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Economic and Technical Feasibility of Grain Chilling in Brazil

Daniela de Carvalho Lopes and Antonio José Steidle Neto*

Federal University of São João del-Rei, Campus Sete Lagoas, Rodovia MG 424, km 47, Sete Lagoas, 35701-970, Minas Gerais, Brazil

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Abstract:

Grain quality is critical due to the more stringent food-safety demands. Chilled aeration has become a popular technology for preventing grain spoilage during storage, mainly in warmer regions. However, a limiting factor in broad-scale adoption of chilling is the general belief that this technology is much more expensive than other post-harvest methods, such as the aeration with ambient air. In this work, ambient and chilled aeration were simulated considering the three major grain-producing regions in Brazil. Also, three storage capacities (95, 5000, 10500 t), five-grain types (corn, coffee, rice, bean, soybean), and two storage periods (beginning at the first and the last months of the harvest period) were used in the study, totalling 180 simulation scenarios. Based on these simulations a comparative cash flow analysis was performed aiming at evaluating the influence of the product, storage period, region, and silo size on the costs and profits from using these technologies. Results were strongly affected by the weather patterns of the studied regions, market values of grain, storage sizes, and fan operation hours. Chilled aeration should be economically competitive with ambient aeration, and the two technologies appeared as low-risk investments in Brazil, achieving average profits for 20 years by considering the time of money of US$ 68 and 59.4 million, respectively. Considering the technical factors, chilling presented higher energy consumption, but showed a greater potential for reducing grain temperatures and resulted in grain dry matter losses around 58% smaller than those verified when using ambient air.

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*Corresponding Author
E-mail: antonio@ufsj.edu.br

1. INTRODUCTION

Grain quality is affected from the time of harvest due to interactions with the environment and is critical due to the more stringent food-safety demands [1]. Preserving grain is a problem since its quality never improves during storage. However, it can be maintained as closely as possible by using proper integrated pest management and controlling factors that negatively affect grain processing and decrease its economic value [2].

If storage conditions are managed correctly, grain can be stored for a long time. Aeration is an established technology, used to move relatively low volumes of cold air through stored grain bulks for controlling grain temperatures and reducing damaging organisms [3]. The beneficial effects of aeration also include the control of moisture migration, helping the sustainability of favourable storage conditions for the safe preservation of grain quality. This technology is particularly important for food industries, agricultural cooperatives, and farms due to the regulatory constraints on the use of chemicals for pest control, as well as the problems associated with insect, mite, and fungal resistance [4, 5].

Depending on the weather conditions, as well as the geographic location, aeration with ambient air cannot achieve the temperatures that inhibit insect activity even with an efficient control strategy [6,7]. In these cases, chilled aeration is recommended since it uses a refrigeration unit to control the relative humidity and temperature of the air entering the grain storage independent of ambient conditions [8].

Chilling technology has become more popular, been successfully used in many countries and for different grain types during the past years [9-11]. Mainly in some tropical and subtropical regions, the use of chilled aeration is more efficient in lowering insect and mould populations, as well as maintaining the germination, when compared to ambient aeration and other management methods [4,5,12]. Another benefit is that chilled grain can be safely stored at higher moisture content for a limited time than dry grain. Further, if the grain is stored for long periods, chilling has the potential to suppress pest development [13].

However, ambient aeration systems are still dominant for temperature management of stored grains [6,14,15]. One possible limiting factor in the broad-scale adoption of chilled aeration is the general belief that this technology is economically unviable or much more expensive than other post-harvest methods [5]. Indeed, the capital investment for chilling equipment is high, but long-term costs, when amortized over time, can be competitive with ambient air aeration [8].

In this context, more research on the technical and economic feasibility of chilled aeration is required. The few recent studies found are applied only to ambient air aeration or to specific grain, equipment, and storage capacities [8,15,16]. Further, most of them did not consider lifetimes of projects greater than one year.

This study is a comparative technical and economic analysis between ambient and chilled aeration, considering different airflow rates, grain types, storage capacities, and weather conditions. The technical analysis involved the final grain temperature and moisture content, considering the safe storage recommendations, as well as aeration time, energy requirements, and grain dry matter loss after the technology application. The economic calculations included operating and fixed capital costs, aiming at contributing to a better understanding of investments and profits from using these technologies, also motivating the chilled aeration adoption by food industries, cooperatives, and farms.

2. METHODOLOGY

2.1. Technical Simulations

During simulations, three Brazilian regions (South, Southeast, and Centre-West) deemed as major producers of grain and with different climates were evaluated. According to Alvares *et al*. [17] and following Köppen's classification, the predominant climate in the Centre-West region is tropical with dry winters (Aw), while the Southeast is characterized by a humid subtropical climate, with dry winters and hot summers (Cwa). The southern region is predominantly characterized by an oceanic humid climate without a dry season and with hot summers (Cfa). The Centre-West, Southeast and Southern regions were respectively represented by the cities of Diamantino (14° 24' S, 56° 27' W, 269 m altitude) located at the State of Mato Grosso, São Lourenço (22° 6' S, 45° 0' W, 875 m altitude) located at the State of Minas Gerais, and Cruz Alta (28° 37' S, 53° 36' W, 452 m altitude) located at the Rio Grande do Sul State.

Further, small, medium, and large size silos (95, 5000, and 10500 t), as well as three airflow rates (3, 6, and 9

Table 1: Beginning Storage Periods According to the Different Grain Types and Brazilian Regions used during Simulations

	Centre-West	Southeast	South
Beans	January and April	December and March	December and April
Coffee	April and July	April and July	April and July
Corn	February and June	February and June	January and June
Rice	January and May	March and June	February and May
Soybean	January and April	January and May	March and May

$m^3\ h^{-1}\ t^{-1}$), were simulated, corresponding to the most common commercial Brazilian aeration systems and representing a wide range of operating conditions. For each grain type (corn, coffee, rice, bean, and soybean) and aeration technology (chilling or ambient air), it was simulated the storage beginning at the first and the last months of the harvest period (Table **1**), as reported by Conab [18].

When combining the three regions, two storage periods, five-grain types, three storage capacities, and two aeration technologies, 180 aeration scenarios were simulated. Software was written in the Java programming language, capable of simulating both chilled and ambient air aeration processes. It was based on the one-dimensional model proposed by Thorpe [19], which depends on the psychrometric relationships [20] and two main differential equations that describe the heat and mass transfer in beds of ventilated grains:

$$\frac{\partial\theta}{\partial t}\left\{\rho_b\left[c_g + c_w U_p\right] + \varepsilon\rho_a\left[c_a + R\left(c_w + \frac{\partial h_v}{\partial T}\right)\right]\right\} = \rho_b h_s \frac{\partial U_p}{\partial t} - u_a\rho_a\left[c_a + R\left(c_w + \frac{\partial h_v}{\partial T}\right)\right]\frac{\partial\theta}{\partial y} + \rho_b\frac{dm_s}{dt}(Q_r - 0,6h_v) \quad (1)$$

$$\frac{\partial U_p}{\partial t} = -\frac{\rho_a u_a}{\rho_b}\frac{\partial R}{\partial y} + 0.6\frac{dm_s}{dt}(1 + 1.66U_p) \quad (2)$$

Where θ is the grain temperature (°C), t is the time (s), ρ_b the bulk density of the grain (kg m^{-3}), c_g is the specific heat of grain (J kg^{-1} $°K^{-1}$), T is the air temperature (ºC), c_w is the specific heat of water (J kg^{-1} $°K^{-1}$), U is the grain moisture content (%d.b.), ε is the grain porosity (decimal), ρ_a the density of intergranular air (kg m^{-3}), c_a is the specific heat of the air (J kg^{-1} $°K^{-1}$), R the humidity ratio of air (kg kg^{-1}), h_v is the latent heat of vaporization of water (J kg^{-1}), h_s is the differential heat of sorption (J kg^{-1}), u_a the air velocity (m s^{-1}), y is the vertical coordinate (m), m_s is the grain's dry matter loss (%), and Q_r the heat of oxidation of grain (J s^{-1} m^{-3}).

During simulations, the heigh of grain bulk was divided into ten sections in the direction of the airflow (vertical direction) and their limits were called nodes (Figure **1**). For the first node, located near the air input, it was assumed that temperatures of grain and air are equal and that grain moisture content is in equilibrium with the relative humidity of aeration air. Grain moisture contents and temperatures of the other nodes were calculated after each time interval (3600 s) iteratively by using equations 1 and 2, which were solved using the finite difference numerical technique. The Chung-Pfost equation was applied as an equilibrium relative humidity model since it is one of the formulations approved by the ASAE for this purpose [1]. Equations proposed by Thompson [21] were used as an auxiliary model to determine the grain dry matter loss.

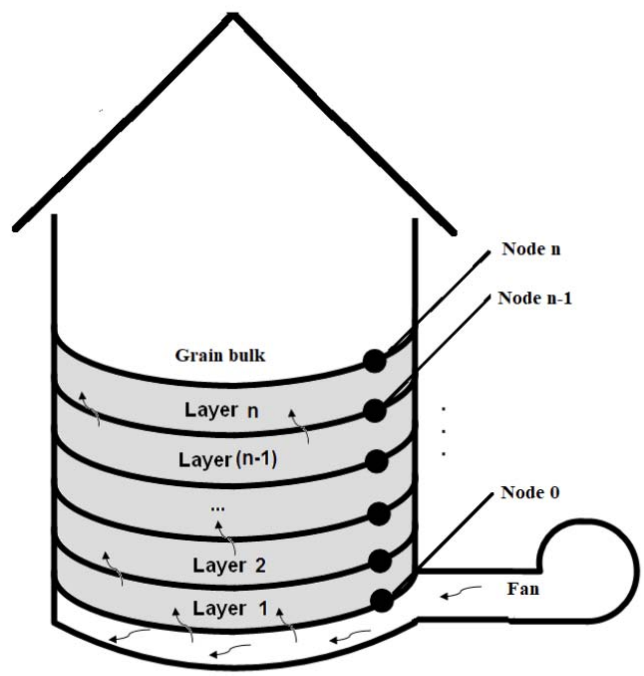

Figure 1: The scheme used to represent the grain layers during simulations of the aeration process.

It was assumed that clean and dry grain was stored for six months following the safe storage practices. The initial distributions of grain moisture content and

Table 2: Meteorological Data of the three Brazilian Regions used during Simulations

	Centre-West	Southeast	South
Minimum dry-bulb temperature (°C)	17.2	7.8	4.2
Maximum dry-bulb temperature (°C)	39.8	35.0	33.0
Average dry-bulb temperature (°C)	27.4	21.6	19.8
Minimum relative humidity (%)	35.0	21.0	45.0
Maximum relative humidity (%)	99.9	99.9	99.9
Average relative humidity (%)	80.8	74.1	89.1

temperature were considered uniform, that is, all layers with the same initial moisture content and temperature. The initial temperature of the grain was 35°C, while safe moisture contents were calculated for each grain type for a water activity of 0.7 [22,23]. Thus, the initial moisture contents of rice and soybean were 12% (w.b.), while those of coffee, corn, and bean were 13% (w.b.).

Five years (2012 to 2017) of meteorological data (dry-bulb temperature and relative humidity of the air) at an hourly scale were obtained from the Brazilian National Institute of Meteorology [24] for the three studied regions and used to simulate the conditions of ambient aeration air during the simulated period. A consistency analysis was performed on the meteorological data with electronic spreadsheet functions to remove all inconsistent values. Visual analysis of graphs relating the variables to time was also used as a complementary tool. Data gaps of 1 to 3 hours were filled with the mean values of the time before and after. Dry-bulb temperature and relative humidity values relating to the five years were averaged and the model equations were applied iteratively considering their hourly variations. Table **2** shows the minimum, maximum, and average values of the meteorological data used during simulations for the three regions studied. Further, the AERO strategy [25] was considered for controlling the ambient air aeration. This controller was simulated since it can maintain grain quality with minimal energy input, automatically adjusting its control setpoints according to different climates and storage systems.

Chilled aeration was simulated considering air relative humidity of 70% and air temperature two degrees below the target final grain temperature (21ºC). These values were based on the main control parameters used for grain aeration management. As reported by several experimental studies [26-28], mould and mite growths are dependent mainly upon the relative humidity of the air, with values below 70% suppressing considerably the development of these microorganisms. On the other hand, grain infesting insects are very sensitive to low temperatures, since most of them are of tropical or subtropical origin [29]. Research trials [30,31] proven that stored product insect development is significantly suppressed below 21°C and generally stops below 16°C. According to Navarro *et al*. [29], insect damage caused under these temperature conditions is minimal. As the potential for maintaining low uniform grain temperatures in tropical and subtropical regions is limited, simulations were performed considering the target final grain temperature of 21°C. However, when ambient aeration for the same scenario was simulated and grain reached lower temperatures, the target grain temperature for chilling simulations was also decreased.

The final grain temperature and moisture content, as well as the aeration time and grain dry matter loss, were compared to those recommended for safe storage and also used as input for economic analysis when calculating a storage risk factor and the grain revenues.

2.2. Economic Analysis

Economic analysis was performed based on the cash flow model [32,33], which is the balance of the number of revenues and expenses during the lifetime of the project, with year zero considering no revenues and the capital investment as expenses:

$$C_f^i = G_r^i - (D_c^i + M_c^i + E_c^i + L_c^i + T_x^i)\,(1 + R_f) \qquad (3)$$

Where C_f is the balance of the number of revenues and expenses (US$), i is the year considered in the cash flow (varying from 1 to the lifetime of the project), G_r is the grain revenues (US$), D_c is the depreciation cost (US$), M_c is the maintenance costs (US$), E_c is the electrical energy costs (U$$), L_c is the labour costs

(US$), T_x is the Federal taxes and fees (US$) and R_f is the risk factor associated with unsafe storage conditions (dimensionless).

A project lifetime of 20 years was used based on the average useful life of the silos and the other equipment required for the aeration operation [13]. Additionally, the Brazilian currency(R$) was divided by 3.30 to be converted to US$, following data reported by BCB [34] and considering the simulation period.

The capital investments were estimated according to the prices and market in the studied Brazilian regions, considering the storage capacity and aeration technology [35-37]. For both technologies, the initial costs included fans, thermometry cables, and sensors, as well as the installation of ducts and all equipment and changes required for the aeration system operating. Investment in chilling also included the refrigeration unit. When applying ambient aeration, capital costs for small, medium, and large-scale systems were US$ 11,682.69, US$ 33,667.62, and US$ 56,464.64, respectively. For chilled aeration, these values were US$ 46,730.67, US$ 134,670.48, and US$ 225,858.56.

Grain revenues were calculated as the selling price of the product [38], variable according to the storage region, multiplied by the grain quantity, discounted the dry matter losses that occurred during the aeration process. For each year considered in the cash flow, this value was adjusted according to the inflation rate of 9% a year [34], to reflect the change in the value of money over time.

The annual costs of depreciation and maintenance were each calculated at 10% of the capital investment [8,15,39] and adjusted according to the inflation rate. The energy costs were calculated based on the electrical power consumption of each scenario and Brazilian energy prices corrected for inflation. Labour costs and tax rates adjusted by inflation completed the project expenses, comprising the employee wage of US$ 24.24 per day [40], the social tax costs of 70% of the wage [41], and other tax rates of 10% of the capital investment [18].

Further, a risk factor was incorporated to the expenses by considering that grain temperatures higher than 21ºC after aeration should raise costs associated with fumigation and quality loss control, while grain temperatures lower or equal to 21ºC will result in an opposite effect. Thus, for each degree of final grain temperature above this threshold, expenses were increased by 5% and for each degree below 21ºC expenses were decreased by 5% [8,39,42].

Cash flows of each simulated scenario were evaluated by the economic indices payback period (PP), benefit-cost ratio (BCR), internal rate of return (IRR), and net present value (NVP), following methodology reported by Steidle Neto and Lopes [15] and Lopes *et al*. [43].

The payback period (PP) is the smallest period in which the initial investment can be recovery together with interest at a specified rate. This index was calculated iteratively, seeking the number of years required for recovering the initial investment in the aeration technology by the cumulative revenues. Profitable projects presented payback periods smaller than their lifetimes.

The benefit-cost ratio (BCR) is also called profitability index and represents the discounting project revenues divided by its capital investment. Feasible projects presented a BCR greater than one, indicating that the sum of the benefits exceeded the costs of the project. This economic index was calculated as:

$$BCR = \left(\sum_{i=1}^{L} \frac{C_f^i}{(1+k)^i} \right) \Big/ C \tag{4}$$

Where BCR is the benefit-cost ratio (dimensionless), C is the initial investment (US$), k is the annual inflation rate (%), and L is the lifetime of the project (years).

Internal rate of return (IRR) represents the profit rate of investment regardless of an attractiveness rate, also called the interest rate, which describes the perceived quality and utility of a product or project [44]. IRR was calculated iteratively by Lagrange interpolation, searching the rate at which the project returns the NPV of zero. This result was compared with the attractiveness rate of 7%, reported by Mugabi and Driscoll [42] as the minimum acceptable return percentage that the grain storage systems must earn to be profitable. Thus, a project was economically viable if IRR was greater than the attractiveness rate.

The net present value (NPV) is the most frequent index used for making economic decisions since it requires information about the rate of return, regulatory and market possibilities, as well as hedging options [32]. This index represents the present value of all revenues and costs during the period of analysis of the investment, with values greater than zero indicating profitability. NPV was calculated by subtracting all project expenses from revenues, discounting inflation rate referred to the year zero of the cash flow:

$$NPV = \sum_{i=1}^{L} \frac{C_f^i}{(1+k)^i} - C \quad (5)$$

Where NPV is the net present value (US$).

3. RESULTS

Results of simulations performed in this study showed that chilled aeration can be economically competitive with ambient aeration in Brazil (Figures **2-4**). From the 180 simulated scenarios, all ambient aeration systems were profitable and only ten chilled aeration configurations were not worthwhile. These occurred when simulating small corn and rice storage capacities (up to 95 t) in Centre-West and South regions of Brazil. Also, chilling aeration was economically unviable in the Southeast of Brazil when storing corn in small size silos.

Most of the profitable scenarios resulted in lengths of time required to recover the cost of aeration investments smaller than three months, which was considered as immediate payback periods (PP). Exceptions were payback periods of chilling aeration in the three studied regions when storing soybean in small storages, which were around four years, corresponding to a fifth of the project lifetime. When storing corn in small size silos in Brazilian Centre-West and aerating grain with ambient air this index was also four years. For the same conditions in the South and Southeast, the payback periods were around 2 years.

BCR values of the profitable scenarios (Figure **2**) most differed among grain types, varying from 2.1 to 5.0, with an average of 2.5 (±0.7). These results indicate that the sums of the benefits were at least greater than twice the costs, both for chilling and ambient aeration. Higher BCR values were observed when aerating coffee with ambient air in medium and large size silos (5000 and 10500 t) in the three studied Brazilian regions. This was also the scenario that most differ from its chilling equivalent, presenting a BCR 46% greater. When comparing the other chilling and ambient aeration scenarios, differences did not exceed 8%.

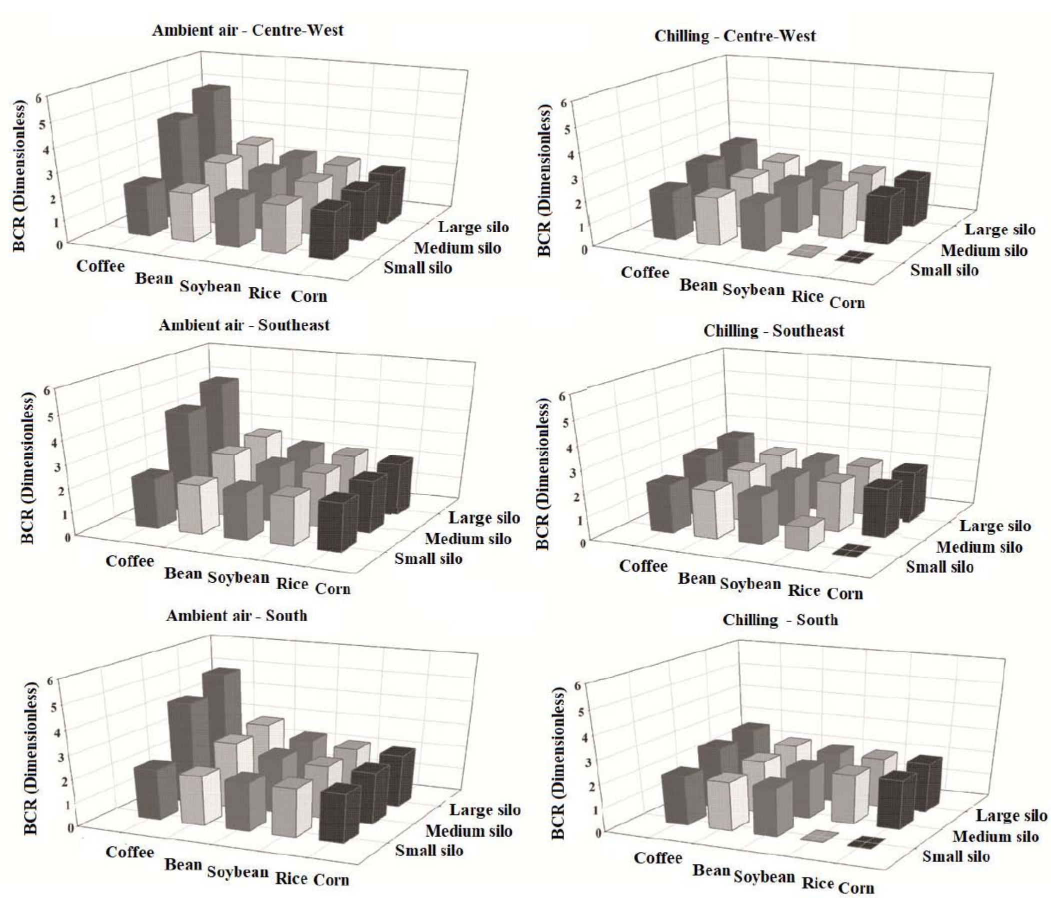

Figure 2: BCR values of profitable aeration scenarios.

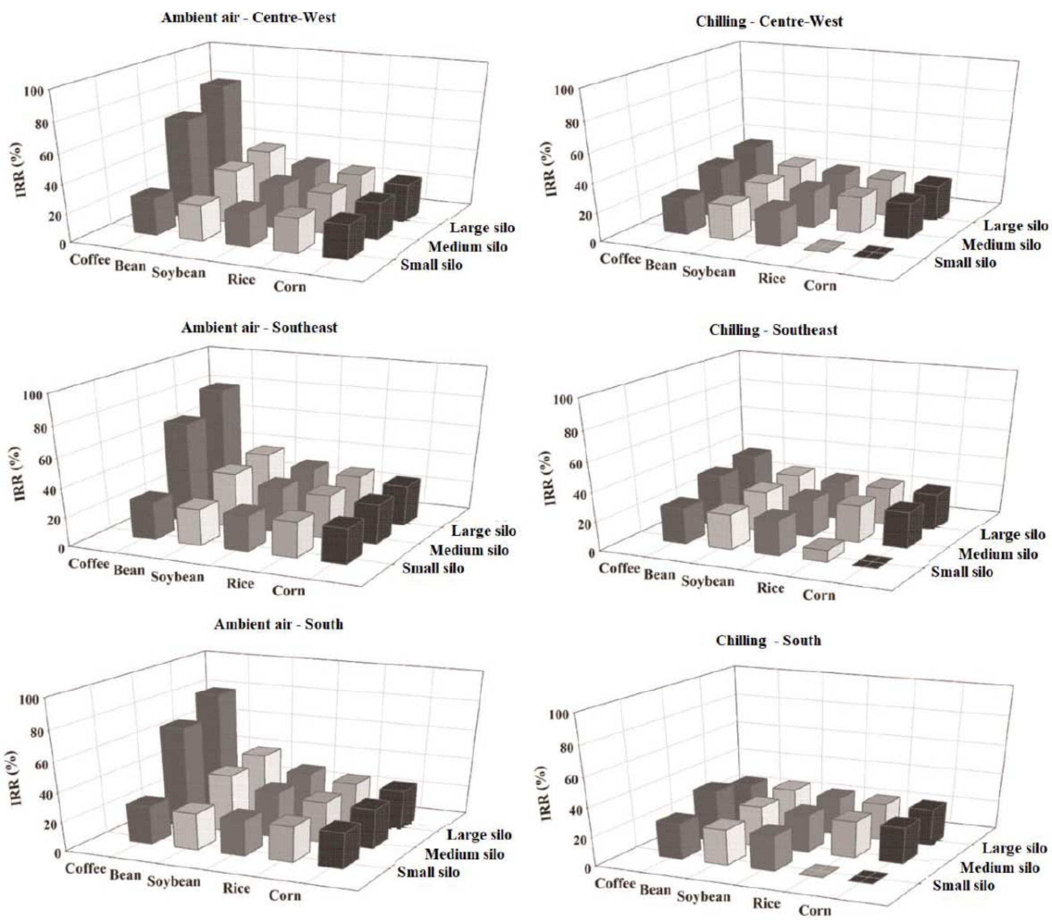

Figure 3: IRR values of profitable aeration scenarios.

The IRR values of profitable scenarios varied from 24.2 to 82.0% with an average of 31.4 (±12.7) and with major differentiation found among grain types (Figure **3**). Following the same trend of the other economic indices, the greater IRRs were verified for large-size silos used for coffee and equipped with ambient air aeration in the three studied regions studied, which were 56% greater than their equivalent chilling scenarios. When considering the other grain types differences between IRRs of chilling and ambient aeration were around 12%. For both aeration technologies, all worthwhile IRRs were largely ahead of the attractiveness rate of 7%, presented by Mugabi and Driscoll [42], for describing the perceived quality and utility of grain storage systems.

NPV values of profitable scenarios were the most variable according to the different storage sizes and grain types, but this index varied little between aeration technologies (Figure **4**). As expected, large size bins and grains with higher economic values were associated with greater NPVs. According to the simulations, coffee aeration in large size bins was more profitable for both chilling and ambient air, followed by the aeration of the bean. The simulated profits of grain aeration in Brazil for 20 years by considering the time of money varied from US$ 38,653 to US$ 314.85 million, with an average of U$$ 60.32 million (± 88.52).

This trend of NPV equality in terms of aeration technology and differentiation regarding grain type is also verified when analysing the index values per tonne of stored grain. The minimum NPV per tonne was US$ 0.34 and was observed for ambient corn aeration in medium-size bins in Centre-West. The maximum NPV per tonne was verified for coffee aeration in medium-size silos with ambient air in Centre-West and with chilled air in Brazilian South (US$ 45.30 per tonne).

When considering the technical factors, simulated chilling presented the greater potential for achieving the cooling effect recommended for safe grain storage, achieving an average final grain temperature of 18.9°C (±2.0). When using ambient air aeration, the average final grain temperature was 22.6°C (±4.0) The aeration cooling effects simulated for the evaluated systems,

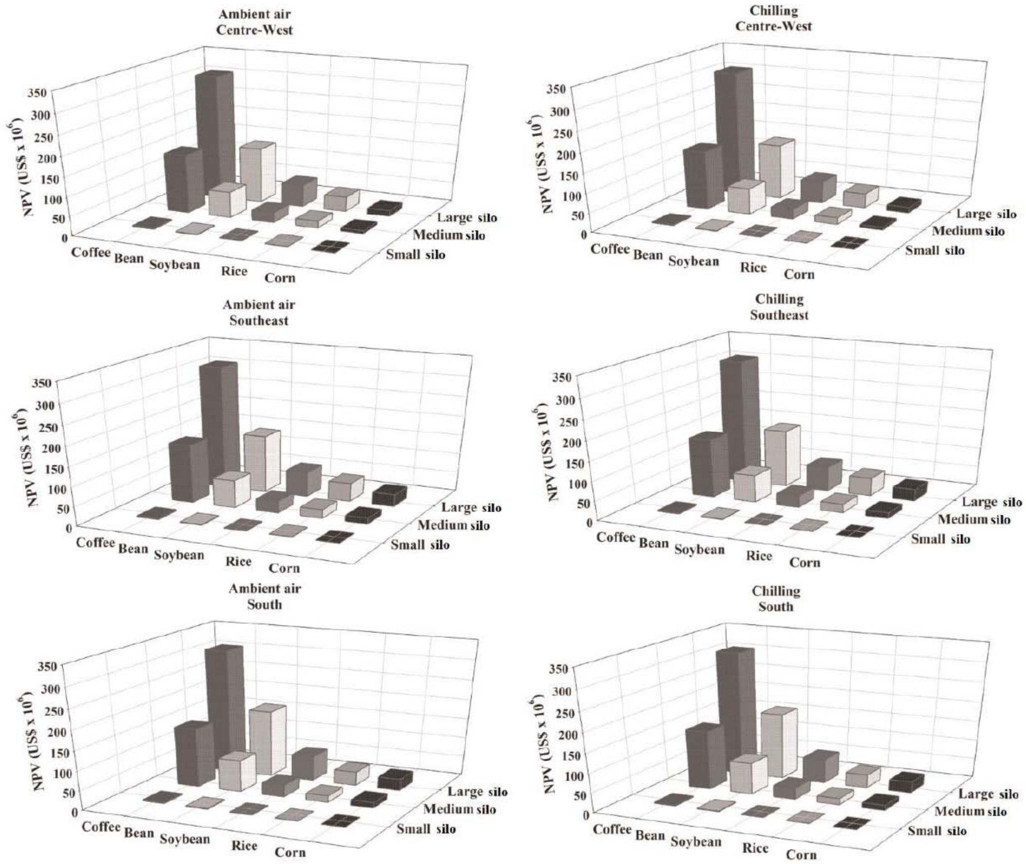

Figure 4: NPV values of profitable aeration scenarios.

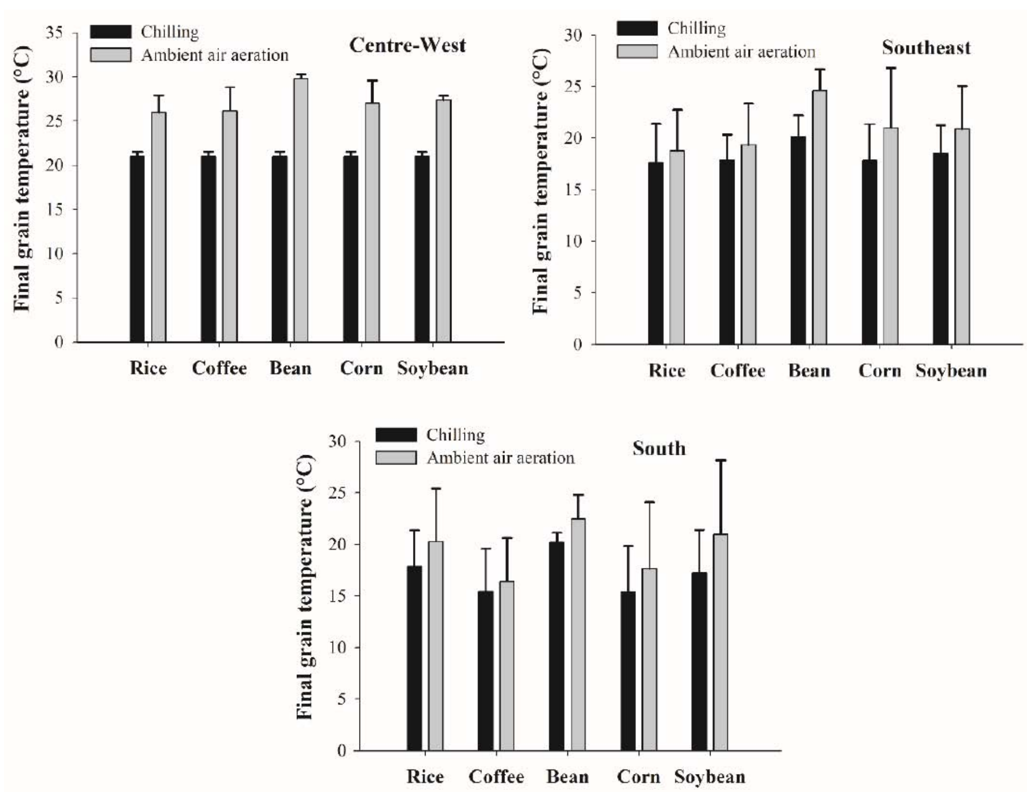

Figure 5: Average final grain temperatures according to different grain types and regions, considering chilling and ambient air aeration.

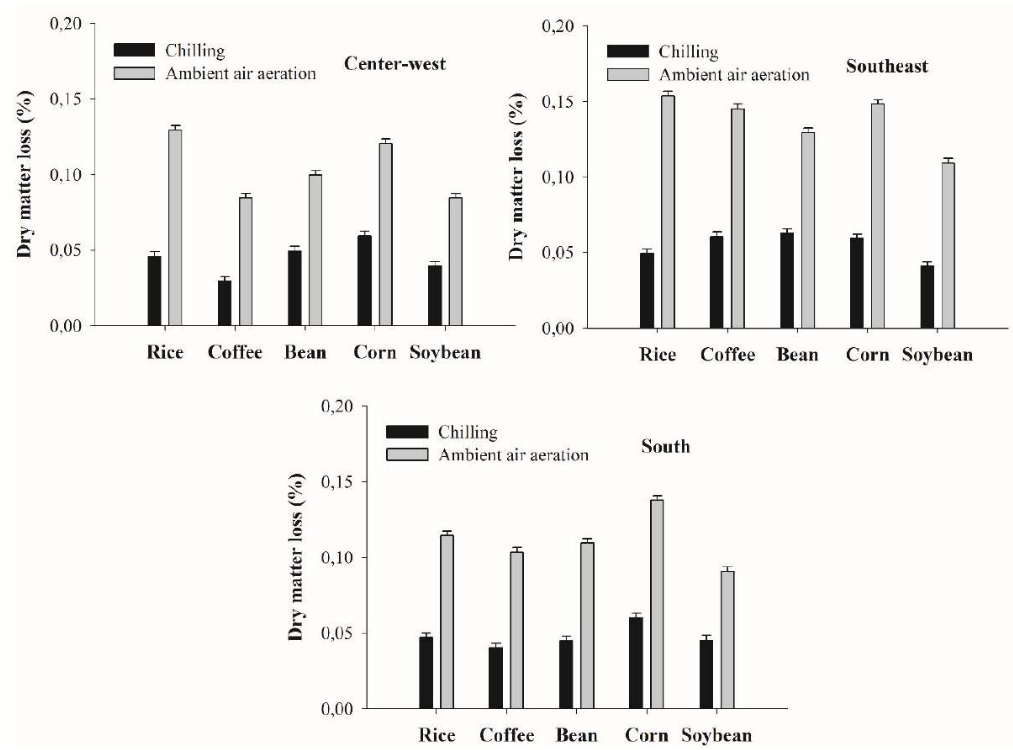

Figure 6: Average final dry matter losses according to different grain types and regions, considering chilling and ambient air aeration.

was strongly affected by the weather patterns of the regions studied and grain type (Figure **5**), while the influence of the storage period was limited.

Chilling resulted in grain dry matter losses around 58% smaller than those verified when using ambient air aeration, reaching values between 0.03 and 0.06%, with an average of 0.05 (± 0,003). Aeration with ambient air resulted in grain dry matter losses from 0.08 to 0.15%, with an average of 0.12% (± 0,003), as shown in Figure **6**.

Other factors that affected the technical and economic analyses were the fan operation and energy consumption of both technologies. The energy consumption of ambient air aeration scenarios ranged from 0.11 to 1.56 kW h t^{-1}, with an average of 0.41 kW h t^{-1} (±0.42). For chilling, the values were between 0.16 and 4.1 kW h t^{-1}, with an average of 2.78 kW h t^{-1} (±0.77). Average aeration times with ambient air in the Brazilian Centre-West, Southeast, and South were 145 (±80), 195 (±81), and 174 (±70) hours, respectively. When simulating chilling, average aeration times fell to 90 (±61), 81 (±39), and 76 (±33) hours, respectively.

4. DISCUSSION

Overall, both chilled and ambient aeration presented favourable economic indices, indicating low-risk investments. The high capital investment required to chilling equipment combined with unfavourable rice and corn selling prices was the main factor that affected the profitability of chilled aeration in small storages in this study. In these cases, it is recommended that farmers associate with cooperatives to share initial and fixed costs (insurance, taxes, and fees) related to chilling, as well as to increase the stored bulk volume. Another option is to use the ambient air aeration, storing the grain for shorter periods when this technology is not capable of achieving the temperatures that inhibit insect activity.

Selling prices of grain vary considerably in the Brazilian market from region to region, as well as from grain to grain, contributing to differences between some economic indices and sometimes making chilled aeration economically unfeasible. Corn was the least valuable product, with an average selling price 95% lower than the average coffee selling price, which is the most valuable Brazilian grain. When evaluating the rice selling prices, values found in the Centre-West and South were around 22% lower than those verified in the Southeast. According to Conab[18], the Centre-West and South are among the major producers of rice in Brazil, while the Southeast is the region where the production is smallest. Due to the large offer, rice prices in the major producer regions have been decreased from 5.8% to 12.7% during the harvest period in Brazil. Probably, if rice or corn is stored by food industry, its selling price tends to increase due to the added value to the final product and this can make the scenarios economically feasible.

The high cost of chilled aeration is due to the refrigeration unit, which is still expensive in Brazil, resulting in a capital investment around 75% more expensive than ambient aeration [35-37]. But, if this technology becomes more popular in the country due to the knowledge about its technical and economic benefits for the long term, its initial cost tends to decrease.

When considering the technical factors, results agree with the information presented by Navarro [3], who affirmed that chilling tends to lower grain temperatures more efficiently than ambient air aeration mainly where ambient air conditions are not suitable to cool grain. Trials conducted by Morales-Quiros *et al*. [7] in Central Kansas also showed the potential of chilling for lowering grain temperatures, additionally reducing insect development and reproduction rate.

Generally, the potential for ambient aeration in Brazil was observed, but in some situations aeration with ambient air did not reach the temperatures recommended for safe storage, causing risks associated with grain spoiling and dry matter losses. This occurred mainly in the Centre-West, which was the less suitable region for ambient aeration, achieving final grain temperatures around 26ºC. The final grain temperatures for South and Southeast were approximately 20 and 21º, respectively, when using ambient aeration. Counting the three studied regions, ambient aeration achieved temperatures below or equal to 21ºC in 40.4% of the simulated scenarios. Individually, the percentiles were 13.8%, 43.3%, and 60.0% for Centre-West, Southeast, and South, respectively. The average temperatures in chilled silos were 5.9, 2.9, and 3.13ºC lower than those aerated with ambient air for Brazilian Centre-West, Southeast, and South, respectively.

The simulated grain dry matter losses were all below 0.5%, which is reported by several authors [1,45-47] as the threshold for occurring visible moulding, mycotoxin contamination, and downgrading of lots. Lower dry matter losses positively affect the economic feasibility of the aeration system, as well as the grain quality. The higher losses were observed for the scenarios where aeration with ambient air was limited due to the weather patterns, with Centre-West appearing as the more impaired region in this study.

On average, chilling required around 67% more energy than ambient air aeration, which was expected since chilling traditionally demands large energy inputs from the storage systems. These results are similar to those in Morales-Quiros *et al*. [7], where chilling required around 73% more energy than ambient air aeration when cooling wheat in Central Kansas. Rulon *et al*. [8] found an energy consumption near 4.5 kW h t^{-1} when evaluating the chilled aeration of popcorn in the USA, and Steidle Neto and Lopes [15] reported energy consumption of 0.46 kW h t^{-1} when aerating corn with ambient air in Brazil.

Despite the higher energy consumption, chilling showed a greater potential for reducing grain temperatures, mainly in Centre-West where this technology should be used due to aeration with ambient air did not reach the temperatures recommended for safe storage. Further, aeration with ambient air required running the fans more frequently and for more hours than the chilled ones. Considering the aeration times, simulations indicated that chilling aeration resulted in grain cooling 37.9%, 58.5%, and 56.3% faster in the Centre-West, Southeast, and South, respectively.

5. CONCLUSIONS

Results of simulations showed that the cost of chilling should be competitive with ambient air aeration in Brazil, both of them resulting in low-risk investments and worthwhile projects. Average simulated profits of grain aeration in Brazil for 20 years by considering the time of money and the use of ambient air was approximately 12.6% larger than those obtained with chilling. Simulated chilling aeration tends to be more profitable for high economic value grains, medium or large size silos, and at regions where ambient air aeration is not capable of achieving final grain temperatures considered safe for storage, justifying the added expense of this technology. When considering the cooling effects of both technologies, aeration with ambient air should be technically feasible in the South and Southeast of Brazil, but it did not reach the temperatures recommended for safe storage at Centre-West, causing risks associated with insect infestations and grain deterioration. Thus, chilling was recommended for medium and large-scale industries, cooperatives, and farms located in this region. Generally, chilling presented higher energy consumption, but showed a greater potential for reducing grain temperatures, also resulting in smaller grain dry matter losses.

DISCLAIMER

Simulations discussed in this paper are for research purposes only. For recommendations about specific projects please contact the authors.

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DECLARATION OF COMPETING INTEREST

The authors declare no conflict of interest.

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