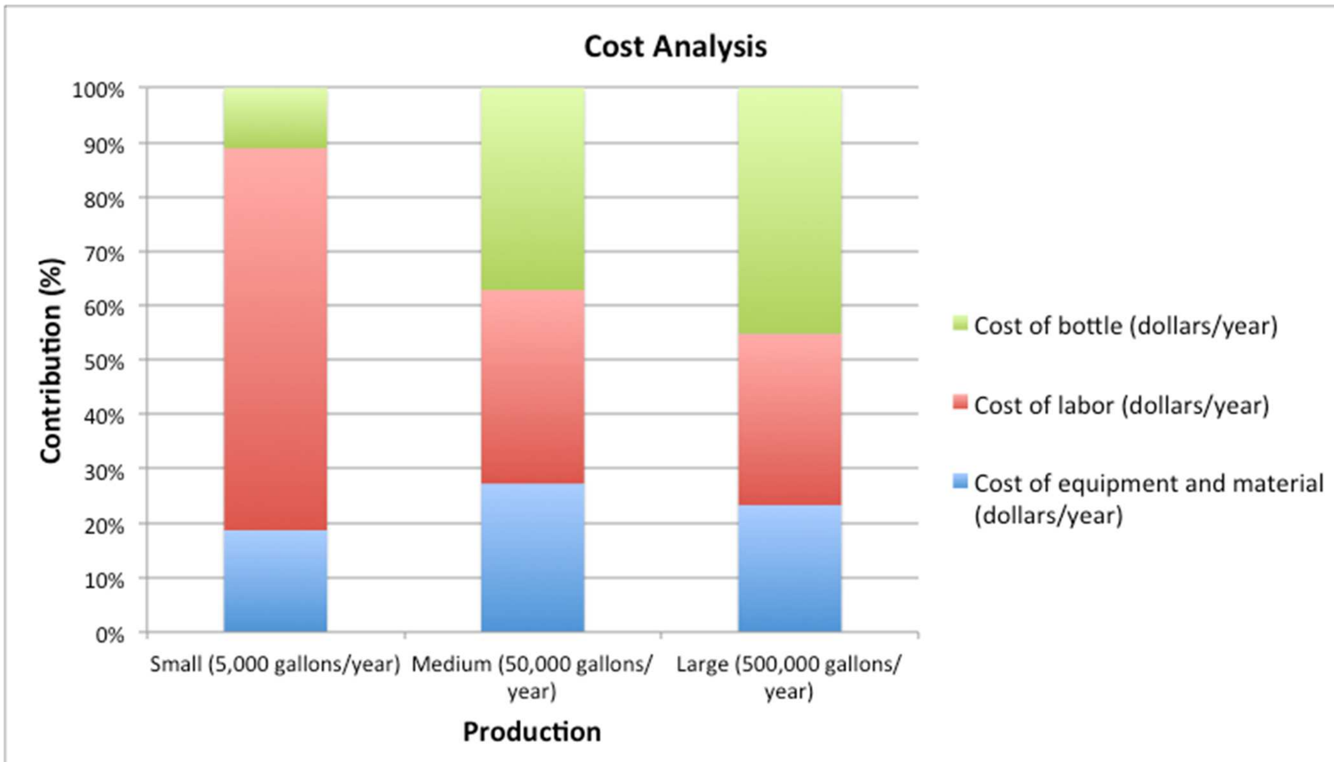

Figure 6. Annual cost analysis of contribution of each part

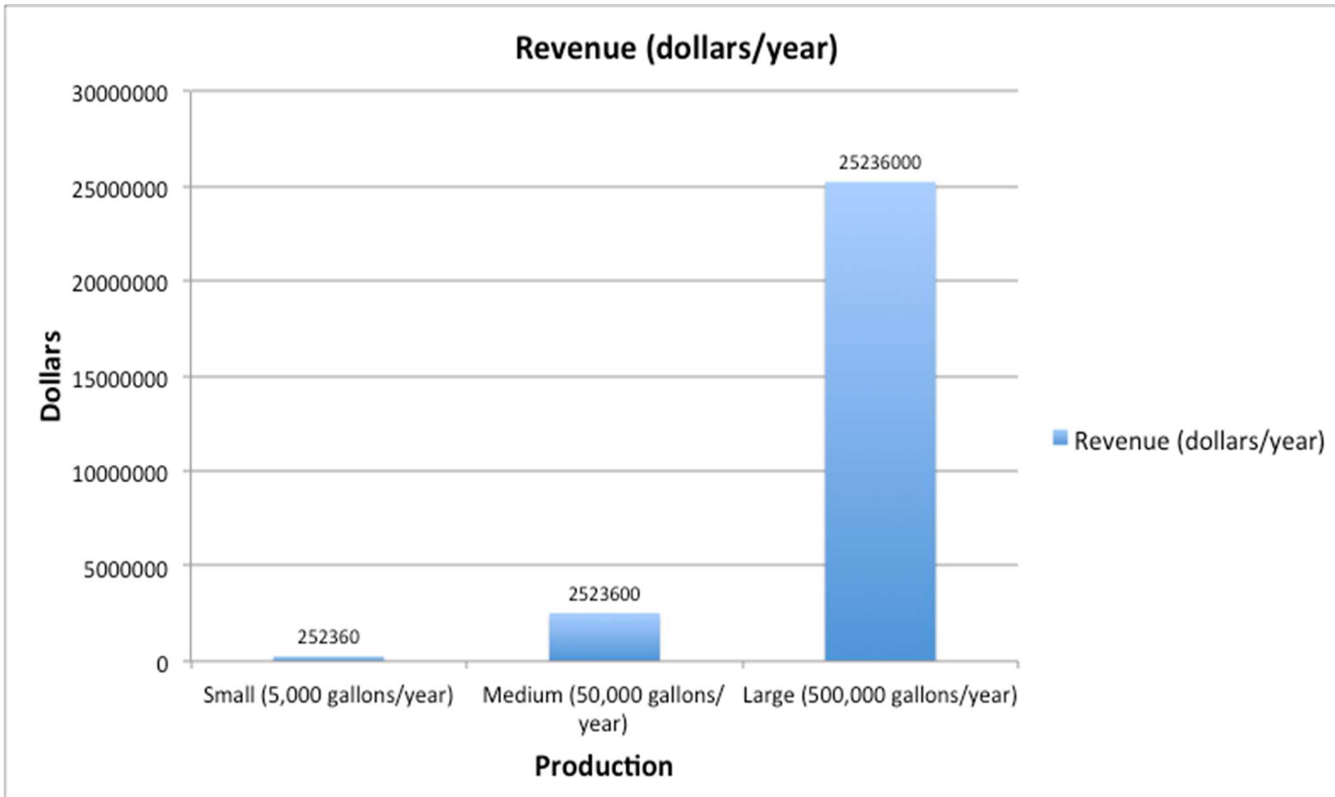

Figure 7. Total annual revenue

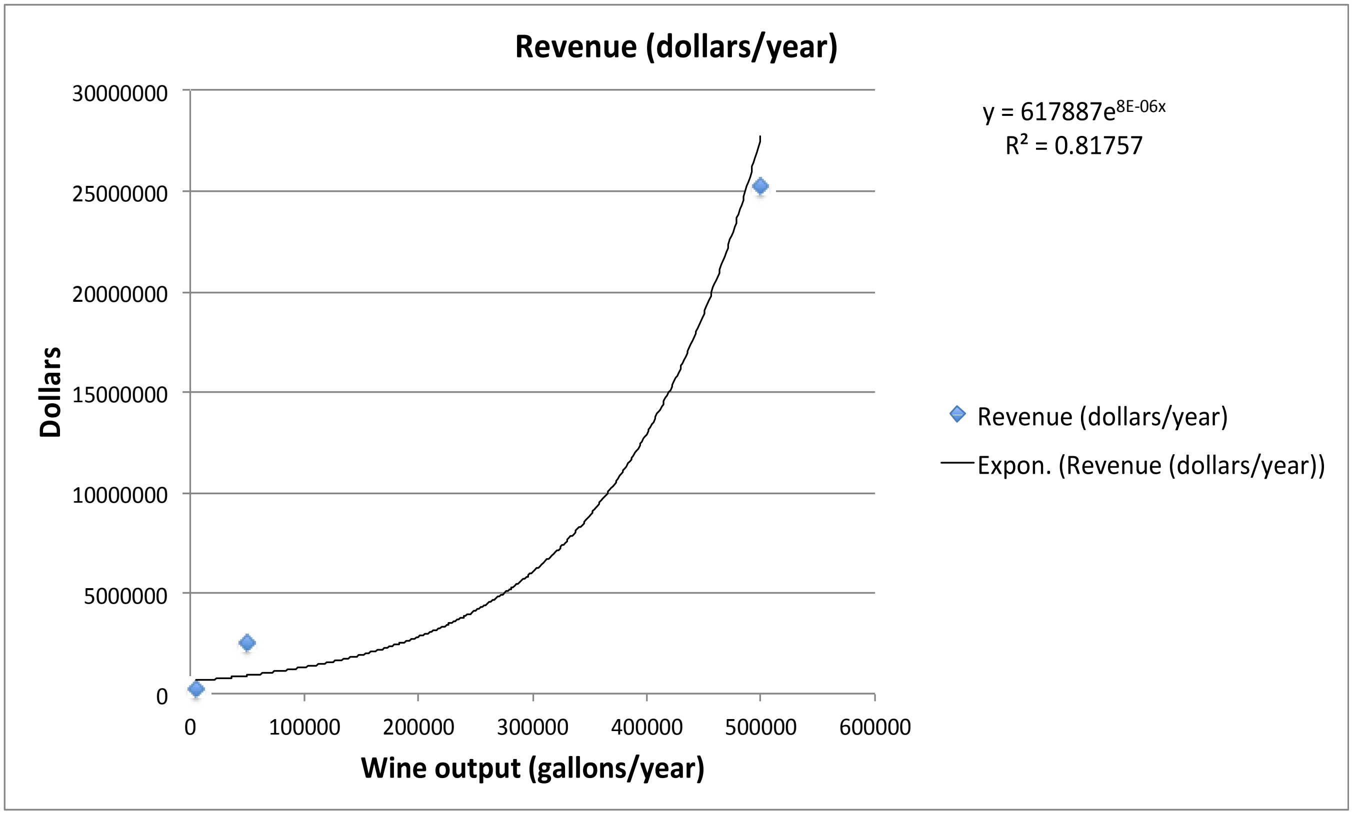

Figure 8. Annual revenue relationship among three scales (exp.)

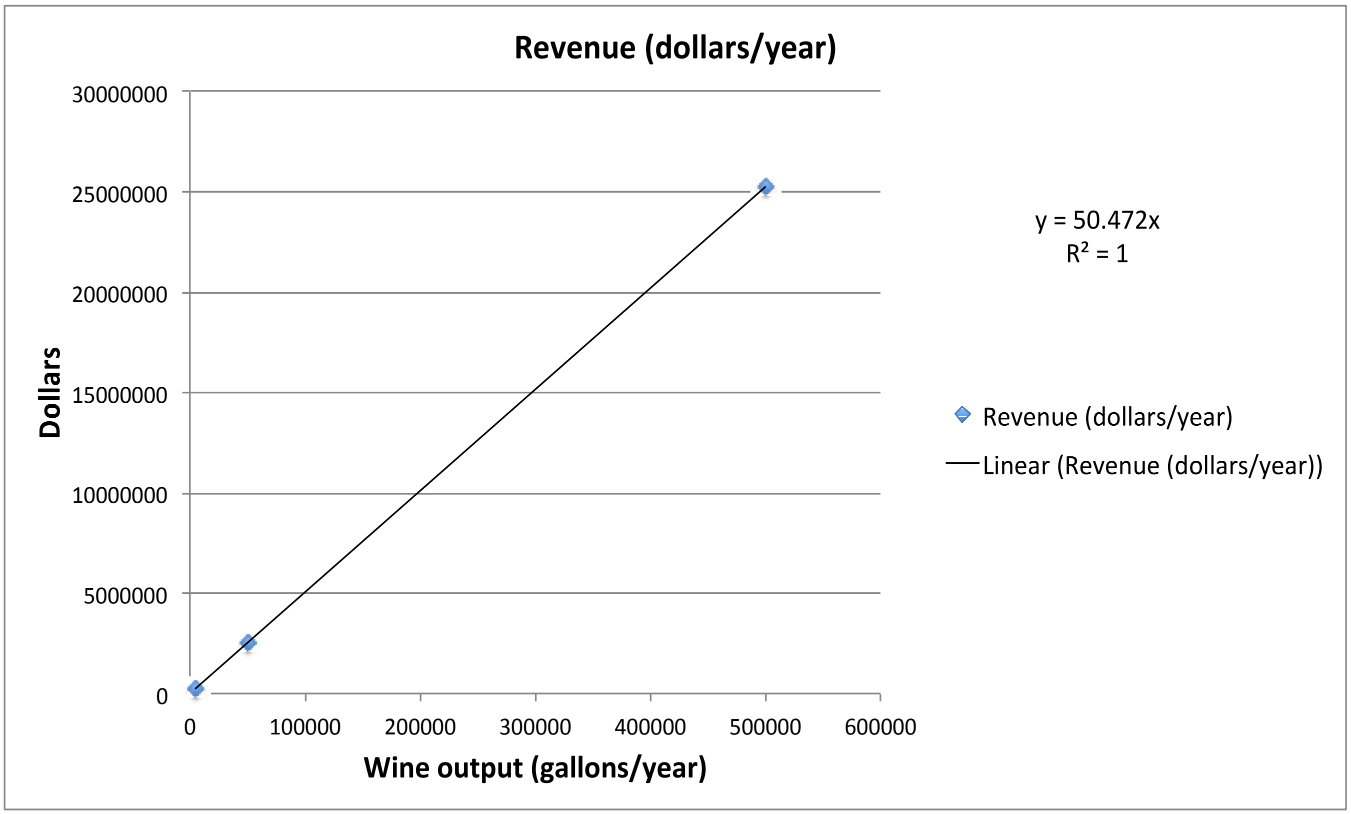

Figure 9. Annual revenue relationship among three scales (linear)

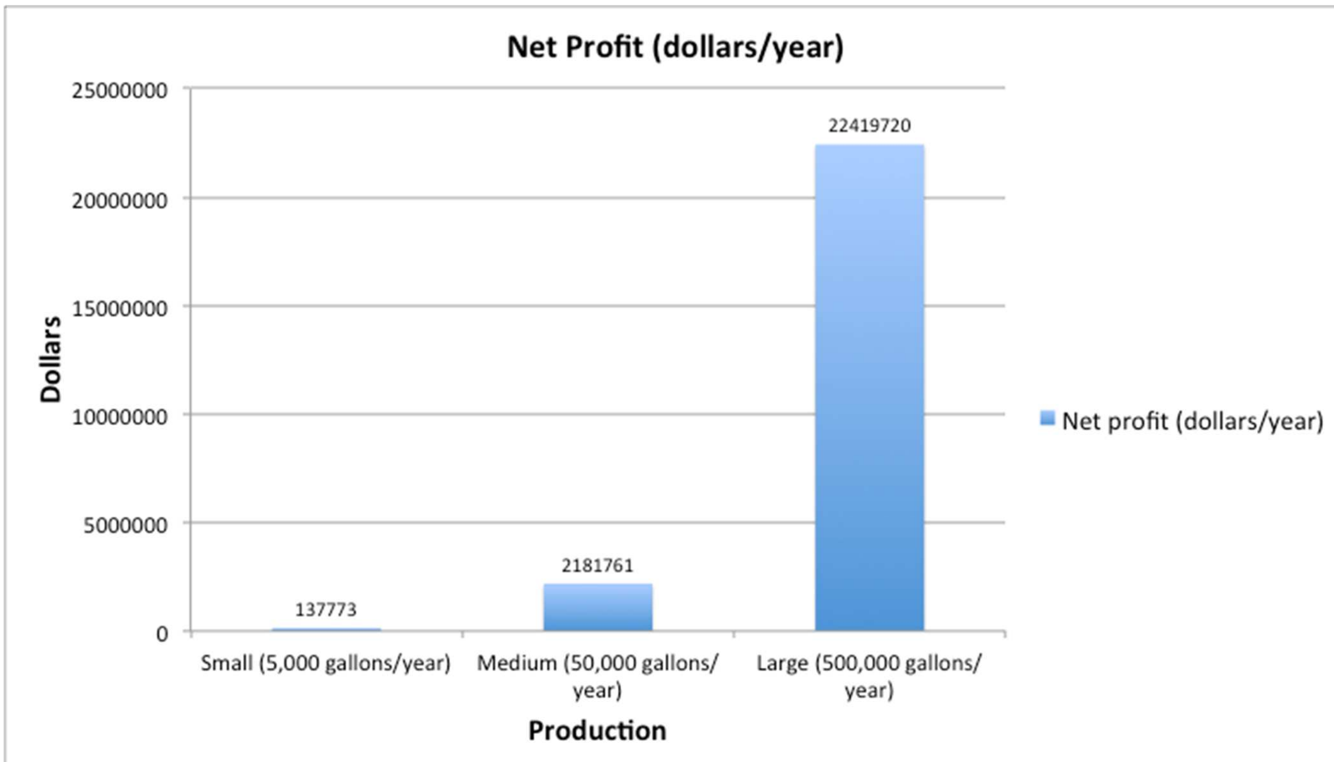

Figure 10. Total annual profit

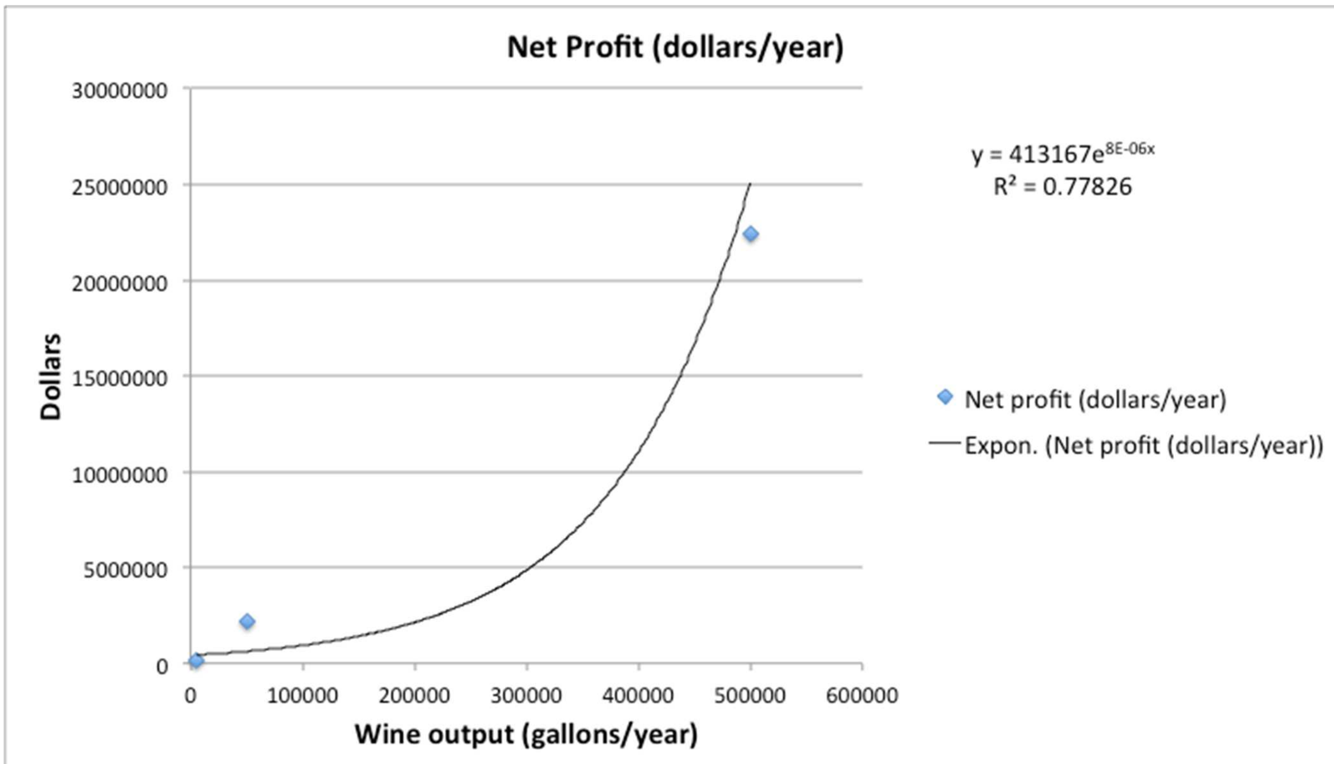

Figure 11. Annual profit relationship among three scales (exp.)

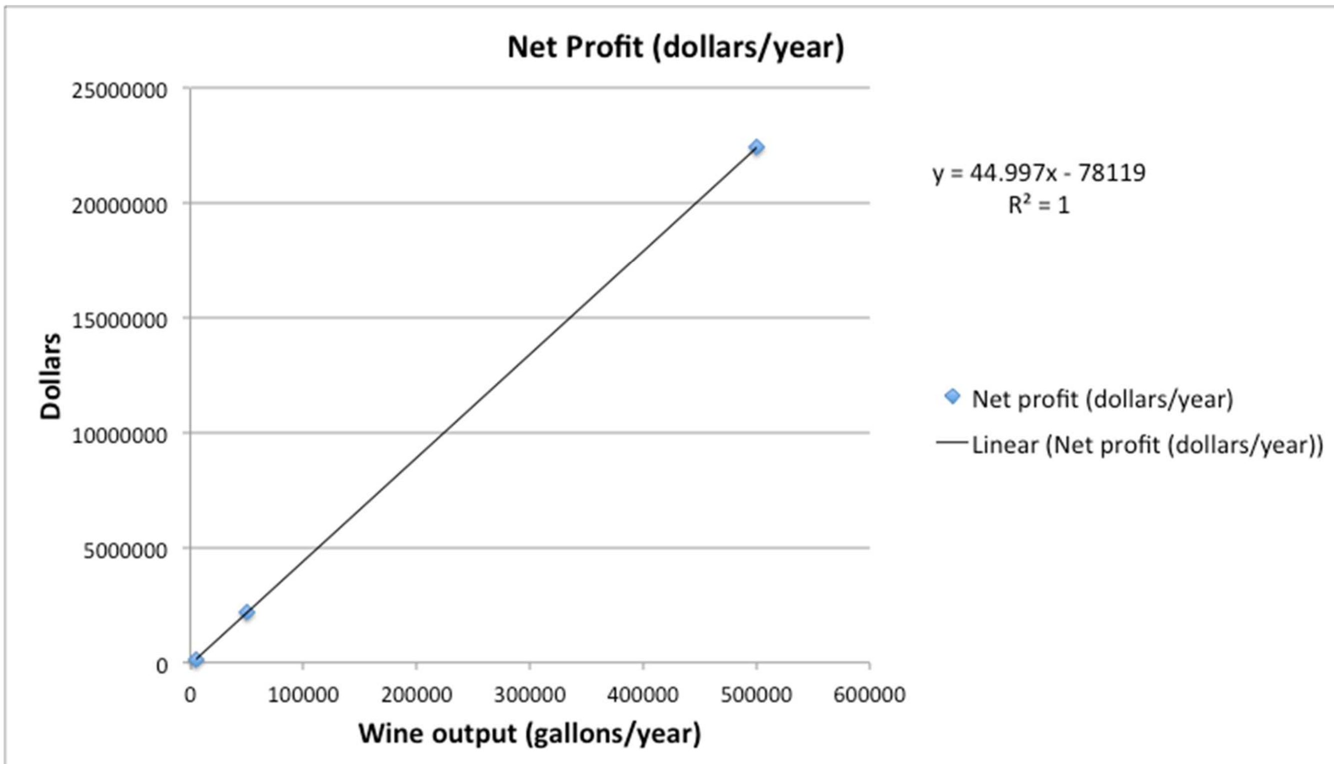

Figure 12. Annual revenue relationship among three scales (linear)

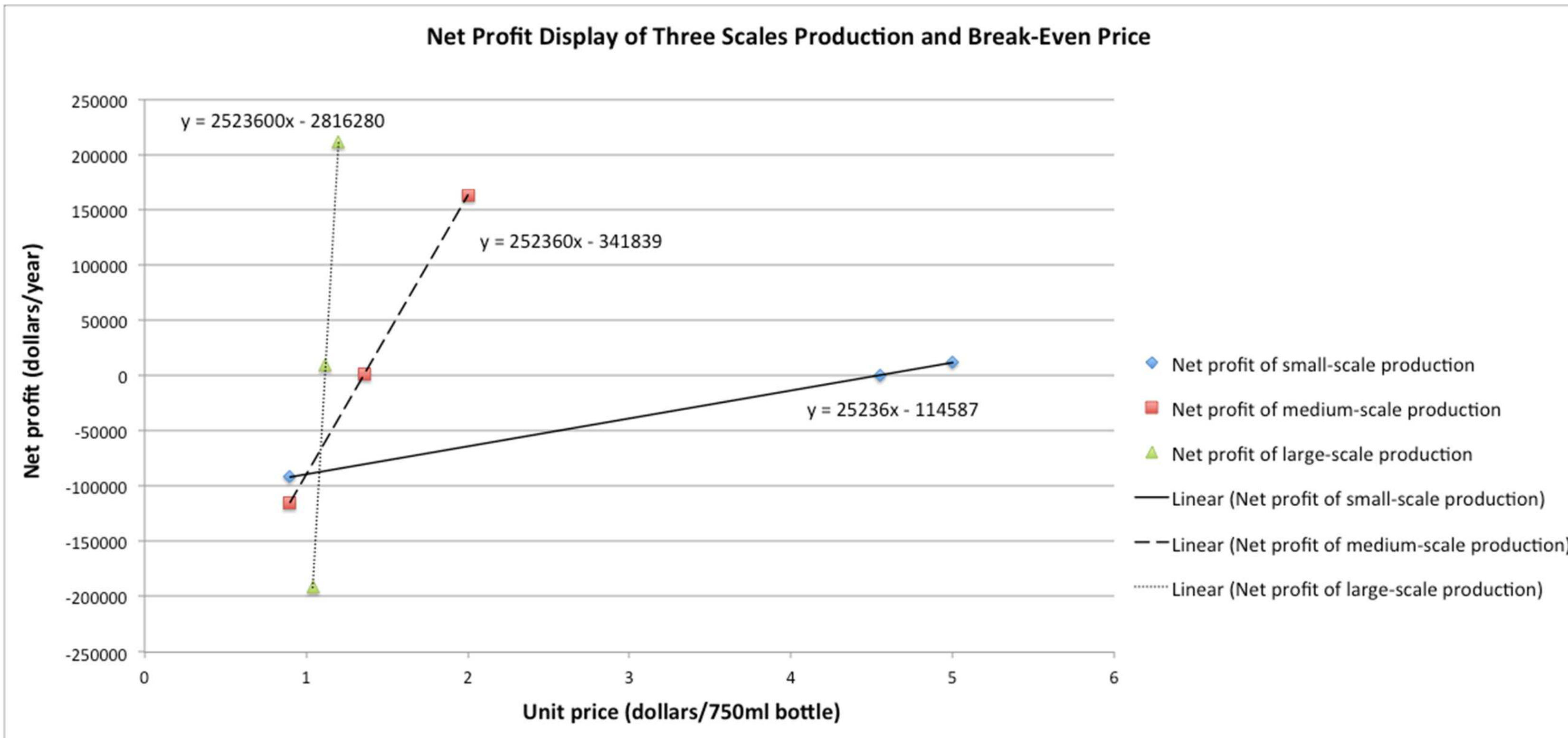

Figure 13. Net profit and break-even price

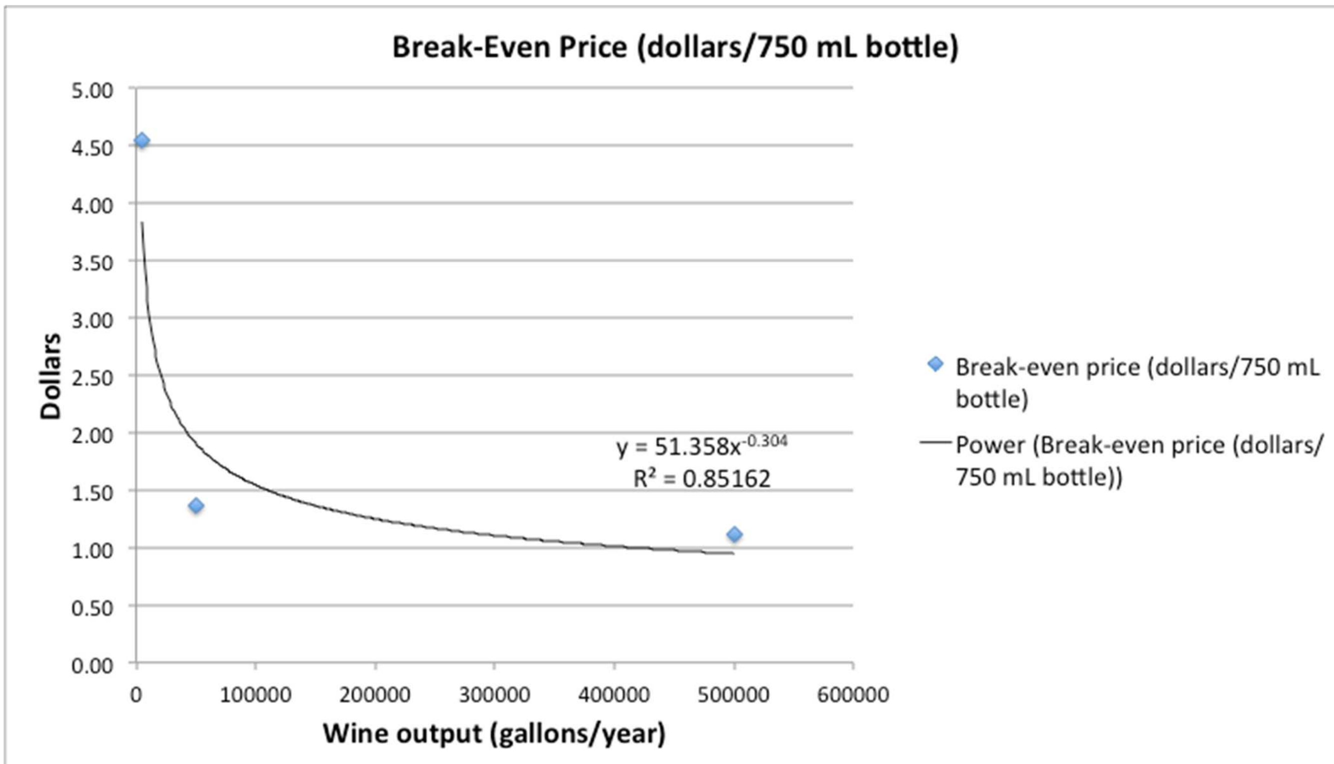

Figure 14. Break-even price relationship among three scales (power)

Table 1. Data inventory for energy and water consumption (per 750 mL bottle)

	Vine planting	Wine making	Bottle Manufacture	Distribution
Energy (kJ)*	560	949	1010	455
Water (gallon)**	29.06	1.41	0	0

*EioLCA, 2014
**Fusi et al., 2014

Table 2. Data inventory for greenhouse gas emission (g CO_2 equivalents per 750 mL bottle)*

	Vine planting	Wine making	Bottle Manufacture	Distribution
CO_2	24.1	28.3	40.7	33.6
CH_4	0	0	0	0
N_2O	37.9	0	0	0
HFC/PFCS	0	0	0	0
Total	62	28.3	40.7	33.6

*EioLCA, 2014

Table 3. Data inventory for solid waste disposal (g per 750 mL bottle)*

	Vine planting	Wine making	Bottle Manufacture	Distribution
Nitrate	0.48	0	0	0
Sulfur	2.21	0	0	0
Glyphosate	0.17	0	0	0
Mancozeb	0.24	0	0	0
Dimethomorph	43.13	0	0	0
Metiram	0.24	0	0	0
Copper oxychloride	0.23	0	0	0
Marc and lees	0	270	0	0
Stalks	0	50	0	0
Glass	0	0	170	0
Total	46.7	320	170	0

*Fusi et al., 2014

Table 4. Data inventory for TEA

Scale		Small (5,000 gallons/year)	Medium (50,000	Large (500,000 gallons/year)
Land (acre)		7	70	700
Grape output (Mg)		42	420	4200
Tillage*	Amount of machine	1	5	20
	Machine work time (h)	47.2	95	236
	Fuel consumption (gallon/h)	0.25	1.25	5
	Work efficiency (m^2/h)	600	3000	12000
	Machine cost (dollars/machine)	500	500	500
Fertilizer*	Amount of fertilizer (lb)	105	1050	10500
	Fertilizer cost (dollars/Mg)	300	300	300
Harvester**	Amount of machine	1	1	1
	Machine work time (h)	3	30	300
	Fuel consumption (gallon/h)	4.8	4.8	4.8
	Work efficiency (Mg/h)	14	14	14
	Machine cost (dollars/machine)	170,000	170,000	170,000
Fermentation Tank cost (dollars)*		40000	230000	900000
Oak barrel***	Unit cost (dollars/gallon)	15	15	15
	Total cost (dollars)	75600	756000	7560000
Bottling equipment cost (dollars)****		7000	130000	500000
Bottle cost***	Unit cost (dollars/750 mL bottle)	0.5	0.5	0.5
	Total cost (dollars)	12700	127000	1270000
Crush, press, rack, filter equipment cost (dollar)****		15000	80000	500000
Full time employee or wine making process (person)****		2	3	22

*Alibaba, 2014
**Novak and Burg, 2013
*** The vintner's vault, 2014
****Dillon et al., 1992

Table 5. Annual economic data

Scale		Small (5,000 gallons/year)	Medium (50,000	Large (500,000 gallons/year)
Grape vine	Recycle	0	0	0
Tillage (dollars/year)	Labor	472	950	2360
	Machine	33	167	700
	Energy	36	360	3600
Fertilizer (dollars/year)		14	140	1400
Harvest (dollars/year)	Labor	30	300	3000
	Machine	12,000	12,000	12,000
	Energy	43.2	432	4320
Fermentation Tank (dollars/year)		2,700	15,500	60,000
Oak barrel (dollars/year)		5,040	50,400	504,000
Bottling equipment (dollars/year)		470	8700	35000
Bottle (dollars/year)		12,700	127,000	1270,000
Crush, press, rack, filter equipment (dollars/year)		1,000	5,400	35,000
Labor cost for full time employee (dollars/year)		80,000	120,000	880,000
Cost of equipment and material (dollars/year)		21,336	93,099	656,020
Cost of labor (dollars/year)		80,502	121,250	885,360
Cost of bottle (dollars/year)		12,700	127,000	1270,000
Total cost (dollars/year)		114,587	341,839	2,816,280
Revenue (dollars/year)		252,360	2,523,600	25,236,000
Net profit (dollars/year)		137,773	2,181,761	22,419,720

CHAPTER 5. GENERAL CONCLUSIONS AND FUTURE WORK

General Conclusions

The present thesis has conducted analysis, assessment and modeling with regard to different kinds of agricultural processing including storage, drying and processing regarding changing the form and characteristics of agricultural products for a complex grain farm including a vineyard with grain and red wine as products.

The time-dependent model established and the experiment results obtained in Chapter 2 has showed that hermetic storage is effective on controlling of the infecting of red flour beetle (*Tribolium castaneum*) and maize weevil (*Sitophilus zeamais*) during wheat and maize storage. 100% mortality of red flour beetle (*Tribolium castaneum*) was obtained in 12 days under hermetic condition and hermetic treatment become effective after 6 days. 100% mortality of maize weevil (*Sitophilus zeamais*) was obtained in 12 days under hermetic condition and hermetic treatment become effective on after 9 days storage.

The study of Chapter 3 has showed that the efficiency of the DOROTHY cyclone moisture removal system operating in winter is comparable to common drying systems used in industry and thus could work well under winter condition and its efficiency was acceptable. However, compare to the fall trial, the efficiency of winter trial was the half (2760 Btu/lb water removal to 1480 Btu/lb water removal). Which illustrated the system could work well in winter but could work with high efficiency in fall. The environmental temperature is important to achieve the high efficiency of the DOROTHY system.

In Chapter 4, the information with regard to environment and economy to help to make decision when establishing a winery have been provided by conducting LCA (Life cycle assessment) and TEA (Techno-economic analysis) for the particular red wine production processes. For life cycle assessment, for the input impact, bottle manufacture and wine making contributed the most impact on energy consumption while vine planting contributed the most impact on water consumption. For the output impact, vine planting and bottle manufacture contributed the most impact on greenhouse gas emission while bottle manufacture and wine making contributed the most impact on solid waste disposal. For techno-economic analysis, the annual cost was 114,587 dollars per year, 341,839 dollars per year, and 2,816,280 dollars per year separately for small (5,000 gallons per year), medium (50,000 gallons per year), and large (500,000 gallons per year) scales, and the relationship among the three sizes production fitted the exponential increase well but fitted the linear increase better. The labor cost contribution to total cost decreased while production size increased, and the bottle cost contribution to total cost increased while production size increased. The annual revenue was 252,360 dollars per year, 2,523,600 dollars per year, and 25,236,000 dollars per year separately for small, medium, and large scales, and the relationship among the three scales production followed the exponential increase well but it fitted linear increase perfectly as it was calculated purely based on production scale. The annual profit was 137,773 dollars per year, 2,181,761 dollars per year, and 22,419,720 dollars per year separately for small, medium, and large scales, and the relationship of the annual net profit among the three scales followed the exponential increase well but due to the effect of the annual revenue, it fitted linear increase better. The break-even prices were 4.55 dollars, 1.36 dollars and 1.12 dollars per 750 mL bottle separately for winery sizes of 5,000, 50,000 and 500,000 gallons per year, the larger the winery size, the lower the break-even price, and fits power decrease well.

In general, several models were developed and analyses were conducted in the present thesis. The methods of analysis and modeling to characterize, understand and predict agricultural processing was implemented. The results obtained and the models developed could be useful when conduct optimization of agricultural processing.

Future Work

In order to relieve the problems of the shortage of food and energy as well as environmental impacts, a lot of work with respect to optimizing agricultural processing by analyzing and modeling it would be done. As for the specific applications in the present thesis, a large-scale hermetic storage model could be established based on the data collected and model developed in Chapter 2. Commercial trials could be operated, and further development to improve its environmental adaptation could be made for the DOROTHY cyclone moisture removal system. The life cycle assessment and techno-economic analysis could be improved by considering adding a glass bottle factory to the winemaking process when establishing a winery with the output around 500,000 gallons per year.

APPENDIX. DETERMINATION OF THE EFFECT OF HERMETIC TREATMENT WITH AND WITHOUT VACUUM GREASE ON LIDS

Objective

The objective of the present experiment was to test the effect of hermetic treatment by comparing the mortality change of maize weevil (*Sitophilus zeamais*) in both hermetic treatment with lid and hermetic treatment with lid and vacuum grease, therefore help to determine the proper materials and methods for the hermetic treatment in Chapter 2.

Materials and Methods

Adult maize weevil (*Sitophilus zeamais*) was attained from laboratory cultures, cultivated on a food substrate of maize. The cultures were retained in an incubator and maintained at a constant temperature of 24± 0.8 °C.

Maize grain of fresh commercial hybrid Fontanelle 6T672 grown at the Agricultural Engineering-Agronomy farm 12 kilometers west of Ames, Iowa. It was harvested and dried without the addition of heat. It was cleaned to remove broken maize and foreign material and no pesticide was used. The maize was stored at 4 °C until used.

A laboratory scale hermetic storage model with small glass jars was used. Treatment condition of temperature of 27 °C was chosen.

A chamber of model Fisher Scientific Isotemp Chromatography Refrigerator (Thermo Fisher Scientific Inc., Waltham, MA USA 02451) was used in this experiments, with heating and temperature controls, maintained at 27 °C.

Canning jars (4 oz, Ball Glass Mason Jars, Hearthmark, LLC dba Jarden Home Brands, Daleville, IN USA 47334) were utilized. Each jar was loaded with maize to nearly full and was weighed.

For hermetic treatment with lid, utilized canning jars with hermetic lids, while for hermetic treatment with lid and vacuum grease, utilized canning jars with hermetic lids and vacuum grease (Dow Corning High Vacuum Grease, Dow Corning Corporation, Midland, MI USA 48686), with applying the vacuum grease to the edge of the lid.

The experimental design (Table 1) consisted of two factorials (days and hermetic treatments), with mortality being the dependent variable. Days had 5 levels (3rd, 6th, 9th, 12th, and 30th), while hermetic treatments had 2 levels (with lid and with lid and vacuum grease). Total of 10 treatments were used (a balanced design of 5 with lid and 5 with lid and vacuum grease). The jars with lids had five levels of days while the jars with lids and vacuum grease also had five levels of days. Each of the 10 jars contained 10 weevils.

To determine mortality, each jar from the 10 treatments was examined for dead insects on the day to which it was randomly assigned. Based on a combination of observed rigor mortis features (Gullan and Cranston, 2000), by following the method that Yakubu et al. (2011) used in their study, insects were counted as dead if they were curled up or had outstretched legs or immobile or found lying on their side/back or unattached to maize kernels or found to flow with kernels when jar was tilted or found to have any combination of these features. Both of the treatments counts were done on days 3, 6, 9, 12, and 30. The number of dead bugs of each jar was recorded and divided by 10 to obtain the mortality.

Results and Discussion

For the treatment with lid, the mortality of maize weevil (*Sitophilus zeamais*) reached 100% in 6 days, but decreased to 90% in the sample of 9 days and decreased to 10% in the sample of 12 days (Figure 1 and Table 2). This illustrates the mortality decreased after 6 days of storage and the hermetic treatment with lid was not effective.

For the treatment with lid and vacuum grease, the mortality of maize weevil (*Sitophilus zeamais*) reached 100% in 6 days and kept until 30 days (Figure 1 and Table 2). This illustrates the mortality did not decrease and the hermetic treatment with lid and vacuum grease was effective.

Compared to the treatment with lid, the treatment with lid and vacuum grease was more effective on forming the hermetic condition. Therefore, the treatment with lid and vacuum grease was chosen for the hermetic treatment and its data of mortality was used as one replication in the results and discussion of Chapter 2.

Conclusions

The results of the present experiment showed that the mortality of the treatment with lid decreased after 6 days of storage, while no mortality decrease was observed in the treatment with lid and vacuum grease. Compared to the treatment with lid, the treatment with lid and vacuum grease was more effective on forming the hermetic condition. As conclusion, the treatment with lid and vacuum grease was determined as the hermetic treatment of Chapter 2.

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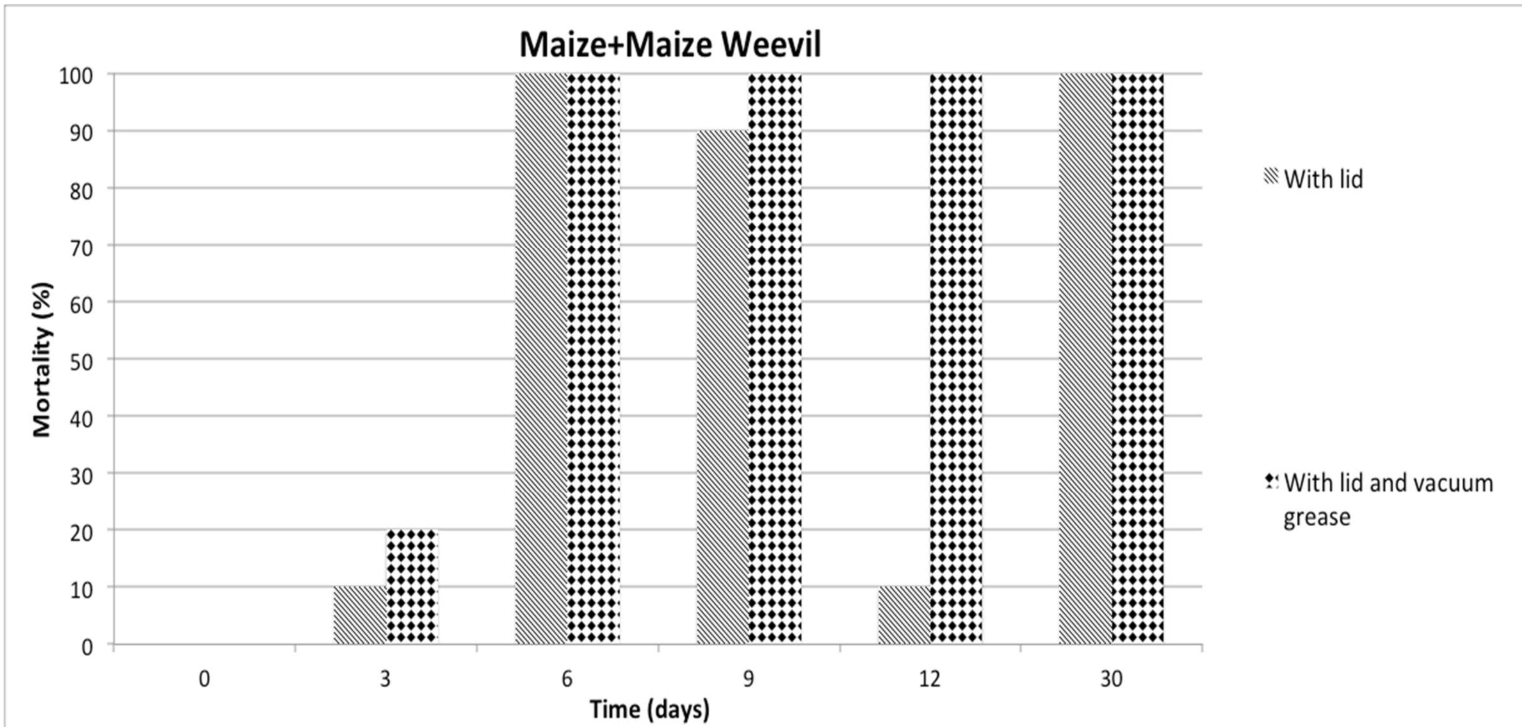

Figure 1. Mortality of each treatment

Table 1. Experimental design

Days	Hermetic treatments
3	With lid
6	With lid
9	With lid
12	With lid
30	With lid
3	With lid and vacuum grease
6	With lid and vacuum grease
9	With lid and vacuum grease
12	With lid and vacuum grease
30	With lid and vacuum grease

Table 2. Data of maize weevil

Time (days)		With lid
3	Maize weight (g)	90.23
	Mortality (%)	10.00
6	Maize weight (g)	94.02
	Mortality (%)	100.00
9	Maize weight (g)	92.36
	Mortality (%)	90.00
12	Maize weight (g)	95.01
	Mortality (%)	10.00
30	Maize weight (g)	90.98
	Mortality (%)	100.00
Time (days)		With lid and vacuum grease
3	Maize weight (g)	92.03
	Mortality (%)	20.00
6	Maize weight (g)	90.17
	Mortality (%)	100.00
9	Maize weight (g)	93.01
	Mortality (%)	100.00
12	Maize weight (g)	90.02
	Mortality (%)	100.00
30	Maize weight (g)	90.58
	Mortality (%)	100.00