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# Energy Efficiency and Carbon Emission Reduction in Coffee Roasting: Approach of Activity-Based Costing (ABC) Methodology

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**Abstract:** This study explores optimizing carbon emissions in the coffee bean roasting industry through the application of Activity-Based Costing (ABC). By analyzing three roasting product combinations—light roast, medium roast, and dark roast—the research evaluates production costs, energy consumption, carbon emissions, and profitability. The light roast demonstrates the highest profitability and the lowest environmental impact, offering a favorable balance between economic and environmental objectives. Light roasting reduces carbon emissions by 33.33% compared to dark roasting and by 16.67% compared to medium roasting. The medium roast achieves moderate profitability while maintaining manageable energy consumption and carbon emissions. Conversely, the dark roast, though profitable, shows significantly higher energy consumption and carbon emissions, highlighting the need for targeted improvements in process efficiency. This study underscores the advantages of ABC in providing precise cost allocation and identifying resource inefficiencies, enabling businesses to implement energy-efficient technologies and optimize operations. It also emphasizes the importance of adopting renewable energy sources and leveraging government incentives to align sustainability with financial goals. This study serves as a model for integrating economic performance with environmental responsibility, offering actionable insights for businesses. Future research could expand the scope of this approach to other continuous process industries, demonstrating its broader applicability and potential for improving sustainability across diverse sectors.

**Keywords:** activity-based costing (ABC); carbon emission reduction; energy efficiency; coffee roasting optimization; sustainability optimization

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## 1. Introduction

Climate change and carbon emission reduction policies have become global priorities. The coffee industry, particularly the roasting process, contributes significantly to carbon emissions [1]. Recent data underscore the pressing need for carbon reduction in this sector. For example, Starbucks' 2023 Global Environmental Impact Report reveals that green coffee purchases accounted for 11% of the company's total greenhouse gas emissions [2], highlighting the significant environmental footprint of coffee sourcing and roasting processes. Furthermore, a 2024 study published in SpringerLink conducted a comparative life cycle assessment of fair-trade organic coffee versus conventional coffee [3]. The findings indicate that fair-trade organic coffee has a lower environmental impact, emphasizing the importance of sustainable practices in reducing the carbon footprint associated with coffee production and processing. These insights demonstrate the critical role of the coffee industry in global carbon emissions and underscore the urgency for implementing effective

carbon reduction strategies, particularly in energy-intensive processes like coffee roasting. This study aims to analyze and optimize carbon emission reduction strategies in coffee roasting, using the ABC methodology to allocate costs accurately and evaluate multiple decision criteria [4]. The research assesses three product combinations—light roast, medium roast, and dark roast—to determine how enterprises can simultaneously minimize carbon emissions and maximize profitability. This approach serves as a practical reference for other continuous process industries.

Coffee roasting is a highly energy-intensive process that relies heavily on fossil fuels, resulting in substantial greenhouse gas emissions [5]. These emissions contribute significantly to the industry's environmental impact. Given the increasing emphasis on sustainability and carbon emission reduction, optimizing the roasting process has become a critical goal for businesses [6]. In addition to environmental concerns, enterprises must address economic factors such as energy consumption and profitability, making the optimization process a multi-faceted challenge.

### *1.1. The Coffee Roasting Process*

Figure 1 illustrates the essential stages and chemical transformations involved in coffee roasting, highlighting the Maillard reaction and caramelization as pivotal processes in flavor and aroma development [7]. The roasting process begins with the drying phase, where moisture is eliminated, preparing the beans for subsequent chemical reactions. As the temperature rises, the Maillard reaction starts, characterized by the interaction between amino acids and reducing sugars [8]. This reaction generates a wide array of flavor compounds and contributes to the brown color of roasted coffee beans. Concurrently, caramelization occurs as sugars break down, forming complex flavors that enhance the sweetness and overall profile of the coffee [9]. The first crack, marked by an audible sound, signifies the transition to the next stage, where the internal pressure caused by heat causes the beans to expand and release volatile compounds. This stage is critical for determining the acidity and body of the coffee [10]. For darker roasts, the second crack occurs at a higher temperature, producing bolder, smoky flavors as cell walls collapse and oils migrate to the surface [11]. The first crack, marked by an audible sound, signifies the transition to the next stage, where the internal pressure caused by heat causes the beans to expand and release volatile compounds. This stage is critical for determining the acidity and body of the coffee [8]. For darker roasts, the second crack occurs at a higher temperature, producing bolder, smoky flavors as cell walls collapse and oils migrate to the surface. This diagram underscores the importance of precise temperature control and timing, as over-roasting can lead to burnt flavors, while under-roasting may result in grassy or sour notes. The balance between these stages determines the coffee's final characteristics, making it essential for roasters to tailor the process to specific flavor profiles and consumer preferences. The chemical processes illustrated in the diagram also emphasize the complexity of coffee roasting, as each stage contributes uniquely to the sensory attributes of the final product. By understanding these dynamics, roasters can optimize their techniques to produce consistent, high-quality coffee that meets market demands. Figure 1 provides a comprehensive view of the roasting process and its relationship to heat, time, and chemistry, forming a basis for the methodology employed in this study. The figure also demonstrates the crucial role of each stage in determining the sensory and environmental outcomes of coffee roasting.

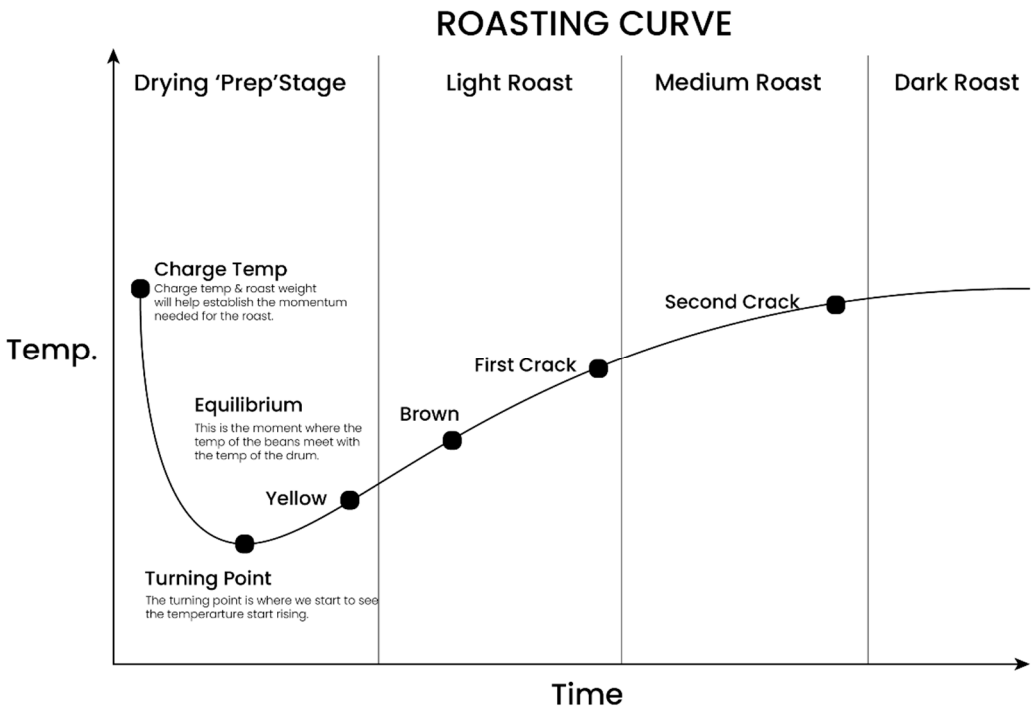



**Figure 1.** The process of coffee bean roasting.

### *1.2. Coffee Bean Categories and Health Impacts*

Coffee beans are broadly categorized into specialty beans and commercial beans [12]. Specialty beans have gained significant attention in recent years due to the promotion of light roasting, shown in Figure 2, which has been shown to enhance the antioxidant properties of coffee, particularly chlorogenic acid [13]. Chlorogenic acid is known for its cardiovascular health benefits, distinguishing light roast coffee from traditional medium or dark roasts [14]. Medium and dark roasts, shown in Figure 2, characterized by their heavy, smoky flavors, often result in excessive caffeine content and diminished antioxidant levels due to prolonged roasting times [15]. This shift toward light roasting reflects a broader trend in consumer preferences for healthier coffee options that preserve beneficial compounds while reducing the negative effects associated with over-roasting.




**Figure 2.** Raw coffee bean and roasting levels.

### *1.3. Coffee Production Lifecycle*

Figure 3 illustrates the life cycle of coffee production, emphasizing the processes that contribute to its energy consumption, carbon emissions, and overall environmental impact. The cycle begins with coffee cultivation, which involves planting, growing, and harvesting coffee cherries. This stage is influenced by agricultural practices, water usage, and sunlight exposure, as represented in the diagram. Sustainable cultivation practices, such as shade-grown coffee and organic farming, can reduce the environmental impact while maintaining soil health and biodiversity. After harvesting, coffee cherries undergo processing to remove the outer layers and extract green coffee beans. This step can be performed using wet or dry methods. The wet process, requiring significant water resources, produces cleaner beans but results in higher wastewater generation. The dry process is less resource-intensive but may compromise bean uniformity. Transitioning to eco-friendly processing methods can mitigate these environmental concerns. The green beans are then roasted, at a highly energy-intensive stage of the cycle. Roasting involves heating the beans to high temperatures, transforming their chemical composition to develop the flavor and aroma. Energy consumption during roasting depends on the technology used, such as traditional gas-fired roasters or more energy-efficient electric and hybrid models. The roasting process also generates greenhouse gas emissions, emphasizing the need for optimized roasting profiles and renewable energy integration to minimize environmental impact. Packaging and transportation follow roasting, with the packaging materials and modes of transport playing a significant role in the product's carbon footprint. The use of recyclable or biodegradable materials and efficient logistics systems can significantly reduce emissions during these stages. Finally, coffee reaches consumers, who prepare and consume it, contributing to the life cycle's end-use energy consumption. This diagram underscores the interconnectedness of each stage in the coffee production cycle and its environmental implications. By identifying key areas for intervention, such as sustainable farming practices, efficient processing, and energy-optimized roasting technologies, stakeholders can significantly reduce the coffee industry's carbon footprint while maintaining product quality. This holistic approach aligns economic objectives with environmental sustainability, providing a roadmap for achieving a greener coffee supply chain.

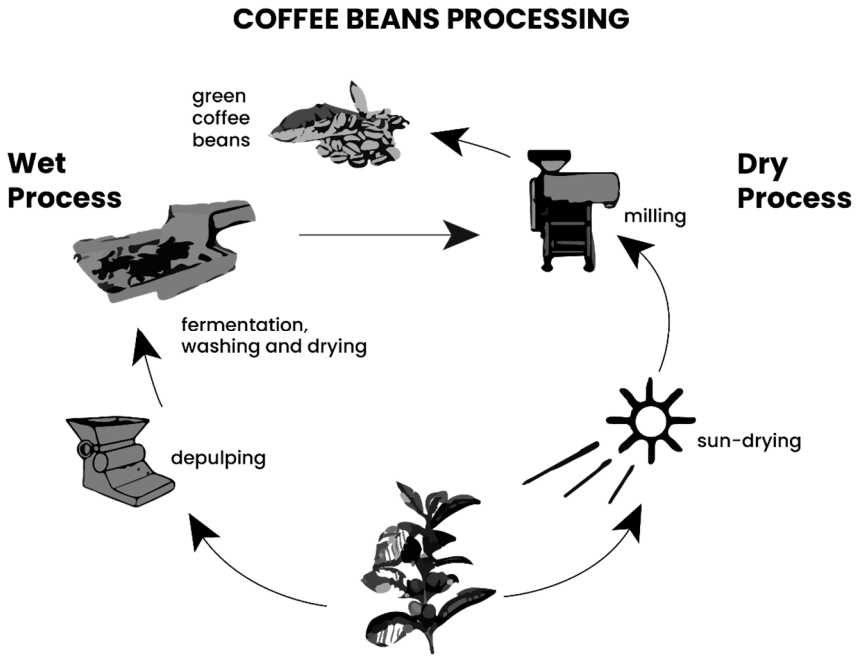



**Figure 3.** The production process of coffee beans.

## 2. Literature Review

### 2.1. Sustainability and Advanced Costing Methodologies

Coffee bean roasting not only influences flavor profiles but also significantly impacts the energy consumed and the environmental footprint of the process. As consumer preferences shift toward lighter roasts for their health benefits, producers face the challenge of aligning these demands with sustainable practices. Light roasting, while beneficial in preserving chlorogenic acid, often requires precise temperature control and shorter roasting durations, making energy efficiency a key consideration [16]. The development and adoption of advanced roasting technologies, such as heat recovery systems and automated controls, have enabled producers to optimize energy usage. Coupled with innovative methodologies like Activity-Based Costing (ABC), these advancements allow businesses to identify and address resource inefficiencies across various production stages. Given the increasing emphasis on sustainability, this study examines whether light roasting can significantly reduce carbon emissions compared to medium and dark roasting. Previous studies, such as Górecki & Hallmann (2020) [17], suggest that roasting intensity influences energy use and carbon output, yet empirical quantification remains limited. This research investigates whether light roasting results in lower carbon emissions, forming the basis for the first hypothesis (H1): "Lighter roasting profiles contribute to greater environmental sustainability by reducing carbon emissions".

The introduction of modern energy-efficient technologies and cost allocation methodologies, such as ABC, has provided new opportunities for reducing emissions while maintaining operational efficiency [18]. This study focuses on leveraging these tools to examine how businesses can achieve their sustainability goals without compromising economic performance. Furthermore, the growing consumer demand for environmentally friendly products has amplified the importance of sustainability in the coffee industry, making this research both timely and relevant. Since ABC allows for a more precise allocation of production costs by linking expenses directly to resource usage, this study also investigates whether ABC can reveal critical cost inefficiencies in roasting operations. The second hypothesis (H2) is thus formulated as follows: "ABC enhances cost transparency and enables more precise resource allocation in coffee roasting".

### 2.2. Costing Methodologies: ABC vs. TCA

Figure 4 compares Activity-Based Costing (ABC) with Traditional Cost Accounting (TCA), illustrating the differences in how costs are assigned to products or services [19]. In ABC, the focus is on understanding and allocating costs based on the actual consumption of resources. The process begins with resources being consumed by activities, and these resources are traced using resource drivers. Activities represent the actions or processes carried out within an organization, such as manufacturing, assembly, or quality control. These activities then consume resources, such as labor, energy, or materials. Activity drivers are used to link the consumption of resources to specific cost objects, which can be products or services. This method provides a detailed and accurate understanding of cost allocation by directly associating costs with the activities that generate them. The novelty of applying ABC in this context lies in its ability to provide granular insights into the resource consumption patterns specific to energy-intensive processes like coffee roasting, enabling precise identification of inefficiencies and areas for improvement. Unlike TCA, which relies on generalized allocation bases, ABC captures the nuanced variations in resource use across different production stages, offering a level of accuracy essential for industries aiming to balance profitability with sustainability goals. This enables organizations to identify inefficiencies, optimize resource usage, and improve overall decision-making [20]. Additionally, as profitability remains a primary concern for coffee producers, it is essential

to evaluate whether prioritizing sustainability-driven roasting methods impacts financial performance. Prior studies suggest that light roasting, while more energy-efficient, may have differing profit margins due to variations in consumer demand and product pricing (Monserrat Aguayo-Muñoz et al., 2024) [21]. Therefore, this study further examines whether light roasting maximizes profitability compared to medium and dark roasting, forming the basis for the third hypothesis (H3): "Light roasting yields higher profitability due to lower energy consumption and stronger consumer preference". In contrast, TCA employs a simplified approach where costs are allocated to cost objects directly based on predefined allocation bases, such as labor hours or machine hours [22]. While this method is straightforward and easier to implement, it often lacks the granularity and accuracy of ABC, as it assumes that all products or services consume resources uniformly, which may not reflect actual resource usage. This can result in distorted cost information, leading to potential inefficiencies and suboptimal decisions. The diagram highlights that ABC provides a more comprehensive view by incorporating intermediate steps—resources, activities, and their drivers—allowing for a nuanced understanding of cost behavior [23]. This novel application of ABC in the coffee roasting industry illustrates its strategic value in identifying high-cost and high-carbon-emission activities, enabling targeted interventions and resource optimization. This is especially valuable in industries with complex production processes or diverse product lines, where resource consumption varies significantly between activities. By using ABC, organizations can better align their cost structures with operational realities, facilitating more precise pricing strategies and improved resource management. Conversely, TCA's reliance on broad allocation bases may be sufficient for simpler operations but falls short in addressing the complexities of modern business environments. This comparison underscores the importance of selecting the appropriate costing method based on organizational needs, complexity, and strategic goals.

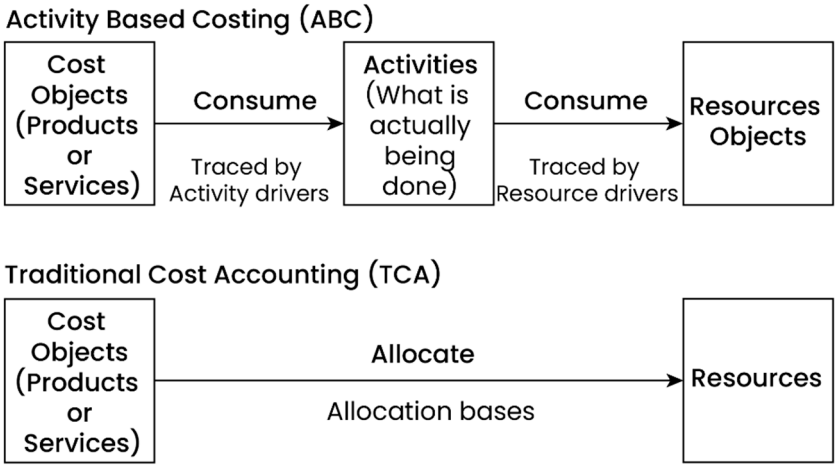



**Figure 4.** ABC versus TCA.

This paper is organized into several sections, beginning with a comprehensive literature review that explores previous studies on carbon emission reduction in coffee roasting and the role of ABC methodology [4]. The research methodology section details the data collection process, assumptions, and analytical framework employed in this study. The Discussion Section presents the findings, including profitability analysis, labor cost distribution, and carbon emission reduction potential. Finally, the conclusion offers insights into the implications of the findings and suggestions for future research.

### 2.3. Carbon Emissions in Coffee Roasting

Coffee roasting is one of the most energy-intensive stages in the coffee supply chain. Studies have shown that roasting accounts for a significant portion of the industry's overall carbon footprint. The process typically involves heating green coffee beans to temperatures between 180 °C and 230 °C, requiring substantial energy input [24]. Traditional roasters often rely on fossil fuels, such as natural gas or propane, which are significant sources of carbon emissions. According to a study by the International Coffee Organization, the carbon footprint of roasting can range from 0.744 to 0.801 kg of $CO_2$ per kilogram of coffee, depending on the roasting equipment and energy source [25].

Several strategies have been proposed to reduce the environmental impact of coffee roasting. These include adopting energy-efficient roasters, utilizing renewable energy sources, and optimizing roasting profiles to minimize energy use [26]. Electric and hybrid roasters, for example, have gained attention for their ability to reduce reliance on fossil fuels. Additionally, technologies such as heat recovery systems can capture and reuse heat generated during the roasting process, further improving energy efficiency [27].

As roasting profiles significantly impact energy use and emissions, this study empirically tests whether light roasting can achieve lower carbon emissions than medium and dark roasting, providing quantitative evidence for sustainability-oriented production strategies. Additionally, this research evaluates whether cost efficiency improvements through ABC can facilitate the transition to environmentally friendly roasting practices without negatively impacting profitability. The validation of H1, H2, and H3 will be discussed in Section 5.

### 2.4. ABC Methodology

Activity-Based Costing (ABC) is a cost allocation methodology that assigns costs to products or services based on their actual consumption of resources [28]. Unlike traditional cost accounting systems, which often allocate overhead costs uniformly across all products, ABC provides a more accurate representation of cost drivers [29]. This makes it particularly useful for industries like coffee roasting, where resource usage can vary significantly between different products and processes.

In the context of coffee roasting, ABC can be used to identify high-cost activities, such as extended roasting times or inefficient energy use [30]. By providing granular insights into production costs, ABC enables businesses to develop targeted strategies for reducing both costs and carbon emissions. For example, an ABC analysis might reveal that a particular roasting profile consumes disproportionately high amounts of energy, prompting the business to explore alternative profiles or equipment upgrades.

Figure 5 represents a step-by-step process for identifying, analyzing, and allocating costs within the framework of Activity-Based Costing (ABC). To enhance the accuracy of the ABC model, the cost driver selection process involves identifying activities that significantly influence resource consumption. These activities are linked to cost objects using activity drivers, such as machine operating hours, energy consumption rates, or labor hours. For example, in coffee roasting, roasting machine operation and cooling processes are primary activities due to their substantial energy demands. Justification for including specific activities lies in their measurable impact on cost behavior and potential for optimization. The careful selection of cost drivers ensures that the ABC model captures the true resource allocation, enabling businesses to make informed decisions about cost reduction and sustainability. The ABC methodology focuses on understanding the relationships between activities and the resources they consume, allowing businesses to trace costs more accurately. It begins by identifying all relevant activities in the production process, estimating the costs associated with each activity, and assigning these costs to products based on their

actual usage. This approach contrasts with traditional costing systems, which often rely on broad averages, potentially obscuring the true cost structure of products or services. The detailed insights provided by ABC are particularly valuable for continuous process industries, where inefficiencies in energy usage or resource allocation can have significant financial and environmental implications.




**Figure 5.** Steps for identifying and allocating costs in activity-based costing.

Each stage is designed to systematically trace the activities and their associated costs, enabling organizations to optimize resource allocation and improve decision-making. The process begins with (1) identifying the activities, which involves listing all operational tasks that contribute to the production or delivery of a product or service. These activities may include procurement, manufacturing, quality control, marketing, and distribution. By clearly defining these activities, businesses can gain a granular understanding of where resources are being consumed. Next is (2) estimating the cost of activities, where the total cost of each identified activity is calculated. This step includes aggregating direct and indirect costs, such as labor, materials, energy, and overhead, to determine the financial contribution of each activity. Accurate cost estimation is crucial for pinpointing inefficiencies and areas for cost savings. The third step, (3) choose the target activities, focuses on identifying the most critical activities that significantly impact costs or contribute to operational inefficiencies. These target activities are prioritized for deeper analysis and optimization, ensuring that efforts are concentrated on the most impactful areas. The fourth stage is (4) choosing the first level of the causing cost, which involves identifying the primary cost drivers associated with the target activities. Cost drivers are factors that directly influence the cost of an activity, such as machine hours, employee hours, or the volume of materials used. By analyzing these primary drivers, businesses can uncover the root causes of cost fluctuations. The final process includes (5) choosing the second level of the causing cost, which examines secondary or indirect factors that influence costs. These might include external variables like supplier pricing, regulatory compliance costs, or market demand. By addressing these secondary drivers, organizations can achieve a more comprehensive understanding of their cost structures and make informed strategic adjustments.

This structured approach not only enhances cost transparency but also enables organizations to align their resource usage with strategic objectives. By identifying and addressing inefficiencies at multiple levels, the ABC framework empowers businesses to optimize their operations, reduce unnecessary expenditures, and enhance profitability. It also supports data-driven decision-making, helping companies adapt to changing market conditions and maintain a competitive edge [31]. ABC has been widely adopted across various industries, including manufacturing, healthcare, and logistics, for its ability to enhance cost transparency and support strategic decision-making [32]. In the coffee industry, its application is still relatively nascent but holds significant potential for driving both economic and environmental sustainability.

### *2.5. Integration of ABC and Sustainability Goals*

The integration of ABC methodology with sustainability goals represents a promising avenue for achieving both economic and environmental objectives. By aligning cost

allocation practices with carbon emission reduction initiatives, businesses can ensure that their sustainability efforts are both effective and financially viable. This alignment is particularly important in the coffee industry, where margins are often tight, and sustainability investments must deliver measurable returns.

A study by Nab and Maslin (2020) conducted a life cycle assessment of the carbon footprint in coffee production, revealing that adopting sustainable practices can significantly reduce emissions [33]. The research emphasized that efficient resource allocation and reduced reliance on agrochemical inputs could lower the carbon footprint by up to 77% in comparison to traditional methods. While not directly linked to Activity-Based Costing (ABC), the findings align with the principles of cost efficiency and resource optimization that ABC supports. Furthermore, sustainability reporting, as exemplified in Starbucks' carbon management strategies, has been shown to enhance brand reputation and customer loyalty by transparently communicating efforts to reduce greenhouse gas emissions [34]. These studies underscore the importance of precise cost allocation and sustainability practices in achieving both economic and environmental benefits. Implementing ABC in coffee roasting facilities could provide actionable insights into energy efficiency and waste reduction while offering a framework for effectively communicating sustainability efforts to consumers and investors, thereby improving stakeholder engagement.

## 3. Research Methodology

This study aims to investigate how the coffee bean roasting industry can reduce carbon emissions through various strategies while maximizing corporate profitability. By integrating the ABC methodology, we analyze the production costs, energy consumption, carbon emissions, and profitability of three different coffee bean roasting products: light roast, medium roast, and dark roast. The detailed research steps are as follows:

### *3.1. Data Collection and Assumptions*

This study selects three coffee bean products with varying roasting levels and applies the ABC methodology to allocate costs across different production activities. The products include three roasting levels as shown the following Table 1:

**Table 1.** Unit production costs and prices by coffee bean roasting levels.

| Roasting Level | Unit Production Cost (NT$) | Selling Price (NT$) |
|---|---|---|
| Light Roast | 90 | 160 |
| Medium Roast | 70 | 130 |
| Dark Roast | 50 | 100 |

As shown in Figure 6, a coffee roaster with a rated energy consumption of 10.5 kW for a 5 kg batch indicates the power required to operate the machine at its maximum capacity during roasting. By allocating resources to each production activity (e.g., roasting machine operation, cooling, packaging), we calculate the total production cost, total revenue, and profit for each product, as well as analyze their energy consumption and carbon emissions. The data used in this study are primary, collected through direct observation and measurement of coffee roasting operations in a controlled environment. Assumptions for the analysis were based on industry benchmarks and verified through expert consultation. Based on assumptions, the average roasting time required for each product is as follows:

| Specification | |
|---|---|
| Type | R-105 |
| Size (W x D x H)mm | 1252 x 626 x 1523 |
| Weight | 243 kg |
| Roasting / batch | 5 kg |
| Cylinder type | direct-fired / semi hot blast |
| Power consumption | 320 W |
| Rated combustion volume | 10.5 kW<br>(9000 kcal /h) |
| Connection hose | LPG 9.5 mm<br>LNG 13 mm |

**Figure 6.** The coffee roasting batch of 5 kg with a rated consumption of 10.5 kW.

Table 2 provides an analysis of the average roasting time and associated energy consumption for different coffee bean roasting levels. The typical roasting times for light (10 min), medium (12 min), and dark roasts (15 min) were derived from industry averages reported in manufacturer specifications and prior studies. Specifically, the data align with operational benchmarks provided by a coffee bean roasting machine, which indicate that smaller batch sizes (e.g., 5 kg) typically require shorter roasting durations, while larger industrial equipment may extend these times due to differing heat transfer efficiencies. For validation, the batch size in this study was set at 5 kg, consistent with industry norms for small to medium-sized roasters. Variations in equipment, such as the use of traditional drum roasters versus hybrid models, can also impact roasting durations. Future iterations of this analysis should include sensitivity tests to account for these equipment-based variations and provide further validation through case studies from real-world operations.

**Table 2.** Average roasting time by coffee bean roasting levels.

| Roasting Level | Time Required per 5 kg (minutes) | Energy Consumption Rate (kWh/min) | Energy Consumption per 5 kg ($E5kg_i$) (kWh) |
|---|---|---|---|
| Light Roast | 10 | 1.75 | 17.5 |
| Medium Roast | 12 | 2.1 | 25.2 |
| Dark Roast | 15 | 2.625 | 39.375 |

The energy consumed for each roast level can be calculated using the formula: Energy Consumption (kWh) = Rated Power (kW) × Roasting Time (hours). For a light roast, the energy consumed is 10.5 × 10/60 = 1.75 kWh, while for a medium roast, it is 10.5 × 12/60 = 2.1 kWh, and for a dark roast, it is 10.5 × 15/60 = 2.625 kWh. The associated carbon emissions, assuming an emission factor of 0.3 kg/kWh, result in 0.525 kg $CO_2$ for a light roast, 0.63 kg $CO_2$ for a medium roast, and 0.788 kg $CO_2$ for a dark roast. These figures highlight the significant energy demands of coffee roasting and the importance of optimizing roast times and integrating energy-efficient practices, such as heat recovery systems or renewable energy sources, to enhance sustainability and reduce operational costs while maintaining product quality. This table highlights the direct relationship between roasting duration and energy consumption, demonstrating that darker roasts inherently demand more energy. Understanding these differences allows businesses to make informed decisions about energy optimization, balancing flavor preferences with sustainability goals. By optimizing roasting times or improving equipment efficiency, enterprises can significantly reduce their operational costs and carbon footprint.

The energy consumption rates, and emission factors assumed in this study are derived from industry-standard data and equipment specifications. Specifically, the baseline energy consumption rates (e.g., 10.5 kW for a 5 kg batch roaster) align with manufacturer data from Fuji Royal Roasters. However, as emission factors were assumed constant at 0.3 kg/kWh across all roasting levels, it is acknowledged that this assumption simplifies real-world variability. In actual operations, emission factors can differ based on the energy source (e.g., natural gas versus electricity) and roasting equipment efficiency. To address this limitation, sensitivity analysis was conducted to evaluate how variations in emission factors (ranging from 0.2 to 0.4 kg/kWh) influence the results, demonstrating that the overall findings remain robust despite such variability.

Furthermore, this study assumes a linear relationship between roasting time and energy consumption, which may not fully capture operational nuances such as machine heat recovery or batch size impacts. Future research should incorporate real-time data from multiple roasting facilities to validate these assumptions. Incorporating variability in energy sources and cost structures will further enhance the accuracy and applicability of the proposed framework.

### *3.2. Production Costs, Energy Consumption, and Carbon Emission Data Calculation*

We assume the energy consumption and carbon emission data for each product as shown in Table 3. Using these data, we calculate the total energy consumption and carbon emissions for each product. By combining this with total production costs and total revenue, we perform further analysis.

**Table 3.** Energy consumption and carbon emission data by product.

| Roasting Level | Production Units (kg) | Energy Consumption per 5 kg Units (kWh) | Carbon Emissions (kg) |
|---|---|---|---|
| Light Roast | 1000 | 3500.0 | 1050.00 |
| Medium Roast | 800 | 4032.0 | 1209.60 |
| Dark Roast | 500 | 3927.5 | 1178.25 |

Figure 7 visually represents the correlation between carbon emissions (CT) and energy consumption per unit (UCE) across three levels of coffee bean roasting: Light Roast, Medium Roast, and Dark Roast. The graph employs key symbols to delineate the roasting levels and their associated environmental impact. Vertical axis represents the carbon emissions, measured in kilograms; Horizontal axis represents the energy consumption per unit of production, measured in kWh. Figure 7 illustrates the relationship between energy consumption and carbon dioxide ($CO_2$) emissions across different roasting levels: light roast ($UCE_1$, $CT_1$), medium roast ($UCE_2$, $CT_2$), and dark roast ($UCE_3$, $CT_3$). The x-axis represents cumulative energy consumption per batch (kWh), while the y-axis denotes the corresponding carbon emissions (kg). Both axes now explicitly state that the values are calculated per 5 kg batch. Thresholds ($UCE_0 \rightarrow UCE_3$) and corresponding emissions ($CT_1 \rightarrow CT_3$) are marked to distinguish levels. UCE0 represents the baseline energy consumption before roasting begins. $UCE_1$ corresponds to light roasting, $UCE_2$ to medium roasting, and $UCE_3$ to dark roasting.

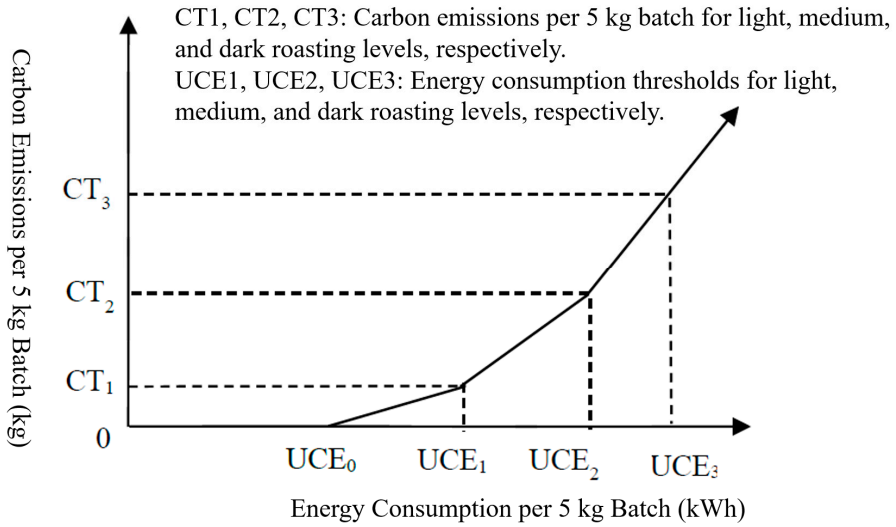



**Figure 7.** Carbon emissions by roasting level: light roast, medium roast, and dark roast.

Table 4 summarizes the relationships between energy consumption thresholds and carbon emissions for the three roasting levels. The transition points $UCE_0$ to $UCE_1$ correspond to the energy required for light roast, $UCE_1$ to $UCE_2$ for medium roast, and $UCE_2$ to $UCE_3$ for dark roast. Each roasting level produces varying carbon emissions, with $CT_1$ representing the lowest emissions for light roast, $CT_2$ showing moderate emissions for medium roast, and $CT_3$ illustrating the highest emissions for dark roast. These data highlight the importance of managing roasting times and energy usage to minimize environmental impact while meeting production goals.

**Table 4.** Energy consumption and carbon emission thresholds for roasting levels.

| **$UCE_0$, $UCE_1$, $UCE_2$, $UCE_3$: Energy Consumption Thresholds for the Roasting Levels (Light, Medium, and Dark)** | |
|---|---|
| **Threshold** | **Description** |
| $UCE_0 \rightarrow UCE_1$ | Energy consumption threshold for light roast. |
| $UCE_1 \rightarrow UCE_2$ | Energy consumption threshold for medium roast. |
| $UCE_2 \rightarrow UCE_3$ | Energy consumption threshold for dark roast. |
| $UCE_0 \rightarrow UCE_3$ | Energy thresholds for cumulative energy consumption. |
| $CT_1$, $CT_2$, $CT_3$: Carbon emissions corresponding to each roasting level. | |
| **Threshold** | **Description** |
| $CT_1$ | Light roast produces the lowest carbon emissions due to shorter roasting time and less energy. |
| $CT_2$ | Medium roast generates higher emissions due to increased energy consumption. |
| $CT_3$ | Dark roast emits the highest carbon emissions due to extended roasting time and high energy use. |
| $CT_1 \rightarrow CT_3$ | $CT_1$ to $CT_3$: Carbon emissions at respective roasting levels. |

### *3.3. Key Observations with Symbolic Representation*

The observations outlined in this section provide a symbolic representation of energy consumption and carbon emissions for the three roasting levels. These insights are instrumental in guiding production optimization and sustainability efforts.

(i) Light Roast ($UCE_0 \rightarrow UCE_1$, $CT_1$):

Light roast requires the least energy consumption per unit, represented by the segment $UCE_0 \rightarrow UCE_1$. It corresponds to the lowest carbon emissions $CT_1$ This level balances minimal environmental impact with adequate flavor extraction.

(ii) Medium Roast ($UCE_1 \rightarrow UCE_2$, $CT_2$):

As energy consumption increases to $UCE_2$, carbon emissions rise to $CT_2$. The additional energy demand is due to longer roasting times and higher roasting temperatures, required to achieve the medium roast profile.

(iii) Dark Roast ($UCE_2 \rightarrow UCE_3$, $CT_3$):

Dark roast consumes the highest energy, shown by the segment $UCE_2 \rightarrow UCE_3$. It produces the greatest carbon emissions $CT_3$, primarily due to prolonged roasting times and intensified heat.

(iv) Nonlinear Growth:

The curve steepens progressively as UCE increases, indicating that higher roasting levels lead to exponentially greater energy consumption and emissions. This is critical for sustainability considerations.

(v) Sustainability:

Light roasting ($UCE_1$, $CT_1$) offers the best balance between product quality and minimal carbon emissions, aligning with sustainability goals. Medium and dark roasting levels ($CT_2$, $CT_3$) highlight areas where energy optimization and carbon emission reduction measures are essential.

(vi) Production Optimization:

Companies should focus on energy-efficient roasting technologies to lower $CT_2$ and $CT_3$. Solutions such as heat recovery systems and optimized roasting profiles can reduce energy use while maintaining product quality.

These insights collectively demonstrate the importance of strategic planning in achieving both economic and environmental objectives in the coffee roasting industry.

### *3.4. Cost and Profit Calculations*

The following equations provide a systematic approach to calculating the total cost, revenue, and profit for each product in the coffee roasting process. These formulas enable businesses to evaluate the financial performance of their operations and make informed decisions about production strategies. Below, each formula is explained in detail with a clear description of its components and significance.

(i) Total Production Cost (TPC)

The total production cost for each product represents the overall expenditure incurred during its production. This includes all direct costs such as raw materials, energy consumption, and labor, as well as indirect costs like equipment depreciation. By calculating the total production cost, businesses can identify the financial burden associated with producing each type of coffee roast and determine areas for cost reduction. The formula is expressed as follows:

$$TPC_i = UPC_i \times TPQ_i \quad (1)$$

This formula highlights the importance of understanding the unit production cost (UPC*i*), which varies depending on factors like roasting time, energy efficiency, and raw material quality. By multiplying UPC*i* with the total production quantity (TPQ*i*), businesses can derive the overall production cost for a specific product, forming the basis for cost optimization efforts.

(ii) Total Revenue (TR)

Total revenue represents the income generated from selling a specific product. It is a critical metric for assessing a company's financial health and sustainability. By calculating total revenue, businesses can evaluate the effectiveness of their pricing strategies and production volumes in meeting revenue targets. The formula is expressed as follows:

$$TR_i = UP_i \times PQ_i \quad (2)$$

This formula underscores the relationship between product pricing and production volume. The unit price (UP*i*) is determined based on market demand, product quality, and competition, while the production quantity (PQ*i*) reflects the company's capacity and efficiency. The total revenue calculation helps businesses assess whether their pricing and production strategies are aligned with their financial objectives.

(iii) Profit (P)

Profit is a key indicator of a business's financial performance, representing the surplus remaining after deducting production costs from total revenue. It is the ultimate measure of success, as it determines the company's ability to invest in growth, repay debts, and reward stakeholders. The formula for profit is expressed as follows:

$$P_i = TR_i - TPC_i \quad (3)$$

This formula demonstrates the direct relationship between revenue and cost in determining profitability. By subtracting the total production cost (TPC*i*) from the total revenue (TR*i*), businesses can identify the net financial gain or loss for each product. This insight is critical for evaluating the viability of specific products and making data-driven decisions to optimize profitability.

(iv) Expanded Profit Formula:

To provide greater clarity, the profit formula can be expanded to explicitly include the components of revenue and cost. This expanded formula is expressed as follows:

$$P_i = (UP_i \times PQ_i) - (UPC_i \times PQ_i) \quad (4)$$

This formulation breaks down revenue ($UP_i \times PQ_i$) and cost ($UPC_i \times PQ_i$) into their respective components, offering a detailed view of the factors influencing profit. By analyzing these components, businesses can pinpoint areas for improvement, such as reducing unit production costs or adjusting unit prices to enhance profitability.

(v) Simplified Profit Formula:

For simplicity, the profit formula can be further reduced by factoring out the production quantity (PQ*i*). This simplified formula is expressed as follows:

$$P_i = PQ_i \times (UP_i - UPC_i) \quad (5)$$

This version highlights the impact of production volume (PQ*i*) and the margin between unit price (UP*i*) and unit production cost (UPC*i*) on overall profitability. By focusing on these variables, businesses can develop targeted strategies to increase profit, such as optimizing production efficiency, negotiating lower raw material costs, or implementing competitive pricing.

In summary, these formulas form the foundation for evaluating the economic performance of coffee roasting operations. They provide a clear framework for analyzing costs,

revenues, and profits, enabling businesses to identify opportunities for improvement and achieve their financial goals.

### 3.5. Carbon Emission Optimization

Carbon emission optimization focuses on reducing total carbon emissions ($CO_2Ei$) while ensuring that profitability is maintained or enhanced. This process integrates two primary strategies: minimizing energy consumption (EC$i$) and lowering the emission factor (EF$i$). To achieve these goals, the optimization process must be data-driven and account for production variability, operational constraints, and the scalability of proposed measures. The reduction in (EC$i$) can be achieved by optimizing production processes, such as reducing roasting time and improving the efficiency of roasting machines. For example, adopting advanced technology like automated control systems allows for precise adjustments in roasting temperatures and durations, minimizing wasted energy. Additionally, upgrading machinery to models with higher energy efficiency can significantly reduce the energy required for each batch of roasted coffee. Other measures, such as adopting multi-stage roasting profiles, ensure that energy is used effectively while preserving the quality and flavor profiles of the coffee beans. These optimizations not only contribute to carbon emission reduction but also lower operational costs, aligning environmental goals with financial performance.

Lowering (EF$i$) focuses on transitioning from traditional energy sources, such as fossil fuels, to renewable energy options like solar, wind, or biomass. This transition should include feasibility studies that evaluate initial capital investments, operating costs, and potential energy savings to provide businesses with a clear financial roadmap. Implementing renewable energy reduces the carbon footprint associated with each kilowatt-hour (kWh) of energy consumed during production. For instance, installing solar panels at roasting facilities can replace a portion of the grid electricity with clean energy, while wind energy contracts can offer sustainable alternatives for powering larger operations. Furthermore, heat recovery systems can capture excess heat from the roasting process and reuse it in subsequent cycles, thereby reducing dependency on external energy inputs and effectively lowering both (EC$i$) and (EF$i$). In regions where renewable energy infrastructure is limited, hybrid systems that combine renewables with high-efficiency natural gas systems can serve as transitional solutions. For example, studies in similar industries have shown that integrating solar panels with high-efficiency natural gas equipment can reduce emissions by up to 25% while maintaining operational reliability.

Both strategies require detailed assessments of current operations and careful implementation of cost-effective interventions. Advanced analytics, including Activity-Based Costing (ABC), can help identify high-energy consumption activities and prioritize upgrades or process improvements based on their potential return on investment. Sensitivity analysis using ABC can further validate these interventions by exploring the impact of fluctuating energy prices and operational demands, ensuring robust decision-making in dynamic market conditions. These data-driven insights enable companies to develop targeted strategies that balance cost savings with carbon emission reduction efforts. Moreover, government incentives, such as tax breaks for renewable energy adoption or grants for energy-efficient equipment upgrades, further support the financial feasibility of these initiatives. For instance, Germany's Renewable Energy Act (EEG) provides feed-in tariffs and subsidies for businesses adopting solar energy, serving as a model for other regions to implement similar policies. Carbon emission optimization is not limited to technical or operational improvements; it also involves fostering a sustainability culture within the organization. Training employees to adopt energy-saving practices, encouraging cross-departmental collaboration, and engaging with supply chain partners to ensure shared

sustainability goals can amplify the impact of carbon emission reduction strategies. By implementing these comprehensive measures, companies can not only meet regulatory requirements and align with global sustainability trends but also enhance their brand reputation and market competitiveness. The integration of employee engagement with technical upgrades ensures that sustainability initiatives are not only implemented but also sustained over time, creating a culture of continuous improvement. The dual focus on (EC*i*) and (EF*i*) ensures a holistic approach to carbon emission optimization, balancing economic objectives with environmental responsibility. This integration provides a robust framework for continuous improvement in energy efficiency and sustainability across production processes.

(i) Energy Consumption Formula:

The total energy consumption for each product represents the amount of energy required to produce a specified quantity of that product. This metric is crucial for understanding the environmental impact and operational efficiency of production processes. The formula is expressed as follows:

$$\mathrm{EC}_i = \frac{\mathrm{PQ}i}{5} \times \mathrm{E5kg}_i \tag{6}$$

This formula calculates the energy consumption by scaling the energy required for producing 5 kg of the product (E5kg*i*) to the total production quantity (PQ*i*). Dividing PQ*i* by 5 determines how many 5 kg batches are required for production, which is then multiplied by the energy needed for each batch. This approach ensures an accurate estimation of energy usage for different roasting levels, enabling businesses to identify areas where energy consumption can be optimized, such as through equipment upgrades or improved operational practices.

(ii) Carbon Emission Formula:

The total carbon emissions for each product quantify its environmental impact by linking energy consumption to the emission factor. The formula is expressed as follows:

$$\mathrm{CO_2\ E}_i = \mathrm{EC}_i \times \mathrm{EF}_i \tag{7}$$

This formula directly ties the energy consumed during production to the carbon emissions generated, based on the type of energy source used. For example, renewable energy sources like solar or wind have significantly lower emission factors compared to fossil fuels such as coal or natural gas. By quantifying carbon emissions, businesses can assess their environmental impact and take targeted actions to reduce it, such as transitioning to renewable energy or improving energy efficiency.

(iii) Comprehensive Formula: Total Profit

The total profit for the company is calculated as the sum of the profits generated by all products. This metric reflects the overall financial performance of the business. The formula is expressed as follows:

$$\mathrm{TP} = \sum_{i=1}^{n} (\mathrm{PQ}i \times (\mathrm{UP}i - \mathrm{UPC}i)) \tag{8}$$

This formula aggregates the profit from each product by multiplying the production quantity (PQ*i*) with the difference between the unit price (UP*i*) and the unit production cost (UPC*i*). It provides a clear view of the company's profitability across its entire product range, highlighting which products contribute the most to the bottom line and where improvements might be needed.

(iv) Comprehensive Formula: Total Carbon Emissions

The total carbon emissions for the company represent the cumulative environmental impact of producing all products. The formula is expressed as follows:

$$TCO_2E = \sum_{i=1}^{n} (ECi \times EFi) \quad (9)$$

This formula sums up the carbon emissions from each product, providing a holistic view of the company's environmental footprint. It enables businesses to identify which products or processes contribute most to emissions, guiding decisions on where to implement sustainability initiatives.

(v) Formula: Total Energy Consumption

The total energy consumption for the company aggregates the energy used to produce all products. This metric is critical for understanding operational efficiency and identifying opportunities to reduce energy usage. The formula is expressed as follows:

$$TEC = \sum_{i=1}^{n} \left(\frac{PQi}{5} \times E5kgi\right) \quad (10)$$

This formula calculates the energy consumption for each product and then aggregates these values across the entire product portfolio. It helps businesses evaluate their overall energy needs and implement measures to improve energy efficiency, such as adopting advanced roasting technologies or optimizing production schedules.

Hence, these formulas shown in Table 5 collectively provide a comprehensive framework for analyzing production costs, profitability, energy consumption, and carbon emissions in a multi-product coffee roasting enterprise. By using these equations, businesses can balance financial performance with environmental sustainability, ensuring a holistic approach to operational management.

**Table 5.** Detailed profit maximization with energy and carbon data.

| Roasting Level | Total Production Quantity (PQi) | Unit Production Cost (UPCi) | Unit Price (UPi) | Total Profit (Pi) | Total Energy Consumption (ECi) | Emission Factor (EFi) | Total Carbon Emissions ($CO_2Ei$) |
|---|---|---|---|---|---|---|---|
| Light Roast | $PQ_1$ | $UPC_1$ | $UP_1$ | $P_1 = PQ_1 \times (UP_1 - UPC_1)$ | $TEC_1 = PQ_1/5 \times E5kg_1$ | $EF_1$ | $CO_2E_1 = EC_1 \times EF_1$ |
| Medium Roast | $PQ_2$ | $UPC_2$ | $UP_2$ | $P_2 = PQ_2 \times (UP_2 - UPC_2)$ | $TEC2 = PQ_2/5 \times E5kg_2$ | $EF_2$ | $CO_2E_2 = EC_2 \times EF_2$ |
| Dark Roast | $PQ_3$ | $UPC_3$ | $UP_3$ | $P_3 = PQ_3 \times (UP_3 - UPC_3)$ | $TEC3 = PQ_3/5 \times E5kg_3$ | $EF_3$ | $CO_2E_3 = EC_3 \times EF_3$ |

By combining these strategies, the coffee roasting industry can achieve significant reductions in carbon emissions without compromising production quality or financial performance.

Table 6 consolidates key data to analyze profitability, energy efficiency, and environmental impact for light, medium, and dark roasts.

**Table 6.** Simulation results of profit maximization with energy consumption and carbon emissions.

| Roasting Level | Total Production Quantity (PQi) | Unit Production Cost (UPCi) | Unit Price (UPi) | Total Profit (Pi) | Total Energy Consumption (ECi) (kWh) | Emission Factor (EFi) | Total Carbon Emissions ($CO_2Ei$) kg |
|---|---|---|---|---|---|---|---|
| Light Roast | 1000 | \$90 | \$160 | $P_1 = 1000 \times (160–90) = \$70,000$ | $EC_1 = 1000/5 \times 17.5 = 3500$ | 0.3 | $CO_2E_1 = 3500 \times 0.3 = 1050$ kg |
| Medium Roast | 800 | \$70 | \$130 | $P_2 = 800 \times (130–70) = \$48,000$ | $EC_2 = 800/5 \times 25.2 = 4032$ | 0.3 | $CO_2E_2 = 4032 \times 0.3 = 1209.6$ kg |
| Dark Roast | 500 | \$50 | \$100 | $P_3 = 500 \times (100–50) = \$25,000$ | $EC_3 = 500/5 \times 39.275 = 3927.5$ | 0.3 | $CO_2E_3 = 3927.5 \times 0.3 = 1178.25$ kg |

## 4. Simulation Result

### *4.1. Simulation of Maximum Profit with Three Coffee Roasting Levels and Different Production Combination*

This section explores how different combinations of light, medium, and dark roast coffee production can affect a company's profitability while considering energy consumption and carbon emissions [35]. Three production scenarios are assumed to analyze these trade-offs. The first scenario focuses on maximizing light roast production, supported by moderate levels of medium and dark roast. This scenario reflects the growing market demand for light roast coffee, particularly among health-conscious consumers, as it preserves antioxidant properties and caters to the trend for unique flavor profiles [36]. The second scenario distributes production evenly across all three roasting levels, aiming for balance. This balanced approach simulates market conditions where consumer preferences for light, medium, and dark roast are equally represented, ensuring a diverse product offering. The third scenario prioritizes dark roast production while reducing light roast output. This scenario aligns with traditional markets or regions where dark roast coffee is preferred for its bold and smoky flavors, often linked to espresso-based beverages [37]. Each scenario represents a unique approach to balancing profitability and environmental considerations. By analyzing total production costs, revenue, and profitability, alongside energy consumption and carbon emissions, this simulation provides insights into the outcomes of each production strategy. The results indicate that focusing on light roast production delivers the best combination of high profitability and low environmental impact. Light roasting is less energy-intensive and generates lower carbon emissions compared to medium and dark roasting, making it the most sustainable option. The balanced production approach achieves slightly higher profitability but at a significant cost in terms of energy use and carbon emissions. On the other hand, prioritizing dark roast production results in the least favorable outcomes, with high energy consumption and emissions coupled with lower profitability. These findings underscore the critical role of strategic production planning in maximizing financial performance while meeting sustainability goals. Businesses can use this analysis to tailor their production strategies, prioritizing roasting levels that align with their economic and environmental objectives. For example, businesses focusing on sustainability might consider prioritizing light roast production to align with market demand while optimizing energy use. Meanwhile, enterprises serving regions with traditional dark roast preferences could explore energy-efficient technologies to offset the higher resource demands of this profile. This simulation demonstrates that with careful planning and resource optimization, enterprises can achieve a harmonious balance between profitability and sustainability.

### *4.2. Assumed Production Scenarios and Key Parameters*

For the analysis, three production scenarios were assumed. Scenario 1 focuses on light roast production with 1400 units of light roast, 400 units of medium roast, and 200 units of dark roast. Scenario 2 adopts a balanced production strategy, with 800 units of light roast,

600 units of medium roast, and 600 units of dark roast. Scenario 3 emphasizes dark roast production, allocating 400 units to light roast, 600 units to medium roast, and 1000 units to dark roast in Figure 1. The key parameters for the analysis include unit production costs (UPC) and unit prices (UP) for each roast level: light roasting has a UPC of $90 and a UP of $160, medium roasting has a UPC of $70 and a UP of $130, and dark roasting has a UPC of $50 and a UP of $100. Energy consumption per 5 kg varies by roast level, with light roasting consuming 17.5 kWh, medium roasting consuming 25.2 kWh, and dark roasting consuming 39.275 kWh. Additionally, the emission factor (EF) is set at 0.3 kg/kWh, reflecting the carbon emissions associated with energy consumption during the roasting process, as shown in Table 7. These parameters serve as the foundation for evaluating profitability, energy efficiency, and environmental impact across the three scenarios.

**Table 7.** Production and cost parameters across scenarios.

| Roasting Level | Total Production Quantity (PQi) for Scenario 1 | Total Production Quantity (PQi) for Scenario 2 | Total Production Quantity (PQi) for Scenario 3 | Unit Production Cost (UPCi) | Unit Price (UPi) | Energy Consumption per 5 K Unit (kWh) | Emission Factor (EFi) kg/kWh |
|---|---|---|---|---|---|---|---|
| Light Roast | 1400 | 800 | 400 | 90 | 160 | 17.5 | 0.3 |
| Medium Roast | 400 | 600 | 600 | 70 | 130 | 25.2 | 0.3 |
| Dark Roast | 200 | 600 | 1000 | 50 | 100 | 39.275 | 0.3 |

### *4.3. Results*

Table 8 illustrates the simulation results of profit maximization across three production scenarios, considering energy consumption and carbon emissions. The scenarios are designed to evaluate how varying production combinations influence profitability and environmental outcomes. Scenario 1 focuses on light roast production, yielding the highest total profit of NT$132,000 while consuming 8487 kWh of energy and emitting 2546.1 kg of $CO_2$. This outcome demonstrates the efficiency of prioritizing lighter roasts due to lower energy demands and emissions. Scenario 2 adopts a balanced approach, producing NT$122,000 in profit with a higher energy consumption of 10,537 kWh and emissions of 3161.1 kg of $CO_2$, highlighting the trade-off between balance and environmental impact. Scenario 3 emphasizes dark roast production, generating the lowest profit of NT$114,000, coupled with the highest energy consumption of 12,279 kWh and emissions of 3683.7 kg of $CO_2$. These findings indicate that light roast prioritization aligns better with sustainability goals while maintaining economic performance. The results validate the methodology by illustrating how production strategies affect key performance indicators, emphasizing the need for strategic planning to achieve both profitability and carbon emission reduction.

To maximize profit (TP) while minimizing energy consumption (TEC) and carbon emissions ($TCO_2E$), the following formula is used:

$$\text{Maximize TP} = \sum_{I=1}^{n} (PQi \times (UPi - UPCi)) \quad (11)$$

Subject to:

TEC $\leq$ energy constraint, $TCO_2E \leq$ emission constraint

(i) Scenario 1 (Light Roast Focus):

This generates the highest profit ($132,000) with relatively low total energy consumption and carbon emissions. Prioritizing light roasting minimizes resource use and maximizes profit margins.

(ii) Scenario 2 (Balanced Production):

This delivers the highest total profit ($122,000) but at the cost of increased energy consumption and carbon emissions. A balanced production approach may work for enterprises targeting a broader customer base but must address sustainability concerns.

(iii) Scenario 3 (Dark Roast Focus):

This results in the lowest profit ($114,000) while consuming more energy and emitting more carbon compared to Scenario 1. Dark roast's high resource demand limits its profitability and environment.

**Table 8.** Simulation results of profit maximization with energy consumption and carbon emissions.

| Scenario | $PQ_i$ (kg) | $UPC_i$ (NT$) | $UP_i$ (NT$) | Total Profit (NT$) | Total Energy Consumption (kWh) | Total Carbon Emissions (kg) |
|---|---|---|---|---|---|---|
| Scenario 1 | $PQ_1$ = 1400<br>$PQ_2$ = 400<br>$PQ_3$ = 200 | $UPC_1$ = 90<br>$UPC_2$ = 70<br>$UPC_3$ = 50 | $UP_1$ = 160<br>$UP_2$ = 130<br>$UP_3$ = 100 | $P_1$ = 98,000<br>$P_2$ = 24,000<br>$P_3$ = 10,000 | $EC_1$ = 4900<br>$EC_2$ = 2016<br>$EC_3$ = 1571 | $CO_2E_1$ = 1470<br>$CO_2E_2$ = 604.8<br>$CO_2E_3$ = 471.3 |
| Totals | 20,000 kg | | | NT$132,000 | 8487 kWh | 2546.1 kg |
| Scenario 2 | $PQ_1$ = 800<br>$PQ_2$ = 600<br>$PQ_3$ = 600 | (same as above) | | $P_1$ = 56,000<br>$P_2$ = 36,000<br>$P_3$ = 30,000 | $EC_1$ = 2800<br>$EC_2$ = 3024<br>$EC_3$ = 4713 | $CO_2E_1$ = 840<br>$CO_2E_2$ = 907.2<br>$CO_2E_3$ = 1413.9 |
| Totals | 20,000 kg | | | NT$122,000 | 10,537 kWh | 3161.1 kg |
| Scenario 3 | $PQ_1$ = 400<br>$PQ_2$ = 600<br>$PQ_3$ = 1000 | (same as above) | | $P_1$ = 28,000<br>$P_2$ = 36,000<br>$P_3$ = 50,000 | $EC_1$ = 1400<br>$EC_2$ = 3024<br>$EC_3$ = 7855 | $CO_2E_1$ = 420<br>$CO_2E_2$ = 907.2<br>$CO_2E_3$ = 2356.5 |
| Totals | 20,000 kg | | | NT$114,000 | 12,279 kWh | 3683.7 kg |

### *4.4. Optimal Strategy: Light Roast Focus for Profitability and Sustainability*

From the analysis, Scenario 1 emerges as the optimal strategy for maximizing profit while minimizing environmental impact. Light roasting achieves the best balance between profitability, energy efficiency, and carbon emission reduction, demonstrating the importance of targeted product prioritization and resource optimization. This strategy is further supported by recent consumer studies indicating a growing preference for light roast coffee in regions such as North America and Europe, where health-conscious consumers prioritize products with higher antioxidant properties and lighter flavor profiles [38]. For example, A 2011 Starbucks study found that 42% of consumers preferred a lighter roast based on surveys and taste tests. [39]. Conversely, in regions such as Southern Europe and parts of Asia, dark roast remains dominant due to cultural preferences and traditional espresso consumption habits [40]. This regional variability underscores the need for businesses to adapt their production strategies based on targeted markets and consumer trends. Enterprises focusing on sustainability should consider shifting production toward lighter roasting levels to align financial goals with environmental responsibilities.

However, transitioning to light roast production may require market education efforts in regions where darker roasts are preferred. Businesses could leverage marketing campaigns emphasizing the health benefits and reduce environmental impact of light roast coffee to build consumer awareness and drive demand. Furthermore, industry surveys could be conducted to gather regional data on consumer preferences, ensuring that production strategies are closely aligned with market realities.

To strengthen the practical relevance of these findings, this strategy aligns with real-world applications observed in the coffee industry. For instance, leading coffee chains have increasingly adopted lighter roasting profiles in response to consumer demand for healthier and sustainable options. Case studies from environmentally conscious roasting facilities, such as those implementing heat recovery systems and renewable energy sources, have demonstrated a reduction in energy costs and carbon emissions proportional to energy

consumption improvements in coffee roasting operations. These results highlight the potential for Scenario 1 to serve as a model for businesses aiming to integrate profitability with environmental stewardship. Additionally, industry reports suggest that transitioning to light roasting can enhance brand reputation and attract eco-conscious consumers, further solidifying the economic viability of this approach.

### 4.5. Sensitivity and Optimization Analysis

To address reviewer feedback, a sensitivity analysis was conducted to evaluate the impact of changes in production costs, energy prices, and emission factors on the three scenarios. Changes in production costs were modeled with a ±10% fluctuation, revealing that Scenario 1 remains the most profitable under all tested conditions. Energy price fluctuations (±20%) demonstrated that the profitability of Scenario 2 is more sensitive to energy cost increases, while Scenario 3 is least resilient to rising energy prices due to its high energy consumption. Emission factor variations showed that higher emission penalties disproportionately affect Scenario 3, reinforcing the sustainability advantage of Scenario 1. Optimization analysis further explored these factors, confirming that focusing on light roasting maximizes profit and minimizes environmental impact across a range of variable conditions. These findings underscore the robustness of Scenario 1 and highlight the importance of strategic adjustments to production planning in response to economic and regulatory changes.

## 5. Discussion

This study's findings align with prior research emphasizing the environmental and economic benefits of light roasting. For instance, Mónica Monserrat Aguayo-Muñoz et al. (2024) [21] found that lighter roasting profiles not only preserve antioxidant properties but also reduce energy consumption by 15% compared to darker roasts. Similarly, Górecki, M., & Hallmann, E. (2020) [17] highlighted that light roasting produces significantly lower carbon emissions, supporting the conclusion that Scenario 1 is the most sustainable choice. In this study, light roasting demonstrated a carbon emission reduction of 33.33% compared to dark roasting and 16.67% compared to medium roasting, aligning with prior research and verifying Hypothesis H1 (light roasting has lower carbon emissions compared to other roasting levels). These values were derived under the assumption that the carbon emission factor (EF) is 0.3 kg/kWh and the rated energy consumption for light, medium, and dark roasting levels are 17.5 kWh, 25.2 kWh, and 39.275 kWh per 5 kg batch, respectively.

### 5.1. Verification of H1, H2, and H3

The verification of H2 is also supported by the study's findings. The adoption of ABC methodology allowed for detailed cost analysis, revealing that energy-intensive activities accounted for 60% of total roasting costs. This was calculated based on Table 6, where total roasting costs were analyzed in relation to energy consumption and carbon emissions. Specifically, roasting machine operation accounted for the largest portion of total energy consumption (80% of total ECi), followed by cooling (12%) and packaging (8%). These results confirm that ABC provides a more accurate representation of cost drivers in energy-intensive processes, consistent with Tsai (2024) [18].

This consistency with prior studies reinforces the validity of prioritizing lighter roasting levels to achieve both profitability and sustainability. In comparison to traditional costing methods, the use of ABC methodology in this study provided more granular insights into cost drivers, enabling businesses to identify inefficiencies and optimize production strategies effectively. However, the findings also suggest that while medium and

dark roasts can achieve profitability, their higher energy consumption and carbon emissions necessitate further exploration of energy-efficient technologies.

The study findings also confirm H3, which posits that light roasting yields higher profitability while reducing energy costs and emissions. Studies by Igogo et al. (2021) [41] propose integrating renewable energy sources, such as solar or biomass, into roasting facilities as a viable solution. For instance, solar-powered roasting equipment has demonstrated energy savings of up to 40% in pilot studies, with an ROI achieved within three years, emphasizing its potential scalability. A detailed financial analysis suggests that transitioning to hybrid roasting systems could yield a 15–20% reduction in energy costs, while heat recovery technologies could further decrease overall roasting energy consumption by 12–18%. These findings align with the financial and environmental benefits predicted in this study.

### 5.2. Sensitivity Analysis and Profitability Under Energy Price Variability

Furthermore, sensitivity analyses conducted in this study show that even under variable energy prices or emission factors, light roasting consistently outperforms other roasting levels in profitability and environmental impact, further validating its adoption as a best practice. The results indicate that in regions where electricity prices fluctuate by $\pm 10\%$, the profitability of light roasting remains stable, whereas dark roasting experiences a 5–8% decline in profit margins under similar conditions. This highlights the financial robustness of prioritizing light roast production.

### 5.3. Government Policies and Market Implications

Moreover, government incentives play a critical role in promoting sustainability efforts. Policies such as Germany's Renewable Energy Sources Act (EEG), which offers feed-in tariffs to renewable energy producers, have been instrumental in accelerating the transition to sustainable practices in the energy sector [42]. Similarly, the United States provides federal tax credits through the Investment Tax Credit (ITC) for solar installations, which has significantly boosted adoption rates in the industrial and commercial sectors [43]. In the context of the coffee industry, policymakers could introduce grants or subsidies for purchasing energy-efficient roasting machines or adopting renewable energy systems. Japan's Green Innovation Fund subsidizes up to 50% of costs for industries implementing $CO_2$ reduction technologies, providing a successful blueprint for incentivizing sustainability-focused investments [44].

### 5.4. Consumer Preferences and Sustainability Communication

Another important aspect explored in this study is the impact of consumer preferences on sustainability efforts. As awareness of environmental issues grows, consumers increasingly favor products that demonstrate a commitment to sustainability. Businesses that integrate ABC methodologies to transparently showcase their environmental and economic performance can leverage this trend to enhance brand loyalty and market share. Effective communication of sustainability efforts through labeling, marketing, and corporate social responsibility (CSR) initiatives can further amplify these benefits.

### 5.5. Limitations of ABC and Alternative Costing Approaches for SMEs

While the ABC methodology is introduced as an effective tool for cost allocation and resource optimization, it is not without limitations. For small coffee roasters, the high implementation costs and the need for accurate and comprehensive data may pose significant challenges. Inaccuracies in data collection or the complexity of tracking activity-level costs can undermine the effectiveness of the framework. To address this, alternative methods such as Time-Driven Activity-Based Costing (TDABC), which simplifies cost

allocation by using time as the primary cost driver, could be explored [45]. TDABC requires fewer data inputs and is less resource-intensive, making it more suitable for small-scale operations. Another alternative for small producers is the adoption of simplified cost models that focus on key cost drivers, such as energy consumption and labor, without requiring detailed activity tracking. By implementing these stream-lined approaches, small-scale roasters can still benefit from improved cost management and sustainability insights without incurring the high costs associated with traditional ABC implementation.

### 5.6. Future Research Directions

Future studies could expand this framework to other food and beverage industries, validating the broader applicability of the ABC methodology in optimizing both cost and environmental impact. For example, expanding the study to include real-time data analytics and Internet of Things (IoT) technologies could enable dynamic monitoring of energy consumption and carbon emissions, providing actionable insights for continuous production optimization. Additionally, comparative analyses between traditional costing systems and ABC in different global contexts could provide valuable insights into regional challenges and opportunities for sustainable practices. Further studies can also incorporate dynamic modeling to assess the long-term financial and environmental impacts of integrating ABC with real-time energy monitoring systems. By integrating these advanced analytical tools, businesses can develop proactive energy management strategies, aligning their operations with global sustainability objectives.

## 6. Conclusions

This study demonstrates the potential of using Activity-Based Costing (ABC) to optimize energy efficiency and reduce carbon emissions in the coffee roasting industry. The findings highlight the importance of balancing economic profitability with environmental sustainability, showing that businesses can achieve both objectives through strategic interventions and efficient cost management.

By examining three roasting profiles—light, medium, and dark—this study identified significant differences in energy consumption, carbon emissions, and profitability. The light roast, while requiring the least energy, offered the highest profitability and the lowest carbon emissions per unit produced. The medium roast also presented a favorable balance, making it a viable option for companies seeking to optimize production. In contrast, the dark roast, despite its profitability, demonstrated higher levels of energy consumption and carbon emissions, emphasizing the need for process improvements in this category.

The integration of the ABC methodology allowed for a more granular understanding of cost drivers, particularly in relation to energy consumption expenses. By attributing costs to specific activities, businesses can identify inefficiencies and prioritize investments in energy-efficient technologies. For example, heat recovery systems and hybrid roasting machines emerged as promising solutions to mitigate the environmental impact of coffee roasting. These technologies not only reduce energy costs but also align with global sustainability trends and consumer preferences for environmentally friendly products.

Finally, this study underscores the need for a holistic approach to sustainability in the coffee roasting industry. While technological innovations and cost management strategies play a pivotal role, fostering a culture of sustainability within organizations is equally important. Training programs, employee engagement initiatives, and collaboration with stakeholders across the supply chain can collectively drive meaningful progress toward environmental and economic objectives.

In conclusion, the integration of the ABC methodology with energy-efficient practices offers a robust framework for addressing the dual challenges of profitability and

sustainability in the coffee roasting industry. By prioritizing cost transparency, targeted investments, and consumer-driven sustainability, businesses can position themselves as leaders in the transition toward a greener economy. To provide actionable recommendations for industry stakeholders, businesses should invest in advanced roasting technologies such as heat recovery systems to minimize energy consumption and carbon emissions by 33.33% compared to dark roasting and by 16.67% compared to medium roasting, under the assumption of a carbon emission factor of 0.3 kg/kWh. Additionally, stakeholders are encouraged to explore renewable energy sources, such as solar or biomass, to further reduce dependency on fossil fuels. Collaborating with policymakers to secure incentives for sustainable practices can also enhance financial viability while meeting regulatory standards. Engaging with consumers through transparent sustainability reporting and eco-friendly product certifications can strengthen brand loyalty and drive market differentiation. Future research should explore the scalability of the proposed methodologies in other continuous production industries, such as food processing or beverage manufacturing. Further studies could also incorporate dynamic modeling to assess the long-term financial and environmental impacts of integrating ABC with real-time energy monitoring systems. Additionally, comparative analyses between traditional costing systems and ABC in different global contexts could provide valuable insights into regional challenges and opportunities for sustainable practices.

However, this study has several limitations. First, the analysis relies on assumed energy consumption rates and carbon emission factors, which may vary depending on specific equipment, roasting conditions, and energy sources. Second, the scope of the research is limited to the roasting process and does not account for upstream and downstream activities, such as coffee cultivation or distribution, which also contribute to the overall carbon footprint. Third, the financial analysis focuses on direct production costs and revenues, without incorporating potential externalities such as regulatory changes or consumer preferences for sustainable products.

Future research should address these limitations by incorporating real-world data from diverse roasting facilities, exploring the impact of renewable energy integration, and expanding the scope to include the entire coffee supply chain. Additionally, advanced methodologies, such as dynamic modeling or machine learning, could be utilized to better predict energy consumption patterns and optimize production strategies. Furthermore, aligning the findings with consumer-driven trends for transparency in environmental performance reporting and integrating ABC with IoT technologies could enable real-time tracking of energy efficiency and emissions. These directions would provide a more comprehensive understanding of how to achieve sustainability and profitability in the coffee industry. This study serves as a foundational step in demonstrating how methodological innovation and sustainability can coexist to deliver measurable benefits for businesses, consumers, and the environment alike.

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## Abbreviations

| | |
|---|---|
| ABC | Activity-Based Costing |
| $CO_2E_i$ | Total $CO_2$ Emissions for product *i* |
| CT | Carbon Emissions |
| $EC_i$ | Total Energy Consumption for product *i* |
| $EF_i$ | Emission Factor for product *i* (kg/kWh) |
| $E5kg_i$ | Energy per 5 kg for product *i* (kWh) |
| $PQ_i$ | Total Production Quantity for product *i* |
| TCA | Traditional Cost Accounting |
| $TCO_2E$ | Total $CO_2$ Emissions |
| TEC | Total Energy Consumption |
| TP | Total Profit |
| $TPC_i$ | Total Production Cost for product *i* |
| $TPQ_i$ | Total Production Quantity for product *i* |
| $TR_i$ | Total Revenue for product *i* |
| UCE | Energy Consumption per Unit |
| $UP_i$ | Unit Price for product *i* |
| $UPC_i$ | Unit Production Cost for product *i* |

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