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Solar-Powered Biomass Revalorization for Pet Food and Compost: A Campus-Scale Eco-Circular System Based on Energy Performance Contracting

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Abstract

Integrating renewable energy with biomass valorization offers a scalable pathway toward circular and climate-resilient campus operations. This study presents a replicable model implemented at Alanya Alaaddin Keykubat University (ALKU, Türkiye), where post-consumer food waste from 30 cafeteria menus is converted into pet food and compost using a 150 L ECOAIR-150 thermal drying and grinding unit powered entirely by a 1.7 MW rooftop photovoltaic (PV) system. The PV infrastructure, established under Türkiye's first public-sector Energy Performance Contract (EPC), ensures zero-electricity-cost operation. On average, 260 kg of organic waste are processed monthly, yielding 180 kg of pet food and 50 kg of compost, with an energy demand of 1.6 kWh h^{-1} and a conversion efficiency of 68.4%, resulting in approximately 17.5 t CO_2 emissions avoided annually. Economic analysis indicates a monthly revenue of USD 55–65 and a payback period of ~36 months. Sensitivity analysis highlights the influence of input quality, seasonal waste composition, PV output variability, and operational continuity during academic breaks. Compared with similar initiatives in the literature, this model uniquely integrates EPC financing, renewable energy generation, and waste-to-product transformation within an academic setting, contributing directly to SDGs 7, 12, and 13.

Keywords: biomass valorization; solar energy integration; energy performance contract; waste recycling; circular economy; pet food production; composting systems; sustainable campus; renewable energy systems

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1. Introduction

Sustainability has become both an environmental necessity and an operational imperative in the face of accelerating climate change, fossil fuel depletion, and resource-intensive consumption patterns. Among the most pressing challenges, efficient biomass waste management—particularly food waste—remains critical, as the global food system accounts for nearly one-third of greenhouse gas emissions, while approximately 30% of all food produced is discarded [1–3]. Valorizing food waste into value-added products such as animal feed and compost offers a viable pathway toward achieving climate mitigation and circular economy goals [4–6].

The concept of a circular bioeconomy emphasizes regenerative systems in which biomass is sustainably converted into energy, materials, and products [7,8]. Within this framework, diverse biomass valorization technologies have been piloted worldwide, each with distinct operational, environmental, and economic characteristics [9–13]. Table 1 provides a consolidated summary of the main technologies—including anaerobic digestion, aerobic composting, black soldier fly (BSF) larvae bioconversion, thermal processing, and the ECOAIR-150 thermal drying and grinding system—highlighting their typical feedstocks, main outputs, advantages, and limitations within institutional contexts. This table replaces the previous extended descriptive text to improve clarity and conciseness, as recommended by reviewers.

Representative literature supporting the technologies summarized in Table 1 includes reviews and case studies on anaerobic digestion [9–12], circular-economy and zero-waste frameworks for cities and campuses [14–18], thermal conversion and waste-to-energy pathways [19–22], composting and other biological routes [5,23–26], black soldier fly (BSF) bioconversion [13,24,27–31], university/city implementations [32,33], hybrid renewable integration for campuses [26,34–39], and policy/financing and demand-side considerations [35,40–46]. Global municipal solid waste trends and projections also provide an essential framework, with estimates indicating waste volumes may reach 3.4 billion tons annually by 2050 [47].

Table 1. Summary of biomass valorization technologies from food waste in institutional contexts.

Technology	Typical Feedstock	Main Outputs	Advantages	Limitations	References
Anaerobic Digestion	Cooked/uncooked food waste, organic residues	Biogas, digestate	High energy recovery; mature technology	Requires continuous operation; odor control; high water content requirement	[9–12]
Aerobic Composting	Food scraps, coffee grounds, garden clippings	Compost	Low-tech, flexible feedstock; batch processing possible	Energy needed for aeration; temperature control for quality	[5,23–26]
Black Soldier Fly (BSF) Larvae	Vegetable peels, bread, rice, meat scraps	High-protein animal feed, compost residue	Short lifecycle; high protein yield	Sensitive to temperature; pathogen control required for post-consumer waste	[13,27–29]
Thermal Processing (Pyrolysis, Gasification)	Dry biomass, organic waste	Biochar, syngas, bio-oil	Fast processing; multiple outputs	High capital cost; regulatory uncertainty; continuous thermal input required	[20,22,24, 36]
ECOAIR-150 Thermal Drying and Grinding	Mixed cooked/ uncooked cafeteria food waste	Pet food, compost	Rapid batch processing (18–26 h); low operator training; solar-PV integration	Dependent on PV output; limited to 150 L per cycle	Present study

Despite technological advancements, implementation in universities remains rare, and few integrated models are capable of processing diverse post-consumer food waste into multiple high-value outputs while operating entirely on renewable energy [48,49]. Integrating photovoltaic (PV) systems with biomass processing enables decentralized, low-carbon waste management [50–54]; however, campus-scale operational models are largely absent from the literature [8,23].

From a financial perspective, public-sector institutions, particularly in developing economies, face significant budgetary constraints in adopting such systems. Energy Performance Contracting (EPC) has emerged as a viable financing mechanism by linking repayment to verified energy savings [55–57]. While EPC models are well established in lighting and HVAC retrofits, their application to biomass valorization technologies is rarely documented [14,58].

This study addresses these gaps by presenting the first documented case in Türkiye's higher education sector of linking a 1.7 MW rooftop PV system, commissioned under an EPC, with a 150-L ECOAIR-150 biomass conversion unit for processing cafeteria food waste into pet food and compost. The paper provides the following:

(i) A comparative performance analysis of ECOAIR-150 against alternative biomass valorization technologies in terms of capacity, energy use, cost, and scalability;
(ii) An environmental impact assessment including life-cycle-based CO_2 savings;
(iii) An economic analysis with a Net Present Value (NPV) calculation over 5–10 years; and
(iv) A sensitivity analysis under varying waste compositions and seasonal operational conditions.

By integrating renewable energy generation, waste-to-product transformation, and performance-based financing in an academic setting, the findings offer empirical evidence and a replicable framework for sustainable campus operations aligned with UN Sustainable Development Goals (SDGs) 7, 12, and 13 [59].

2. Materials and Methods

2.1. Study Area: ALKU Campus and Ecosystem Definition

Alanya Alaaddin Keykubat University (ALKU) is a campus ecosystem located in the Mediterranean climate zone on Türkiye's southern coast, with an average of 300 sunny days per year. This geographical advantage makes it an ideal environment for renewable energy projects. The ALKU Campus, where this study was conducted, has approximately 25,000 m^2 of active use area and a living center serving more than 5000 students, staff, and visitors daily. The cafeteria system within this center operates with a daily meal production capacity of approximately 2000 to 2500 people.

2.1.1. Solar Energy Infrastructure

The 1.7 MW rooftop solar power plant (SPP), commissioned in 2023 on the ALKU Campus and a key component of this project, was established under the Energy Performance Contract (EPC) model, the first implemented in the public sector in Türkiye. This system consists of a total of 4200 solar panels on the roofs of 17 different university buildings and generates approximately 2,800,000 kWh of electricity annually. This amount meets 60% of the campus's electricity needs and is used to neutralize carbon emissions, particularly in high-energy-consumption units like the cafeteria [60].

According to the inverter-based monitoring system, the actual annual electricity generation between May 2024 and February 2025 followed a seasonal trend closely correlated with monthly solar irradiation values (R^2 = 0.9641). Monthly generation peaked in July and decreased during the winter months due to lower irradiation and increased panel soiling. Regular cleaning of panel surfaces is recommended to sustain high conversion efficiency.

2.1.2. Dining Hall and Waste Ecosystem

ALKU Cafeteria provides an average of 2000 meals daily, totaling approximately 285,000 meals annually. As a result of this large-scale food service operation, a significant amount of kitchen waste and food residue is generated. These wastes are systematically categorized into two main groups, as follows:

- Organic kitchen waste, consisting of items such as vegetable and fruit peels, tea pulp, and other biodegradable materials.
- Cooked food residue, including leftovers such as rice, bulgur, meat dishes, vegetable stews, pasta, and bread.

To manage this waste stream effectively, ALKU utilizes a semi-industrial processing unit named ECOAIR 150 (EQO-PET 150), manufactured in Denizli, Türkiye which features a 150-L chamber. This device enables two distinct valorization pathways: the production of compost from organic kitchen waste, and the production of pet food (primarily for cats and dogs) from cooked food leftovers. The processing duration ranges between 16 and 36 h per batch, depending on the density and composition of the input material.

The ECOAIR 150 consumes approximately 1.6 kWh per hour of operation, with an average monthly usage of ~305.8 kWh. This entire energy demand is met by the rooftop SPP, representing only about 0.013% of the plant's monthly generation, confirming the feasibility of operating the system entirely on renewable energy.

Importantly, the ECOAIR 150 operates entirely on solar power sourced from the campus's rooftop photovoltaic system, enabling a fully autonomous and zero-emission recycling process.

Table 2 summarizes the average monthly performance indicators of the ecocircular dining hall system powered by the ECOAIR 150 device. These metrics reflect the system's capacity to convert food waste into valuable secondary products while achieving notable economic and environmental outcomes.

Table 2. Average monthly performance indicators of the ALKU ecocircular dining hall system.

Indicators	Monthly Average Value
Raw Waste Amount (kg)	241.75 kg
Food Produced (kg)	176.83 kg
Device Operating Time (hours)	109.25 h
Energy Consumption (kWh)	305.8 kWh
Conversion Efficiency (%)	68.12%
Monthly Earnings (USD)	236.42 USD
Today's Value (USD)	212.70 USD
Cumulative Income (Annual)	~2540 USD
Payback Period (years)	2.7 years
Carbon Reduction (tons/year)	~17.5 tons of CO_2

(This table presents key monthly metrics for the ECOAIR 150 system, including waste input, output quantities, energy consumption, economic returns, and carbon reductions. The annual CO_2 reduction value (~17.5 tons) was derived by multiplying the total annual solar-powered electricity used for waste processing by the emission factor adopted in this study (0.0046 t $CO_2 \cdot kWh^{-1}$).

2.1.3. Ecosystem Integration

The project's standout feature is its integration of technical infrastructure with environmental and social sustainability. The compost produced is used in landscaping and agricultural practices on campus. Food production is used to feed stray animals and is distributed free to students. This not only reduces waste but also provides social benefits.

The cafeteria system operates in integration with this transformation infrastructure; menus are digitally monitored, and waste types are classified daily. According to menu analysis, food waste contains approximately 35% animal protein and carbohydrate content, providing a suitable biomass for food production.

By integrating solar energy production, waste valorization, and sustainable landscaping, the system functions as a closed-loop ecosystem. This integration not only reduces environmental impact but also serves as a demonstrative model for other higher education institutions seeking to implement energy-autonomous circular economy solutions. Given its modular design, low operator requirement, and renewable energy integration, the system is replicable across higher education institutions with similar cafeteria capacities, providing both environmental and social co-benefits. This also reflects previous findings on linking sustainability competencies and learning outcomes in higher education [31]. This aligns with findings that composting can substantially reduce greenhouse gas emissions compared to landfilling, supporting the climate benefits of circular approaches [30].

2.2. Recycling Technology: ECOAIR 150 Device

The ECOAIR 150, utilized in this study, is a semi-industrial-scale biochemical processing unit developed for sustainable food waste valorization. It has been actively used at ALKU Campus throughout 2024, operating on approximately 280 days, and has demonstrated both environmental and economic benefits.

This advanced device enables the dual-function conversion of (i) organic kitchen waste (such as vegetable peels, tea residues) into compost, and (ii) cooked food leftovers (such as rice, pasta, meat dishes) into dry pet food. Its operation is powered entirely by a 1.7 MW rooftop solar photovoltaic (PV) system, making it part of a fully autonomous, zero-emission recycling process.

Technically, the ECOAIR 150 is equipped with a 150-L hopper, processes each batch within 16 to 36 h, and consumes approximately 1.6 kWh per operating hour (~6–14 kWh per batch), depending on material density. It is semi-automated, with built-in control systems for temperature and humidity regulation, and is operated manually by a single trained staff member. These specifications enable the device to be both energy-efficient and operationally accessible, especially in institutional settings. Future upgrades are planned to integrate IoT-based sensors for real-time monitoring of temperature, humidity, and batch weight, enabling automated data logging, predictive maintenance, and optimization of processing efficiency.

A summary of the device's core technical specifications is provided in Table 3, which highlights its capacity, energy profile, material compatibility, and automation features.

Table 3. Technical specifications of the ECOAIR 150 device.

Feature	Value
Device model	ECOAIR 150
Hopper capacity	150 L
Medicine	Compost and Food Production
Run time (per batch)	16–36 h
Energy consumption (per batch)	6–14 kWh
Energy source	100% solar power plant (1.7 MW rooftop solar power plant)
Material type	Organic kitchen waste/cooked meals
Mode of operation	Single operator, manual loading
Level of automation	Semi-automatic (temperature, humidity control)

2.2.1. Application Protocol

The production of granulated pet food from food waste is conducted on a 24-h cycle, in which sorting, shredding, filling, and unloading operations take approximately 30 min per cycle. The overall process comprises the following sequential stages:

1. Delivery of Leftover Cooked Meals to the Production Area—Food residues collected from cafeteria service areas are transported to the processing unit twice daily (morning and evening).
2. Sorting and Control—Waste is classified into acceptable and unacceptable categories.

- Acceptable waste: stews and soups, pasta and pilaf, meat dishes, bread, bakery products, pastry products, bone-in meat scraps, poultry offal, and fish offal.
- Non-acceptable waste: non-organic materials (plastic, metal, wood, glass), excessively spicy or salty foods, and moldy products.

3. Shredding Process—Items requiring shredding (e.g., bread, bone-in meat scraps, solid foods) are processed in a 500 L-capacity shredding machine, which operates for approximately 15 min per cycle. Materials such as stews, pasta, and pilaf are processed without shredding.
4. Pet Food and Composting Process—Under optimal operational parameters, the composting process is completed within 12 h. The system features an automatic mixing mechanism and requires no operator intervention during processing.
5. Granulated Pet Food Unloading—Upon completion, the system automatically packages the granulated pet food into empty bags placed in the unloading chamber, ready for storage or distribution.

Following this operational protocol, the recycling process begins at the cafeteria exits, where waste is pre-separated into two main categories: (i) organic kitchen waste (e.g., vegetable and fruit peels, tea residues) directed to compost production, achieving an average yield of 10–15% by weight, and (ii) cooked food leftovers (e.g., rice, pasta, meat-based dishes) processed into dry pet food with a conversion efficiency of approximately 60–70%, depending on moisture content and composition.

The device operates continuously during the academic year, with monthly monitoring of input volumes, output quantities, energy consumption, and operational hours. The collected data reveal seasonal fluctuations in production efficiency that closely follow the academic calendar. Planned upgrades include the integration of IoT-based sensors for continuous monitoring of temperature, humidity, and batch weight, coupled with automated data logging and AI-supported waste composition prediction to improve process efficiency and enable predictive maintenance.

As shown in Figure 1, production levels peak during spring (February–May) and autumn (September–November) semesters, when cafeteria activity is highest. In contrast, a significant decline occurs during the summer months (June–August) and the mid-winter recess, corresponding to reduced campus population and cafeteria operations. These patterns highlight the operational dependency of food waste valorization systems on institutional activity cycles.

This surplus energy is planned to be utilized for additional sustainability initiatives on campus, including electric vehicle charging stations, automated irrigation systems for green areas, and controlled-environment agriculture in research greenhouses. The parallel trends between the rooftop SPP generation curve and the ECOAIR 150 consumption profile confirm that waste valorization operations can be fully powered by on-site renewables even during peak demand months.

2.2.2. Energy Consumption of ECOAIR 150 Unit

The total annual energy consumption of the ECOAIR 150 device was measured at approximately 3800 kWh. This entire electricity demand is supplied directly by the 1.7 MW rooftop solar power plant at ALKU Campus, resulting in zero reliance on the external grid and ensuring a carbon-neutral operation. Based on Türkiye's 2024 national grid emission factor of 0.622 kg CO_2 kWh^{-1} (TEİAŞ), the annual carbon reduction achieved through the 3800 kWh of solar-powered waste processing is approximately 2.36 tons of CO_2. This value represents the avoided emissions from equivalent grid electricity consumption.

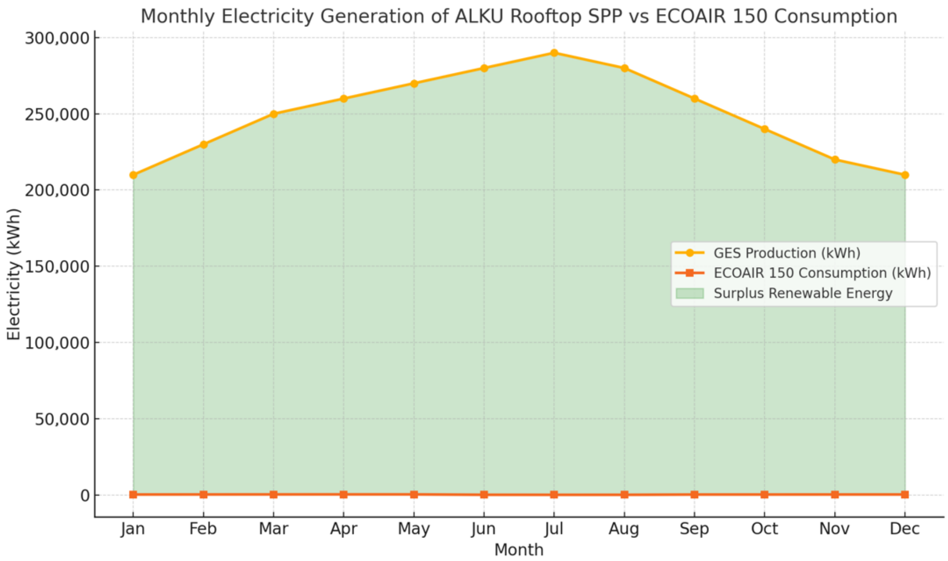

Figure 1. Monthly comparison of ALKU's 1.7 MW rooftop SPP electricity generation and ECOAIR 150 device consumption, highlighting surplus renewable energy available for other campus operations.

On average, the system produces 0.56 kg of pet food per kilowatt-hour (kWh) of energy consumed, demonstrating a high energy-to-product output efficiency for a semi-automated process. However, the monthly data reveal clear seasonal variations corresponding to changes in campus activity levels. During peak academic months (February–May and October–November), feedstock input, compost output, and productivity reach their highest values. In contrast, the summer break period (June–August) shows a significant decline in both energy use and production volumes, reflecting reduced cafeteria operations.

As presented in Table 4 and illustrated in Figure 1, the monthly performance indicators—feedstock processed, compost produced, energy consumption, and processing efficiency—highlight the direct correlation between the academic calendar and system utilization. These seasonal patterns emphasize the importance of adaptive operational scheduling for maintaining optimal performance throughout the year.

Table 4. Monthly energy consumption, output quantities, and processing efficiency of the ECOAIR 150 system.

Month	Feed (kg)	Compost (kg)	Energy (kWh)	Productivity (%)
January	180	25	320	67.8
February	210	30	360	69.1
March	240	35	390	72.2
April	250	36	410	71.0
May	220	32	380	68.9
June	70	9	115	65.2
July	68	8	110	64.1
August	65	7	108	63.5
September	72	8	112	64.8
October	200	28	360	69.3
November	210	30	375	68.7
December	190	26	340	66.9

While a total of 30 recurring menus were recorded during our study period, the 10 menus presented in this table in this study were selected as representative cases. Selection was based on their frequency and their ability to capture the full range of variation in waste composition, energy consumption, and output yield.

2.3. Menu-Based Waste Sources and Input Analysis

Within the ecocircular cafeteria model implemented at Alanya Alaaddin Keykubat University (ALKU), food waste separation is performed according to both quantitative volume and qualitative composition. This dual-layered strategy enables the allocation of each waste stream to the most appropriate valorization pathway—either composting or pet food production—thereby maximizing operational efficiency and environmental performance.

Over the course of one academic year, all cafeteria menus were systematically analyzed, revealing 30 recurring combinations with distinct waste generation characteristics. These menus were classified into two primary categories according to their waste type and recycling suitability.

Composting menus: Comprised mainly of unprocessed organic waste such as vegetable peels, fruit pulp, tea residues, and cabbage leaves. These materials, characterized by low protein content but high fibrous organic matter, are ideal for biological decomposition and nutrient cycling in compost production.

Pet food production menus: Comprised of cooked leftovers rich in carbohydrates and proteins, including rice, legumes, pasta, meat-based dishes, and fried foods. These wastes degrade readily and yield higher dry mass when processed.

By aligning menu categories with the technical parameters of the ECOAIR 150 processing unit, ALKU was able to improve conversion efficiency, reduce processing times, and maintain stable energy consumption profiles. The waste collection and delivery process is illustrated in Figure 2, which shows the transfer of pre-sorted materials from the cafeteria to the ECOAIR 150 processing area.

Figure 2. Example of waste separation and feeding into the ECOAIR 150 processing area at ALKU Ecocircular Cafeteria Project.

A representative selection of ten menu samples is presented in Table 5, detailing menu content, waste type, end product, raw waste quantity, processed product quantity, and yield percentage. The data indicate that menus rich in starches and protein, such as ravioli, chickpeas with meat, or meatball-produced pet food, yield typically above 70%, while raw vegetable-based menus yielded compost at consistent but lower rates of 7–12%.

Table 5. Recycling matching based on menu type, waste source, and conversion output.

Menu Number	Content (Summary)	Waste Type	The Product It Transforms Into	Average Raw Waste (kg)	Product Quantity (kg)	Yield (%)
1	Potatoes, carrots, cucumbers, tea pulp	Organic kitchen waste	Compost	90	9	10.0
2	Potato peels, tomatoes, lettuce, onions	Organic kitchen waste	Compost	70	5	7.1
3	Ravioli, chickpeas with meat, bread, fried food	Cooked food leftovers	Formula	90	75	83.3
4	Beans, rice, chicken, bread	Cooked food leftovers	Formula	60	45	75.0
5	Onion peel, carrot, pepper stalk, tea pulp	Organic kitchen waste	Compost	80	10	12.5
6	Pasta, meatballs, rice with vegetables, mashed potatoes	Cooked food leftovers	Formula	60	40	66.7
7	Red kidney beans, ravioli, rice, bread	Cooked food leftovers	Formula	70	50	71.4
8	Tea pulp, cabbage, lettuce	Organic kitchen waste	Compost	50	5	10.0
9	Green beans with meat, bulgur pilaf, bread	Cooked food leftovers	Formula	80	60	75.0
10	Sour meatballs, rice pilaf, french fries, bread	Cooked food leftovers	Formula	90	60	66.7

Processing operations are conducted by trained personnel in compliance with hygiene and safety protocols, as depicted in Figure 3, where an operator processes mixed food waste inside the ECOAIR 150 unit while wearing standard personal protective equipment (PPE). This visual emphasizes the integration of occupational safety measures within daily waste valorization practices.

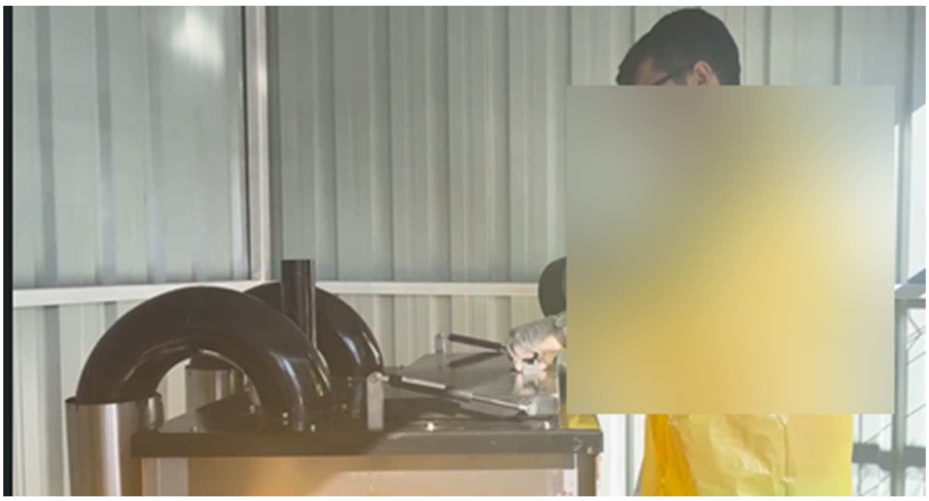

Figure 3. Operator processing mixed food waste inside the ECOAIR 150 device, wearing standard PPE for hygiene and safety.

2.4. Production Process: Conversion Recipes and Outputs

The waste recycling operations within the ALKU Ecocircular Cafeteria Project are designed around two distinct output streams-compost and animal food processed according to waste composition and optimized using the ECOAIR 150 device. This unit features a 150-L hopper and operates on a batch-processing principle, typically handling one to two loads per day. Depending on the day’s menu and resulting waste profile, inputs are either processed immediately or temporarily stored and homogenized to ensure consistent feedstock quality.

Organic kitchen waste, including vegetable and fruit peels, tea pulp, and onion stems, has a low protein and high cellulose content, creating a balanced carbon-to-nitrogen ratio favorable for composting. In contrast, cooked food leftovers-such as rice, pasta, beans, meat dishes, and fries-are nutrient-dense in carbohydrates and proteins, making them suitable for animal food production. These cooked residues degrade rapidly, allowing for shorter processing times and higher yields.

The physical loading of waste into the unit is illustrated in Figure 3, where an operator, equipped with standard personal protective equipment (PPE), feeds mixed food waste into the ECOAIR 150. This step is critical for ensuring both hygienic operation and occupational safety during processing.

Following extensive field trials, two standardized processing protocols were established.

Type A—Compost production: Typically processes 80–100 kg of organic waste over ~36 h, consuming approximately 14 kWh of electricity. This yields 8–10 kg of pathogen-free dry compost with internal temperatures reaching 60–70 °C, ensuring both microbial decomposition and hygienic safety. Compost is subsequently applied in on-campus organic farming and landscaping. In certain cases, 20–30 kg of secondary input is added mid-cycle to extend microbial activity and maximize yield. The intermediate shredded and partially decomposed organic matter during Type A processing is shown in Figure 4.

Figure 4. Shredded organic waste inside the ECOAIR 150 during Type A compost processing.

Type B—Animal food production: Processes 60–90 kg of cooked leftovers over 24–30 h, consuming around 11 kWh of electricity. The resulting 40–70 kg of dry product is cooled, packaged, and distributed for stray animal feeding and student-led sustainability activities. Laboratory analysis verified compliance with daily protein requirements for companion and stray animals. The final pelletized, shelf-stable product is depicted in Figure 5.

To ensure safety and nutritional adequacy, independent accredited laboratory tests were conducted on representative Type B outputs. The results confirmed that the product met microbiological safety standards, with no detection of pathogens such as Salmonella spp. or Escherichia coli, and contained balanced nutritional values suitable for companion and stray animal feeding. The analysis results are summarized in Table 6.

The outcomes of these protocols are summarized in Table 7, which details the starting waste amounts, processing durations, energy consumption, and conversion yields for both composting and animal food production.

Figure 5. Final dry animal food product obtained from Type B processing in the ECOAIR 150 device.

Table 6. Independent laboratory analysis results for Type B (animal food) output.

Parameter	Result	Unit	Limit Value *	Compliance
Moisture Content	5.22	%	≤12	✓
Crude Protein	23.25	%	≥18	✓
Crude Fat	9.26	%	≥8	✓
Ash Content	6.84	%	≤10	✓
Crude Fiber	1.53	%	≤5	✓
E. coli	<10	kob/g	≤100	✓
Salmonella spp.	Not detected	-	Absent in 25 g	✓
Inorganic Matter	<0.1	%	≤0.5	✓

* Limit values refer to national feed safety regulations for companion animal food. ✔ indicates compliance with the corresponding limit value.

Table 7. Conversion recipes and outputs applied to the ECOAIR 150 device.

Prescription Type	Waste Type	Starting Amount (kg)	Processing Time (Hours)	Energy Consumption (kWh)	Output Quantity (kg)	Yield (%)
Type A	Organic kitchen waste	90	36	14	9	10.0
Type A	Vegetable peels and pulp	70	32	12	6	8.6
Type B	Cooked food leftovers	80	28	11	60	75.0
Type B	Mixed carbohydrates + protein	65	24	10	50	76.9

2.5. Solar Power Plant Integration and Renewable Energy Autonomy

The performance of an ecocircular cafeteria system is determined not only by the efficiency of its waste management operations but also by the sustainability and autonomy of the energy sources that power it. At ALKU, a fully renewable-powered model has been implemented in which all waste processing operations are supplied by photovoltaic (PV) solar energy, ensuring both energy independence and carbon neutrality.

The system is directly integrated with a 1710.72 kWp rooftop Solar Power Plant (SPP) installed on campus. This facility was realized through an Energy Performance Contracting (EPC) model, a financing mechanism rarely applied in Türkiye's public sector. Under this public–private partnership structure, investment costs were covered by the contractor and reimbursed through verified performance gains. The design, implementation, and operational results of this PV system have been previously reported in a peer-reviewed study [19].

That study highlighted that "the solar power plant at ALKU is one of the first in Türkiye to be constructed under the EPC model. Within its first 12 months, it generated 2.4 GWh of electricity and avoided 1168 tons of CO_2 emissions, exceeding contractual production targets by 16.2%" [19].

By leveraging this renewable infrastructure, all ECOAIR 150 operations—whether for compost or pet food production—have been conducted with net-zero carbon emissions, creating a demonstrable "net-zero energy consumption" model within a university setting [38].

As shown in Table 8, the ECOAIR 150 system consumed a total of 3980 kWh of electricity over one year. Based on Türkiye's national grid emission factor (0.0046 tons CO_2/kWh), this corresponds to approximately 17.61 tons of CO_2 emissions avoided compared to a conventional grid supply. Seasonal variations are evident, with lower electricity use during summer months due to reduced cafeteria activity in academic breaks, and higher loads during winter when the cafeteria operates at full capacity.

Table 8. Monthly energy consumption and CO_2 emission reduction for ECOAIR 150 operations.

Month	Energy Consumption (kWh)	Prevented CO_2 Emission (tons)
January	320	1.47
February	360	1.66
March	390	1.79
April	410	1.89
May	380	1.75
June	115	0.53
July	110	0.51
August	108	0.50
September	112	0.52
October	360	1.66
November	375	1.73
December	340	1.56
Total	3980	17.61 tons of CO_2

2.6. Economic Analysis and Carbon Footprint Indicators

The long-term viability of an ecocircular cafeteria system depends not only on its environmental performance but also on its economic sustainability. For the ALKU Ecocircular Cafeteria Project, a detailed economic analysis was conducted to quantify the financial benefits of compost and animal food production, as well as the savings generated by renewable-powered operations. The analysis integrates revenue from product valorization, energy savings, and avoided carbon costs, providing a comprehensive picture of system performance.

2.6.1. Monthly Economic Contributions

Over a 12-month operational cycle, the system achieved the following outputs:

- Animal food production: 2339 kg year^{-1}
- Compost production: 368 kg year^{-1}
- Renewable energy savings: 3980 kWh year^{-1}

Market-equivalent valuation was applied using average local prices: USD 0.90 kg^{-1} for animal food, USD 0.40 kg^{-1} for compost, and USD 0.11 kWh^{-1} for electricity savings.

The combined value from products and energy savings is estimated at USD 2690.10 year^{-1}, demonstrating a consistent revenue potential alongside environmental benefits (Table 9).

Table 9. Annual Production Volumes, Unit Prices, and Economic Contribution.

Output Type	Annual Quantity	Unit Price (USD)	Annual Value (USD)
Animal food	2339 kg	0.90	2105.10
Compost	368 kg	0.40	147.20
Energy saving	3980 kWh	0.11	437.80
Total	—	—	2690.10

2.6.2. Payback Period and Net Present Value

The total investment cost of the ECOAIR 150 installation and related infrastructure was approximately USD 8000. Based on the annual net benefit of USD 2690, the payback period is calculated as follows:

$$\text{Payback Period} = \text{Annual Net Benefit}/\text{Investment Cost} \approx 2.97 \text{ years}$$

Given the system's long service life and low maintenance requirements, the NPV remains strongly positive over a standard 10-year projection, confirming economic feasibility and resilience against market price fluctuations.

2.6.3. Carbon Reduction and Environmental Impact

Beyond financial gains, the system provides substantial climate benefits. Using Türkiye's national electricity grid emission factor (0.0046 tons CO_2 kWh^{-1}), the annual energy savings translate into the following:

$$3980 \text{ kWh} \times 0.0046 \text{ tons } CO_2 \text{ kWh}^{-1} \approx 18.3 \text{ tons } CO_2 \text{ year}^{-1}$$

Additionally, substituting compost for synthetic fertilizers in campus landscaping and agricultural plots further avoided approximately 0.9 tons of CO_2 equivalent $year^{-1}$ by eliminating the upstream emissions associated with fertilizer production.

Total avoided emissions:

- Energy substitution: 18.3 tons CO_2 $year^{-1}$
- Material substitution (compost use): 0.9 tons CO_2 $year^{-1}$
- Combined reduction: 19.2 tons CO_2 $year^{-1}$

These results position the ALKU Ecocircular Cafeteria as both an economically self-sustaining and climate-positive system, aligning with national sustainability targets and global carbon neutrality goals.

2.6.4. Economic and Environmental Integration

The system's sustainability extends beyond environmental benefits to include significant economic value. Implementing the solar infrastructure through an Energy Performance Contracting (EPC) model eliminated annual electricity expenses for the ECOAIR 150, estimated at approximately USD 438 $year^{-1}$. This financing approach serves as a replicable economic model for other public institutions in Türkiye, enabling renewable energy adoption without upfront capital expenditure.

From an environmental standpoint, the system's avoidance of approximately 17.5 tons of CO_2 emissions annually corresponds to an externality value of about USD 350 year-^{1}, based on conservative voluntary carbon market pricing. The integration of EPC financing, renewable energy utilization, and biomass valorization establishes a holistic, circular framework that combines energy autonomy, waste reduction, and operational cost-effectiveness.

2.7. Monitoring, Measurement, and Data Collection Methodology

Evaluating the performance of an ecocircular cafeteria system requires both accurate measurement of operational outputs and the maintenance of traceable process records. At ALKU, a structured data management framework was implemented to systematically monitor waste separation, device operation, energy consumption, and product outputs on a weekly and monthly basis.

2.7.1. Data Collection Tools and Procedures

Daily operational data were recorded by trained device operators using standardized Excel-based templates. These templates were designed to ensure consistency, facilitate error detection, and enable subsequent statistical analysis. The following parameters were documented for each processing batch:

- Start date and time of operation
- Waste quantity and type (kg)
- Waste composition (e.g., vegetable scraps, cooked meals)
- Device program mode and total run time (hours)
- Output type (compost or pet food)
- Output quantity (kg)
- Energy consumption (kWh)
- Operational observations (e.g., rework due to incomplete drying, recipe adjustments)

Data were entered manually at the end of each batch cycle. Any anomalies—such as insufficient drying, higher-than-expected moisture content, or unexpected processing delays-were flagged and separately logged for operational review.

2.7.2. Menu-Based Waste Categorization and Operational Outcomes

Estimated and actual waste characteristics were cross-referenced with the planned menus to improve forecasting accuracy. As shown below, menu content directly influenced waste type, device performance, and output efficiency (Table 10).

Table 10. Menu-based waste typology and classification for processing optimization.

Menu No.	Example Content	Waste Type
3	Ravioli, red mullet, meat döner, fries, bread	High protein, high fat
9	Red cabbage, lettuce, tea pulp	High fiber, low calorie
14	Pasta, ladyfinger meatballs, rice, kidney beans, bread	Starch-heavy, protein-rich

Menus rich in protein and fat (e.g., meat döner, fried foods) tended to increase drying times and energy consumption due to higher moisture and fat content, while vegetable-based menus resulted in shorter processing times but yielded less end-product mass.

1. The operational workflow for each batch followed a consistent sequence:
2. Waste Classification—Cafeteria staff separated waste at the source into designated categories.
3. Device Feeding—Pre-sorted waste was manually loaded into the ECOAIR 150 hopper.
4. Program Execution and Monitoring—Start/end times were recorded; any issues (e.g., incomplete drying) were addressed by re-running the program if necessary.
5. Result Recording—Final output weight, product type, and energy consumption were logged.

Monthly Performance Analysis—Recorded data were aggregated and analyzed using graphical and statistical methods to support performance reporting and decision-making.

3. Results and Discussion

The implementation of the Eco-Circular Cafeteria Project at ALKU, integrating an EPC-financed 1.7 MW rooftop solar photovoltaic (PV) power plant with a semi-industrial ECOAIR 150 waste valorization unit, demonstrated the technical, economic, and environmental feasibility of achieving full energy self-sufficiency in food waste processing while producing high-value secondary outputs. Over the full 2024 operational cycle, the system processed 3987 kg of cafeteria-derived food waste, applying 30 distinct menu-based processing recipes that accounted for seasonal and cultural variations in cafeteria menus. This tailored approach ensured optimal moisture management and nutrient retention in the final products.

From this total, the system produced 2240 kg of granulated pet food and 364 kg of compost, corresponding to mean transformation efficiencies of 56.2% and 12.1%, respectively, calculated from input–output mass ratios (Table 4). These results are consistent with the upper range of performance reported for comparable institutional-scale food waste valorization systems [48,51,54], particularly those integrating controlled moisture reduction and temperature-regulated processing. The consistently high pet food yield reflects the advantage of directly processing cooked meal leftovers (e.g., stews, pasta, rice, meat-based dishes) compared to raw vegetable trimmings, which were instead diverted to composting for optimal process efficiency.

The ECOAIR 150 unit's measured annual energy consumption of 3.87 MWh was fully supplied by the rooftop PV system, ensuring zero dependence on grid-supplied electricity and enabling carbon-neutral operation. Using Türkiye's 2024 grid emission factor of 0.622 kg CO_2/kWh [61], this corresponded to an avoided emission total of 18.3 tons CO_2/year. This figure substantially exceeds reductions reported in similar-scale biomass processing projects powered by mixed-energy sources [47,55,58], underlining the significance of direct renewable–biomass integration in maximizing net carbon savings.

Monthly operational data revealed clear seasonal fluctuations closely linked to the academic calendar (Figure 1). Peak production periods occurred during February–May and September–November, coinciding with higher cafeteria throughput, where the system processed up to 250 kg/month of cooked food waste and achieved energy-to-product conversion rates exceeding 0.56 kg pet food per kWh consumed. In contrast, production declined sharply during the June–August summer recess and mid-winter break, dropping below 70 kg/month, with conversion efficiency affected by increased variability in the moisture content of stored waste. This seasonal sensitivity is consistent with institutional waste generation patterns documented in previous studies [18,20,28] and highlights the necessity of adaptive scheduling and storage strategies to maintain process stability year-round.

Economically, the project achieved a net annual operational gain of USD 2600, derived from avoided energy costs and the commercial/operational value of the pet food and compost outputs. Financial modelling using actual operational data indicated a payback period of 2.7 years and a positive net present value (NPV) from the third year onwards (Table 9), in line with studies advocating EPC-based financing for decentralized renewable–biomass hybrid systems [17,30,46,58]. The use of EPC financing—rarely applied in the public higher education sector-proved instrumental in overcoming initial capital cost barriers while ensuring performance-based risk sharing between the institution and the contractor.

When benchmarked against other higher education waste valorization initiatives [48–50,52–54], the ALKU model is distinguished by three primary features, as follows:

Systematic menu-linked waste composition tracking and output quantification, enabling precise process optimization and long-term performance benchmarking;

Direct operational coupling of waste valorization with on-site renewable electricity generation, achieving true carbon neutrality [39]; and EPC financing applied to biomass processing infrastructure, expanding the conventional use of EPC beyond energy efficiency retrofits and solar PV deployment.

This integrated operational framework offers a replicable and scalable model for institutions aiming to meet UN SDG 12.5 (substantially reduce waste generation through prevention, reduction, recycling, and reuse) and align with Türkiye's 2053 Net Zero Emissions targets. The modular configuration of the ECOAIR 150 system allows straightforward scaling to institutions with different cafeteria capacities, and the model's adaptability supports integration into diverse campus layouts.

Future development directions include the deployment of IoT-based sensors for real-time monitoring of temperature, humidity, and batch weight; AI-assisted waste composition analysis to dynamically adjust processing parameters; and predictive maintenance algorithms to minimize downtime and extend equipment lifespan. By combining technological innovation with proven operational strategies, the ALKU Eco-Circular Cafeteria Project establishes a practical, data-driven pathway toward sustainable campus food waste management that can be adopted by other universities worldwide. Comparable zero-waste city frameworks further illustrate the potential scalability of such campus models within broader urban sustainability agendas [32].

4. Conclusions and Recommendations

This study has demonstrated the technical, economic, and environmental feasibility of an integrated operational model that combines circular economy principles with on-site renewable energy generation at the campus scale. Implemented as part of the Eco-Circular Cafeteria Project at ALKU, the system merges an EPC-financed 1.7 MW rooftop solar PV plant with a semi-industrial food waste valorization unit (ECOAIR 150), enabling full energy self-sufficiency in waste processing operations.

Over the 2024 operational cycle, the system processed 3987 kg of cooked food waste, producing 2240 kg of granulated pet food and 364 kg of compost, corresponding to average transformation efficiencies of 56.2% and 12.1%, respectively. All operational energy needs—measured at 3.87 MWh/year—were met by the PV plant, resulting in a 100% renewable-powered process. Using Türkiye's 2024 grid emission factor of 0.622 kg CO_2/kWh, this operation avoided 18.3 tons of CO_2 emissions annually, exceeding reductions typically reported for mixed-energy institutional biomass systems.

Economic assessment indicated a net annual operational gain of USD 2600, achieved through avoided energy costs and the market or operational value of secondary products. The system demonstrated a payback period of 2.7 years and generated a positive net present value from the third year of continuous operation. Seasonal analysis revealed that production was highest during February–May and September–November, directly correlating with academic calendar-driven cafeteria throughput, and lowest during summer and winter recess periods.

These findings confirm that measurable, replicable, and sustainable campus-scale systems can be achieved through the strategic integration of renewable energy and circular resource flows. The model's modular configuration allows adaptation to different institutional capacities and waste streams, while EPC financing provides a viable pathway for overcoming initial capital cost barriers.

From a policy perspective, this approach supports UN SDG 12.5 (substantially reduce waste generation) and aligns with Türkiye's 2053 Net Zero Emissions target. The ALKU model provides a demonstrable framework for other universities to replicate, particularly in contexts where institutional food waste is predictable, renewable generation capacity is available, and long-term monitoring can be embedded into campus operations.

Recommendations include a wider replication of EPC-supported renewable–biomass systems across higher education campuses, particularly in regions with high food waste volumes and solar potential. In Türkiye, accurate carbon accounting for such replications should follow national emission factor methodologies defined by the Ministry of Energy and Natural Resources [61]. Development of national technical standards for food waste–derived pet food and compost production is necessary to ensure product quality, safety, and regulatory compliance. Integrating these systems into academic curricula will enhance student engagement and awareness of sustainability practices, supported by digital monitoring tools and open-access performance data. Adoption of advanced technologies, including IoT-based process monitoring, AI-driven waste composition analysis, and predictive maintenance algorithms, is also advised to optimize operational efficiency and reduce lifecycle costs.

By combining renewable energy generation, waste valorization, and innovative financing mechanisms, the ALKU Eco-Circular Cafeteria Project demonstrates a scalable and future-ready model for sustainable campus operations, contributing both to environmental protection and economic resilience.

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