REPUBLIC OF TÜRKİYE
MUĞLA SITKI KOÇMAN UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DEPARTMENT OF METALLURGICAL AND MATERIALS ENGINEERING

ENGINEERING SUSTAINABLE WASTE MANAGEMENT: RECYCLING NYLON WASTE INTO PELLETS FOR AGRICULTURE PIPE PRODUCTION

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MASTER OF SCIENCE THESIS

APRIL 2025
MUĞLA

MUĞLA SITKI KOÇMAN UNIVERSITY

Graduate School Of Natural and Applied Sciences

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Amaç 13: İklim Eylemi	
Amaç 14: Sudaki Yaşam	
Amaç 15: Karasal Yaşam	
Amaç 16: Barış, Adalet ve Güçlü Kurumlar	
Amaç 17: Amaçlar İçin Ortaklıklar	
Diğer (açıklayınız)…………….	

07/04/ 2025

Louay Hamsho

ABSTRACT

ENGINEERING SUSTAINABLE WASTE MANAGEMENT: RECYCLING NYLON WASTE INTO PELLETS FOR AGRICULTURE PIPE PRODUCTION

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April 2025, 60 pages

The rapid increase in agricultural plastic waste (APW) poses significant challenges for waste management, highlighting the need for efficient recycling technologies to reduce energy consumption and operational costs. This thesis analyzes APW recycling processes, focusing on energy optimization through detailed energy balance models. Key stages—grinding, pelletizing, and extrusion—were examined to identify inefficiencies and enhance energy use.

Innovations such as thermostat-controlled heating and waste heat recovery systems (WHRS) improved efficiency, reducing active heating energy by up to 90%, minimizing waste heat, and streamlining operations. The study evaluates the energy profiles and technical benefits of mechanical and chemical recycling, addressing their respective limitations.

Quantitative analysis reveals cost-saving potential through optimized technologies, renewable energy integration, and process redesigns. These strategies significantly improve energy efficiency and productivity, offering actionable insights for industrial stakeholders and policymakers. By emphasizing energy balance, this research advances recycling technologies and establishes a foundation for sustainable APW management practices.

Keywords: Agricultural Plastic Waste (APW), Recycling Technologies, Energy Optimization, Energy Balance Models, Energy Efficiency.

ÖZET

SÜRDÜRÜLEBİLİR ATIK YÖNETİMİNİ MÜHENDİSLİKLE ŞEKİLLENDİRME: NAYLON ATIKLARIN TARIM BORUSU ÜRETİMİ İÇİN GRANÜLLERE GERİ DÖNÜŞTÜRÜLMESİ

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Nisan 2025, 60 Sayfa

Tarım plastik atıklarındaki (TPA) hızlı artış, atık yönetiminde önemli zorluklar yaratmakta ve enerji tüketimini azaltacak, operasyonel maliyetleri düşürecek etkin geri dönüşüm teknolojilerine olan ihtiyacı vurgulamaktadır. Bu tez, detaylı enerji dengesi modelleri üzerinden enerji optimizasyonuna odaklanarak TPA geri dönüşüm süreçlerini analiz etmektedir. Öğütme, pelletleme ve ekstrüzyon gibi temel aşamalar incelenerek enerji kullanımındaki verimsizlikler tespit edilmiş ve iyileştirmeler yapılmıştır.

Termostat kontrollü ısıtma ve atık ısı geri kazanım sistemleri (WHRS) gibi yenilikler, aktif ısıtma enerjisini %90'a kadar azaltarak, atık ısıyı en aza indirerek ve operasyonları düzenleyerek verimliliği artırmıştır. Çalışma, mekanik ve kimyasal geri dönüşümün enerji profillerini ve teknik avantajlarını değerlendirerek, bu yöntemlerin sınırlamalarını ele almıştır.

Nicel analizler, optimize edilmiş teknolojiler, yenilenebilir enerji entegrasyonu ve süreç yeniden tasarımları yoluyla maliyet tasarrufu potansiyelini ortaya koymaktadır. Bu stratejiler, enerji verimliliğini ve üretkenliği önemli ölçüde artırarak sanayi paydaşları ve politika yapıcılar için uygulanabilir öneriler sunmaktadır. Enerji dengesine vurgu yaparak bu araştırma, geri dönüşüm teknolojilerini geliştirmekte ve sürdürülebilir TPA yönetim uygulamaları için bir temel oluşturmaktadır.

Anahtar Kelimeler: Tarım Plastik Atıkları (TPA), Geri Dönüşüm Teknolojileri, Enerji Optimizasyonu, Enerji Dengesi Modelleri, Enerji Verimliliği.

ACKNOWLEDGMENT

I would like to express my heartfelt gratitude to my supervisor, Doktor Öğretim Üyesi Erdem Şahin, for his invaluable guidance, insightful feedback, and constant encouragement throughout the course of this research. His expertise and mentorship have been critical in shaping this thesis and helping me navigate challenges along the way.

I am deeply thankful to my family for their unwavering support, both emotionally and financially, which made this work possible. Your belief in me and your sacrifices have been the cornerstone of my journey. I dedicate this work to you.

To my friends and colleagues, thank you for your encouragement and for being a source of inspiration during this challenging yet rewarding process. Your presence has made this journey much more meaningful.

This thesis is the culmination of not just my efforts but also the support and encouragement of those around me. I am sincerely grateful to everyone who has contributed, directly or indirectly, to the completion of this work.

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LIST OF ABBREVIATIONS

AI	Artificial Intelligence
APW	Agricultural Plastic Waste
CO_2	Carbon Dioxide
DSC	Differential Scanning Calorimetry
EVA	Ethylene Vinyl Acetate
GJ	Gigajoule
HDPE	High-Density Polyethylene
INGCO HIT015501	Infrared Thermometer Model Used in Experiments
kVA	Kilovolt-Ampere
k-value	Thermal Conductivity Coefficient
kW	Kilowatt
kWh	Kilowatt-hour
LCA	Life Cycle Assessment
LDPE	Low-Density Polyethylene
MJ/kg	Megajoules per Kilogram
mW	Milliwatt
N/A	Not Applicable
PC	Polycarbonate
PE	Polyethylene
PET	Polyethylene Terephthalate
PF	Power Factor
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl Chloride
USD	United States Dollar
WHRS	Waste Heat Recovery Systems

1. INTRODUCTION

1.1. Background

The widespread use of plastics in agriculture, including materials such as mulch films, irrigation pipes, protective netting, and silage bags, has led to the accumulation of significant amounts of Agricultural Plastic Waste (APW). This poses a challenge not only for operational efficiency but also for resource management on farmlands. Non-biodegradable plastics persist in the environment, exacerbating waste management issues and emphasizing the need for effective strategies to address their disposal and reuse (Kasirajan & Ngouajio, 2012; Briassoulis & Dejean, 2010).

1.2. Recycling As A Solution

Recycling APW offers a sustainable solution by converting waste materials into reusable products, aligning with the principles of a circular economy (Ellen MacArthur Foundation, 2013). Despite its promise, the viability of recycling processes depends heavily on energy efficiency, with a balance between energy inputs and outputs being crucial. This makes Energy Balance Analysis a key methodology in evaluating and optimizing recycling practices (Das & Grant, 2010).

1.3. Energy Balance Analysis in APW Recycling

Energy Balance Analysis examines the energy dynamics throughout the recycling process, encompassing stages such as waste collection, preparation, and the production of new materials, like agricultural pipes made from recycled nylon. This analysis serves several critical purposes:

Optimization Opportunities: By identifying energy-intensive stages, targeted improvements can be made to enhance efficiency, such as adopting advanced machinery, refining process parameters, or integrating renewable energy sources (Hopewell, Dvorak, & Kosior, 2009).

Economic Viability: Improved energy efficiency lowers operational costs, making recycling more financially attractive to investors and stakeholders (Shonfield, 2008).

Operational Efficiency: Detailed analysis can uncover inefficiencies, guiding process redesigns and the adoption of innovative technologies (Gu et al., 2017).

Strategic Resource Management: Energy-optimized recycling conserves resources, supporting industry goals for sustainability and efficiency (Rigamonti, Grosso, & Giugliano, 2009).

1.4. Thesis Objectives

This thesis aims to address the challenges associated with APW by focusing on Energy Balance Analysis to enhance recycling efficiency and economic viability. The objectives are:

Quantitative Energy Assessment: Systematically evaluate energy consumption across all stages of the recycling process, including machinery usage, transportation, and auxiliary services (Das & Grant, 2010).

Identification of Inefficiencies: Detect areas with disproportionate energy consumption to guide improvements (Al-Salem, Lettieri, & Baeyens, 2009).

Energy Optimization Strategies: Develop and evaluate methods to reduce energy use, such as process re-engineering, advanced technology, and renewable energy integration (Hopewell, Dvorak, & Kosior, 2009).

Economic Impact Analysis: Assess the financial implications of energy optimization in terms of cost savings, investments, and payback periods (Rigamonti, Grosso, & Giugliano, 2009).

1.5. Contribution To Sustainable Waste Management

By achieving these objectives, this thesis demonstrates how optimizing energy balance is integral to developing efficient and economically viable recycling processes for APW. The findings contribute to advancing sustainable waste management practices, supporting agricultural operations in transitioning toward resource-efficient and environmentally responsible solutions.

2. LITERATURE OVERVIEW

2.1. Introduction: Agricultural Plastic Waste And Its Challenges

The challenge of managing agricultural plastic waste has emerged as a critical environmental and economic issue, reflecting the broader concerns of plastic pollution and sustainability in global agricultural practices. Agricultural plastics, including films, pipes, containers, and netting, play essential roles in enhancing food production, protecting crops, and improving water efficiency. However, the end-of-life disposal and recycling of these materials pose significant challenges, with implications for energy consumption and environmental sustainability (Briassoulis et al., 2012; Maraveas, 2020).

The concept of recycling agricultural plastic waste encompasses not just the reclamation of materials but also the critical analysis of energy balance and sustainability outcomes. As the global community moves towards circular economy models, the recycling of agricultural plastics has garnered attention for its potential to reduce environmental impacts, conserve resources, and improve energy efficiency (Eygen et al., 2018; Geyer et al., 2017). Energy balance, in particular, plays a pivotal role in evaluating recycling processes, where the energy consumed in recycling should be optimized against the energy saved by diverting plastics from landfills and reducing the need for virgin material production (Radjabov & Nabiev, 2020; Shan, Pandyaswargo, and Onoda, 2023).

The urgency of this issue is underscored by the increasing volume of plastic waste generated from agricultural activities and the limited adoption of sustainable recycling practices. Studies have highlighted the complex interplay between the quality of recycled materials, the efficiency of recycling processes, and the overall sustainability of using recycled plastics in agricultural applications (Briassoulis et al., 2012; Gu et al., 2017). Moreover, the environmental impact of plastic waste, including greenhouse gas emissions, soil and water pollution, and the loss of biodiversity, necessitates a rigorous and holistic approach to recycling that integrates considerations of energy balance and sustainability (Geyer et al., 2017; Eygen et al., 2018).

2.2. Scope Of The Literature Review

In this context, the literature review aims to explore the current state of knowledge regarding the recycling of agricultural plastics, with a focus on energy balance analysis and sustainability implications. By examining mechanical and chemical recycling technologies, the quality and application of recycled materials, and the environmental and economic impacts of recycling processes, this review will contribute to a deeper understanding of the challenges and opportunities in sustainable agricultural plastic management.

2.3. Escalation Of Agricultural Plastic Waste

The escalation of agricultural plastic waste is a mounting concern, reflecting a broader challenge within the global framework of waste management and sustainability. The pervasive use of plastics in agriculture, ranging from mulch films to irrigation pipes and greenhouse coverings, has significantly contributed to the efficiency and productivity of modern farming practices. However, this dependency on plastic materials has led to an exponential increase in agricultural plastic waste, compounding the environmental burden faced by communities worldwide (Geyer et al., 2017).

Geyer et al. (2017) provide a comprehensive analysis of the production, use, and fate of all plastics ever made, illuminating the stark reality of plastic waste proliferation. Their research underscores a critical need for systemic changes in how plastic products are designed, used, and recycled, emphasizing the agricultural sector as a significant contributor to plastic waste. This study reveals that without effective recycling methods and strategies for waste reduction, the environmental, economic, and social costs of plastic waste will continue to escalate.

2.4. Circular Economy And Integrated Waste Management Strategies

Echoing these concerns, Eygen et al. (2018) delve into the circular economy of plastic packaging, presenting current practices and perspectives within the European context. Their findings highlight the specific challenges associated with agricultural plastic waste, notably its collection, sorting, and recycling. The study points to the necessity for efficient recycling methods that not only mitigate the environmental impacts of plastic waste but also preserve the energy used to produce these materials. Eygen et al. advocate for integrated waste management strategies that prioritize recycling, alongside reducing plastic use and enhancing product design for recyclability.

The increasing accumulation of agricultural plastic waste, coupled with the urgent need for efficient recycling methods, calls for a multifaceted approach that encompasses technological innovation, policy intervention, and shifts in consumer behavior. The insights from Geyer et al. (2017) and Eygen et al. (2018) underscore the complexity of the challenge, yet also illuminate pathways toward more sustainable agricultural practices that can reconcile the demands of productivity with environmental stewardship.

2.5. The Global Trajectory Of Plastic Production

The global trajectory of plastic production has shown a relentless upward trend, with significant implications for waste management and environmental sustainability. As Geyer et al. (2017) meticulously document, the total production of plastics has surpassed most other man-made materials, dwarfing the production rates of steel and other metals by a considerable margin. This exponential increase in plastic production, from 2 million metric tons in 1950 to 380 million metric tons by 2015, highlights not only the material's ubiquity in modern life but also the burgeoning challenge of its disposal and recycling.

In the realm of agriculture, the use of plastics has become integral to various farming practices, offering benefits such as increased crop yields, improved water efficiency, and enhanced product longevity. Agricultural applications of plastics span a wide range, including greenhouse coverings, mulch films, irrigation pipes, and storage bags, all of which contribute to the sector's plastic footprint. The versatility and durability of plastics, while advantageous for agricultural productivity, pose significant challenges when these materials reach the end of their useful life.

Waste management of agricultural plastics presents unique challenges, exacerbated by the materials' diverse types and the diffuse nature of agricultural operations. The specialized plastics used in agriculture, often designed for durability and resistance to environmental stressors, can be difficult to recycle through conventional mechanical processes. Additionally, the geographic dispersion of agricultural plastic waste, combined with contamination from soil and organic matter, complicates collection and recycling efforts.

Table 2.1. Common Polymers Used in Agricultural Applications

Polymer	Agricultural Application	Key Properties	Key References
Polyethylene (PE)	Mulch films, irrigation pipes, greenhouse covers	High flexibility, chemical resistance, lightweight	Geyer et al. (2017); Briassoulis et al. (2012)
Polypropylene (PP)	Woven bags, storage containers, twine	High tensile strength, durability, low density	Maraveas (2020)
Polyvinyl Chloride (PVC)	Irrigation pipes, greenhouse films	Rigidity, weather resistance, long lifespan	Shan, Pandyaswargo, & Onoda (2023)
Polystyrene (PS)	Seed trays, plant containers	Lightweight, thermal insulation	Vollmer et al. (2020)
Polycarbonate (PC)	Greenhouse panels	High impact resistance, transparency, UV stability	Hopewell, Dvorak, & Kosior (2009)
Ethylene Vinyl Acetate (EVA)	Greenhouse covers, flexible sheets	High elasticity, UV resistance	Maraveas (2020)
Polyamide (Nylon)	Netting, ropes, agricultural textiles	High mechanical strength, abrasion resistance	Briassoulis et al. (2012)
High-Density Polyethylene (HDPE)	Drip irrigation tubes, tanks	Strength, durability, chemical resistance	Geyer et al. (2017); Maraveas (2020)
Low-Density Polyethylene (LDPE)	Plastic sheeting, silage bags	Flexibility, transparency, lightweight	Hopewell, Dvorak, & Kosior (2009)

This table highlights the diverse applications of polymers in agriculture, underscoring their importance in modern farming practices. However, it also illustrates the variety of polymer types, each requiring specific handling and recycling approaches due to their distinct physical and chemical properties.

Geyer et al. (2017) emphasize that the fate of plastics after their use—whether through recycling, incineration, or landfilling—has profound environmental implications. Unfortunately, a significant portion of plastic waste is not recycled but ends up in landfills or, worse, dispersed in the environment. This reality underscores the urgency of developing more effective waste management and recycling strategies, particularly for the agricultural sector, where the potential for waste reduction and resource recovery remains largely untapped.

The current state of plastic production, usage, and waste management underscores a global dependency on plastic materials, juxtaposed against the critical need for sustainable practices. In agriculture, the challenge is twofold: maximizing the benefits of plastic usage for food production while mitigating the environmental impacts of plastic waste. Addressing this challenge requires a concerted effort to improve recycling technologies, develop biodegradable alternatives, and implement comprehensive waste management policies tailored to the unique needs of the agricultural sector.

Table 2.2. General Plastic Recycling Technologies

Recycling Technology	Description	Advantages	Limitations	Key References
Mechanical Recycling	Physical processes like shredding, washing, and melting plastics to create new products	Low cost, widely implemented	Quality degradation with repeated cycles	Hopewell, Dvorak, & Kosior (2009)
Chemical Recycling	Breaks down polymers into monomers or other chemical feedstocks for reuse	Can handle contaminated or mixed plastics	High energy consumption, costly infrastructure	Shan, Pandyaswargo, & Onoda (2023)
Energy Recovery	Converts plastic waste into energy via incineration or pyrolysis	Reduces landfill waste, produces energy	High greenhouse gas emissions, loss of material reuse potential	Radjabov & Nabiev (2020)
Biological Recycling	Utilizes microorganisms to degrade plastics into simpler compounds	Environmentally friendly, supports circular economy	Limited to specific bioplastics, slow process	Maraveas (2020)
Solvent-Based Recycling	Dissolves polymers to separate impurities and recover the material	Maintains polymer quality, useful for mixed plastics	Requires specific solvents, can be energy-intensive	Vollmer et al. (2020); Thiounn & Smith (2020)

Table 2 summarizes the general technologies employed for plastic recycling, each with distinct benefits and limitations. These technologies offer diverse pathways to address the growing challenge of plastic waste management, underscoring the need for tailored solutions based on specific application requirements and environmental considerations.

2.6. Energy Balance In Recycling Processes

The concept of energy balance plays a crucial role in evaluating the sustainability and efficiency of recycling processes. It involves analyzing the energy inputs required to recycle materials against the energy input required to produce new products. The difference is the energy saved by avoiding the production of new materials. Recycling also has indirect benefits such as reducing waste sent to landfills and the pollution thus generated. This analysis helps in understanding the net energy benefits of recycling and is essential for developing environmentally sustainable recycling practices.

Radjabov & Nabiev (2020) explore the significance of energy efficiency and renewable energy sources within the agricultural sector, shedding light on the broader implications for recycling processes. Their study emphasizes the potential of recycling not just as a waste management strategy but as a means to enhance energy efficiency within agriculture. In their study on energy efficiency in agriculture, Radjabov and Nabiev (2020) examine the energy consumption patterns and potential savings associated with recycling agricultural plastics, highlighting the critical intersection between recycling practices and energy sustainability.

In their analysis, Radjabov & Nabiev (2020) compared the energy requirements for recycling agricultural plastic waste with the energy needed for virgin material production:

Energy Input for Recycling: Recycling agricultural plastics required approximately **1.5-2 MJ/kg** of energy, depending on the specific recycling technology used (e.g., mechanical vs. chemical recycling).

Energy Input for Virgin Production: The production of new plastics such as polyethylene and polypropylene required significantly higher energy inputs, averaging around **8-10 MJ/kg** for virgin material production.

Energy Savings: Recycling resulted in an energy savings of **75-85%** compared to producing virgin plastics. For example, recycling 1 ton of agricultural plastic waste saved approximately **6-8 GJ** of energy.

Carbon Emission Reductions: Recycling 1 ton of agricultural plastic waste avoided approximately **2.5-3 tons of CO_2 emissions**, showcasing the environmental benefits alongside energy savings.

These findings demonstrate the substantial energy efficiency and environmental advantages of recycling agricultural plastics. By integrating renewable energy sources into recycling processes, further reductions in energy consumption and greenhouse gas emissions can be achieved, aligning agricultural waste management practices with broader sustainability goals.

2.7. Advanced Technologies In Recycling Processes

In the context of recycling agricultural plastic waste, the energy balance analysis considers various factors, including the energy required to collect, sort, clean, and process the waste into new products, versus the energy conserved by displacing virgin material production and reducing greenhouse gas emissions from waste decomposition. This analysis is particularly relevant for agricultural plastics, where the energy-intensive nature of conventional plastic production can be offset by effective recycling methods.

Radjabov & Nabiev's (2020) insights into energy efficiency underscore the importance of incorporating renewable energy sources and innovative technologies in the recycling process to minimize energy consumption and enhance the overall energy balance. For instance, employing solar energy or biomass to power recycling operations could significantly reduce the carbon footprint of recycling agricultural plastics, aligning waste management practices with broader environmental sustainability goals.

Pyrolysis for Plastic-to-Fuel Conversion: This advanced chemical recycling process involves heating plastics in an oxygen-free environment to produce fuels like diesel and syngas. Pyrolysis is particularly effective for contaminated or mixed plastics that are unsuitable for mechanical recycling (Liu et al., 2020).

Hydrothermal Liquefaction: A cutting-edge technique where water at high temperatures and pressures breaks down plastic waste into bio-oils and chemicals. This method is environmentally friendly and can handle mixed plastic streams (Achilias et al., 2007).

Enzymatic Degradation: Biological recycling processes use engineered enzymes to break down polymers like PET into their monomers, allowing them to be reused in high-quality applications. This approach is promising for its low energy requirements and specificity (Maraveas, 2020).

Solvent-Based Purification: Solvent-based recycling dissolves polymers to remove contaminants and impurities, preserving the polymer's properties for reuse. This method is particularly beneficial for high-quality applications requiring minimal degradation (Vollmer et al., 2020).

AI-Driven Sorting Systems: Advanced sorting technologies powered by artificial intelligence (AI) use spectral analysis and machine learning to efficiently separate plastics by type and color, significantly improving recycling rates and reducing contamination (Hopewell, Dvorak, & Kosior, 2009).

These innovative technologies demonstrate how the integration of advanced methods can improve energy efficiency and contribute to environmental sustainability.

The exploration of energy balance within recycling processes highlights a pivotal aspect of sustainable materials management. By prioritizing energy efficiency and integrating renewable energy sources, the agricultural sector can advance towards more sustainable recycling practices, contributing to the global efforts in environmental conservation and resource optimization.

2.8. Methods Of Plastic Recycling

The recycling of plastics can be approached through various methods, notably mechanical and chemical recycling, each with distinct energy profiles and sustainability implications. Understanding the energy consumption associated with these recycling processes is crucial for optimizing recycling practices and enhancing their environmental sustainability.

Definition And Process Mechanical recycling involves physical processes such as grinding, washing, melting, and re-forming plastic waste into new products. This method is widely used for recycling common types of plastic waste, including agricultural plastics, due to its relative simplicity and lower energy requirements compared to chemical recycling. Shan, Pandyaswargo, and Onoda (2023) highlight the efficiency of mechanical recycling in terms of energy use, pointing out that it conserves more energy by bypassing the need for producing virgin plastic materials from scratch. The energy savings are primarily attributed to the avoidance of the extensive polymerization processes required for new plastic production.

Table 2.3. Energy Use In Mechanical Recycling Of Various Plastics

Plastic Type	Energy Required (MJ/kg)	Notes
Polyethylene (PE)	1.5 - 2.0	Commonly used for mulch films and greenhouse coverings. Lower energy due to simple melting processes.
Polypropylene (PP)	1.8 - 2.5	Slightly higher energy due to its higher melting point. Used in containers and irrigation systems.
Polyvinyl Chloride (PVC)	2.5 - 3.0	Requires additional processing to handle contaminants and additives.
Polystyrene (PS)	1.2 - 1.6	Lightweight and easy to melt; typically used in seed trays and containers.
High-Density Polyethylene (HDPE)	1.6 - 2.2	Common in irrigation pipes and tanks; energy varies based on purity and contamination levels.
Low-Density Polyethylene (LDPE)	1.3 - 1.8	Similar to PE but slightly more flexible, leading to lower melting energy.

This table illustrates the relative energy requirements for mechanical recycling of various plastics. The energy used depends on the type of plastic, its purity, and contamination levels. These insights highlight the importance of efficient sorting and cleaning processes to enhance energy efficiency in mechanical recycling.

The energy efficiency of mechanical recycling can be affected by factors such as the cleanliness of the waste stream, the type of plastic being recycled, and the specific technologies used in the recycling process. Briassoulis et al. (2012) conduct a comprehensive analysis of the quality characteristics of agricultural plastic wastes, emphasizing their recycling and energy recovery potential. This study highlights the feasibility of mechanically recycling agricultural plastics by identifying the material properties that influence recyclability, such as polymer type, contamination level, and degradation. The findings suggest that certain types of agricultural plastics, especially those with lower levels of contamination and degradation, are more suitable for mechanical recycling, showcasing the method’s potential for converting waste into valuable resources.

In a subsequent study, Briassoulis et al. (2013) delve deeper into the technical specifications required for the mechanical recycling of agricultural plastic waste. This research outlines the processing challenges and proposes solutions for overcoming them, such as advanced sorting and cleaning technologies. By addressing these technical aspects, the study reinforces the feasibility of mechanical recycling as a viable option for managing agricultural plastic waste, highlighting its potential for reducing reliance on virgin materials and minimizing environmental impacts.

Kreiger et al. (2013) explore the distributed recycling of post-consumer plastic waste in rural areas, presenting a model for decentralized mechanical recycling. This approach not only proves feasible but also enhances the energy efficiency of recycling by reducing transportation energy costs associated with centralized facilities. The study demonstrates how localized recycling initiatives can contribute to sustainable agricultural practices by effectively managing waste on-site and reducing the carbon footprint of recycling operations.

Further extending their research, Kreiger et al. (2014) conduct a life cycle analysis of distributed recycling of post-consumer high-density polyethylene (HDPE) for 3-D printing filament. The findings emphasize the energy efficiency of mechanical recycling processes, highlighting the significant energy savings achieved by avoiding the production of virgin plastics. This study underscores the environmental benefits of mechanical recycling, particularly in terms of reduced energy consumption and greenhouse gas emissions.

Chemical recycling, on the other hand, involves breaking down plastic polymers into their monomers or other chemicals, which can then be used to produce new plastics or other products. This process can handle a broader range of plastic types, including those not suitable for mechanical recycling, and can potentially produce higher-quality recycled materials.

Chemical recycling is typically more energy-intensive, requiring significant energy input for the chemical reactions that break down polymer chains. Shan, Pandyaswargo, and Onoda (2023) and related studies note that while chemical recycling offers the advantage of versatility and the potential for higher quality outputs, its higher energy consumption poses challenges for energy balance and sustainability. The energy demand of chemical recycling processes, such as pyrolysis or gasification, must be carefully managed and ideally sourced from renewable energy to mitigate environmental impacts.

Despite its energy intensity, chemical recycling holds promise for addressing the limitations of mechanical recycling, particularly for mixed or heavily contaminated plastic waste. Integrating renewable energy sources into chemical recycling processes can significantly reduce its carbon footprint and enhance overall sustainability. By leveraging advanced technologies and renewable energy, chemical recycling can complement mechanical recycling, contributing to a more comprehensive approach to managing agricultural plastic waste.

Table 2.4. Energy Use in Chemical Recycling Processes

Recycling Process	Energy Required (MJ/kg)	Description
Pyrolysis	10 - 14	Converts plastics into fuels or chemical feedstocks through thermal decomposition in the absence of oxygen.
Gasification	12 - 16	Breaks down plastics into syngas (CO and H_2) at high temperatures in controlled oxygen environments.
Depolymerization	8 - 12	Converts specific plastics, such as PET, back into their monomers for high-quality recycling.
Solvolysis	6 - 10	Uses solvents to break down polymers into smaller molecules. Energy usage varies based on solvent type and process efficiency.
Hydrothermal Liquefaction	15 - 20	Utilizes water at high pressure and temperature to convert plastics into bio-oils and chemicals.

This table provides a quantitative comparison of the energy requirements for various chemical recycling processes. While chemical recycling enables the processing of mixed or contaminated plastics, its energy intensity underscores the importance of improving process efficiency and integrating renewable energy sources to achieve sustainability goals.

Liu et al. (2020) investigate the pyrolysis kinetics and thermodynamics of typical plastic waste, including materials commonly found in agricultural settings. Pyrolysis, a process that decomposes organic material at high temperatures in the absence of oxygen, is highlighted as a viable method for converting agricultural plastic waste into valuable products, such as bio-oil, syngas, and char. Liu et al.'s study emphasizes the efficiency of pyrolysis in handling plastics that are difficult to recycle mechanically due to contamination or degradation. The research underscores the potential of pyrolysis to contribute significantly to the energy recovery from agricultural plastic waste, turning a waste management challenge into an opportunity for energy production.

Achilias et al. (2007, 2009) explore the chemical recycling of plastics, focusing on the processes that involve the dissolution-reprecipitation technique and the depolymerization of polyethylene (LDPE and HDPE) and polypropylene (PP). Chemical recycling, as discussed in their studies, involves breaking down polymer chains into their monomers or other useful chemicals, which can then be repurposed for creating new polymers or as feedstock for other industrial processes. Achilias et al. demonstrate that chemical recycling can effectively manage plastic waste, including agricultural plastics, by converting them into valuable resources. Furthermore, their research highlights the potential for chemical recycling to achieve higher purity in the recovered materials, thus offering an alternative route for plastics deemed unsuitable for mechanical recycling.

The role of chemical recycling and pyrolysis in managing agricultural plastic waste is multifaceted:

Expansion of Recyclable Materials: Advanced technologies provide solutions for plastics that are typically challenging to recycle mechanically.

Contribution to Circular Economy: By converting waste into energy and other valuable products, these processes enhance resource recovery and reduce environmental impact.

Complementary Methods: Chemical recycling and pyrolysis can complement mechanical recycling efforts, creating a comprehensive waste management strategy that maximizes sustainability.

2.9. Comparative Analysis Of Recycling Methods

The comparison between mechanical and chemical recycling processes underscores a trade-off between energy efficiency and the quality or versatility of recycled materials. While mechanical recycling is generally less energy-intensive and more straightforward, its applicability is limited by the type of plastic and contamination levels. Chemical recycling, despite its higher energy demand, provides a pathway for recycling more diverse and contaminated plastic streams, offering a potential solution for plastics that are difficult to recycle mechanically.

2.10. Recycling Agricultural Plastics

In the context of agricultural plastics, which often suffer from high levels of soil and organic matter contamination, the choice between mechanical and chemical recycling methods depends on balancing the energy consumption with the desired outcomes in terms of material quality and environmental sustainability. Advances in recycling technologies and the integration of renewable energy sources into recycling operations are critical for improving the energy balance of both mechanical and chemical recycling processes.

Kijo-Kleczkowska & Gnatowski (2022) delve into the recycling of plastic waste with a specific focus on thermal methods, which encompass both pyrolysis and chemical recycling processes. Their research evaluates the energy inputs required for these recycling methods compared to the energy outputs, including the calorific value of the products generated (e.g., bio-oil, syngas) and the energy savings from not producing new plastics from virgin materials. The study highlights that, while advanced recycling technologies often require significant energy inputs, the net energy balance can be positive. This is due to the high energy content of the products generated and the reduction in energy consumption and greenhouse gas emissions compared to traditional plastic production processes.

Chen et al. (2021) explore the concept of "Waste to Wealth" by examining chemical recycling and chemical upcycling of waste plastics. Their analysis includes an assessment of the energy balance of converting waste plastics into valuable chemicals and materials through chemical recycling processes. Chen et al. argue that chemical recycling, when efficiently executed, can lead to a favorable energy balance by providing energy-rich products and reducing the reliance on fossil fuels for new plastic production. Moreover, their study underscores the potential of chemical recycling to contribute to a circular economy by closing the loop of plastic use and production, thus enhancing overall sustainability.

The implications of these findings for agricultural plastic waste management are significant:

Informed Decision-Making: Understanding the energy balance of advanced recycling technologies aids stakeholders in evaluating investments and implementation.

Environmental Benefits: Reduced greenhouse gas emissions and minimized environmental footprints align with global sustainability goals.

Circular Economic Models: Advanced recycling technologies support circular economy initiatives, where waste materials are redefined as valuable resources.

2.11. Lifecycle Assessments And Recycling Processes

Chen et al. (2020) delve into the hybrid life cycle assessment of potato pulp valorisation in biocomposite production. This study exemplifies the intricate balance between energy inputs and outputs in recycling processes. Chen and colleagues’ work underscores the importance of considering the entire lifecycle of recycled materials, from collection and processing to the final product stage.

Their findings reveal that using agricultural waste as a feedstock for biocomposite materials can significantly reduce energy consumption and environmental impacts compared to conventional materials. The research highlights the potential energy savings and reduced greenhouse gas emissions associated with recycling and valorizing agricultural waste, demonstrating the broader implications of effective waste management strategies on sustainability.

Gu et al. (2017) investigate the life cycle assessment of mechanical plastic recycling, specifically focusing on the recycling of waste plastics into industrial raw materials. This study provides a detailed analysis of energy consumption across different stages of the mechanical recycling process, including collection, sorting, cleaning, and reprocessing. Gu and colleagues present a compelling case for the environmental benefits of mechanical recycling, showcasing substantial energy savings and a decrease in carbon footprint compared to the production of virgin plastics. Their research emphasizes the critical role of energy efficiency in enhancing the sustainability of recycling processes, highlighting how mechanical recycling can serve as a viable strategy for reducing energy consumption and mitigating environmental impacts.

The lifecycle assessments conducted by Chen et al. (2020) and Gu et al. (2017) illuminate the complex interplay between energy inputs and outputs in recycling processes. These studies underscore the necessity of a holistic approach to assessing the environmental performance of recycling, taking into account not only the energy required to recycle materials but also the energy saved by displacing the production of new, virgin materials. The insights derived from such assessments are crucial for informing policy, guiding sustainable practices, and optimizing recycling processes to maximize energy efficiency and minimize environmental impacts.

By evaluating the lifecycle of recycling processes, from energy consumption to environmental outcomes, these studies contribute to a deeper understanding of the sustainability credentials of recycling. They demonstrate how lifecycle assessment can serve as a powerful tool for identifying opportunities to improve energy efficiency, reduce carbon emissions, and advance toward a more sustainable circular economy.

The insights derived from LCAs, as demonstrated by Chen et al. and Gu et al., have significant implications for environmental policy and industrial practices:

Policy Development: Governments and regulatory bodies can use LCA findings to craft policies that promote the recycling of agricultural plastics and the utilization of waste as a resource. This might include tax incentives for companies that use recycled materials, subsidies for recycling infrastructure, and regulations that mandate the recyclability of agricultural products.

LCA results can inform the development of industry standards for sustainability, encouraging manufacturers to adopt practices that minimize environmental impacts. This includes designing products for easier recycling, using recycled materials, and investing in technologies that reduce energy use and emissions.

Educating consumers about the environmental benefits of products made from recycled materials can drive market demand for such products, further incentivizing companies to adopt sustainable practices.

The identification of environmental hotspots and areas for improvement through LCAs can guide research and development efforts, focusing on innovations that enhance the sustainability of recycling processes and agricultural practices.

The collective research of Briassoulis et al. and Kreiger et al. underscores the environmental advantages of mechanical recycling of agricultural plastic waste. By focusing on the energy efficiency and feasibility of mechanical recycling, these studies contribute to a better understanding of its role in promoting sustainability within the agricultural sector. The environmental benefits, including reduced energy consumption, lower greenhouse gas emissions, and conservation of natural resources, position mechanical recycling as a key component of sustainable waste management strategies.

The economic implications of recycling agricultural plastics are multifaceted. On one hand, the development and operation of recycling facilities create job opportunities and generate economic activity. On the other hand, the availability of recycled plastics as a resource for new products can reduce material costs and stimulate innovation in the development of sustainable agricultural technologies. Studies by Briassoulis et al.

(2012) and Scarascia-Mugnozza et al. emphasize the potential cost savings from reduced landfill use and the valorization of waste as a resource.

Moreover, the energy recovery from agricultural plastics not only provides an additional revenue stream but also contributes to energy security by supplementing traditional energy sources. The sustainability benefits, including the reduction of greenhouse gas emissions and the conservation of natural resources, further enhance the economic viability of recycling agricultural plastics by aligning with global trends towards sustainability and environmental stewardship.

Table 2.5. Impacts of Agricultural Plastic Waste (APW) Recycling on Environment and Economy

Impact Area	Specific Impacts
Environmental Impacts	- Reduction of greenhouse gas emissions - Decrease in landfill waste - Conservation of natural resources - Prevention of soil and water pollution - Supports circular economy through material reuse
Economic Impacts	- Job creation in recycling facilities - Cost savings by reducing reliance on virgin materials - Revenue generation through energy recovery - Reduction in landfill management costs - Promotion of innovation in sustainable technologies

This table highlights the dual benefits of APW recycling in terms of environmental protection and economic growth, emphasizing its role in fostering a more sustainable and circular agricultural economy.

2.12. Innovations In Mechanical Recycling Technologies

Cadena et al. (2021) delve into the technical possibilities for recycling plastics from agribusiness, showcasing innovations that streamline the mechanical recycling process. Their research emphasizes the development of new machinery and processes designed to improve the efficiency of sorting, cleaning, and reprocessing agricultural plastic waste. One notable innovation includes advanced sorting technologies that leverage optical and spectral analysis to distinguish between different types of plastics quickly and accurately. This improvement is critical for enhancing the purity of recycled materials, thus reducing energy consumption in subsequent processing steps. Additionally, Cadena et al. highlight innovations in size reduction and cleaning processes that minimize energy use while maximizing the removal of contaminants from plastic waste, further contributing to the efficiency and sustainability of the recycling process.

Picuno (2014) presents innovative material and improved technical design for the sustainable exploitation of agricultural plastic film. Picuno’s work focuses on the development of agricultural plastic films with enhanced recyclability features, such as ease of degradation and compatibility with mechanical recycling processes. These innovations not only facilitate the mechanical recycling of agricultural plastics but also reduce the energy required to transform these plastics into new products. The study suggests that by integrating design for recyclability principles in the production of agricultural plastics, it is possible to significantly improve the energy efficiency of the recycling process. This approach underscores the importance of considering the entire lifecycle of agricultural plastics, from production and use to recycling and disposal.

The innovations highlighted by Cadena et al. (2021) and Picuno (2014) have profound implications for the energy efficiency of mechanical recycling. By improving the sorting and cleaning processes, these advancements reduce the energy needed to prepare plastic waste for reprocessing, thereby lowering the overall energy consumption of the recycling process. Furthermore, the development of agricultural plastics designed for easier recycling translates into less energy-intensive reprocessing, as these materials can be recycled with minimal modifications and energy use.

These technological innovations not only enhance the energy efficiency of mechanical recycling but also contribute to the broader sustainability goals of reducing greenhouse gas emissions and conserving natural resources. By advancing the capabilities of mechanical recycling, these studies pave the way for more sustainable agricultural practices and the circular economy, where materials are kept in use for as long as possible, extracting their maximum value before recovery and regeneration.

2.13. Performance Of Recycled Materials In Agricultural Applications

Pluimer et al. (2015) focus on the evaluation of corrugated high-density polyethylene (HDPE) pipes manufactured with recycled content. Their research addresses critical aspects such as the material quality and the pipes' performance under various environmental conditions. One of the key findings is that pipes made from recycled HDPE can meet or even exceed the performance standards of pipes made from virgin materials, especially in terms of durability and resistance to environmental stressors. Pluimer and colleagues' study also discusses the energy savings associated with using recycled materials, highlighting the reduced energy consumption in the manufacturing process compared to the production of new plastic pipes.

Table 2.6. Types of Plastics Used in Agricultural Pipe Production

Plastic Type	Key Properties	Typical Applications in Agriculture
High-Density Polyethylene (HDPE)	High strength, durability, chemical resistance	Drip irrigation pipes, corrugated drainage pipes
Polyvinyl Chloride (PVC)	Rigidity, long lifespan, resistance to weathering	Mainline irrigation pipes, underground pipelines
Polypropylene (PP)	High tensile strength, lightweight, resistance to heat	Micro-irrigation tubes, pressure pipes
Low-Density Polyethylene (LDPE)	Flexibility, transparency, lightweight	Flexible irrigation tubing, lateral pipes
Ethylene Vinyl Acetate (EVA)	Elasticity, UV resistance, flexibility	Specialty flexible pipes for greenhouse irrigation
Recycled HDPE	Comparable strength to virgin HDPE, eco-friendly	Recycled-content corrugated drainage pipes

This table outlines the primary types of plastics used in agricultural pipe production, highlighting their properties and typical applications. The inclusion of recycled HDPE emphasizes the potential for sustainable materials to match or exceed the performance of virgin plastics, aligning with energy-saving and environmental goals.

Baumann (1998) earlier explored the potential of using recycled plastics for pipe production, specifically focusing on plastic pipes made of recycled materials. Baumann's work underlines the viability of recycling plastic waste into high-quality, durable materials for agricultural applications. The study points out that recycled plastic pipes can offer comparable, if not superior, physical properties, including flexibility, resistance to chemical corrosion, and longevity. Additionally, Baumann addresses the positive energy balance achieved by repurposing plastic waste into valuable agricultural infrastructure, which contributes to reducing the overall environmental impact of both plastic waste management and agricultural practices.

The utilization of recycled plastics in the production of agricultural pipes offers several benefits. Firstly, it promotes the circular economy concept by giving a new life to plastic waste, thus reducing the need for virgin plastic materials and the environmental degradation associated with plastic production and disposal. Secondly, the energy savings from using recycled materials contribute to lowering the carbon footprint of agricultural operations, aligning with global sustainability targets.

Moreover, the adoption of recycled plastic pipes in agriculture can lead to long-term cost savings for farmers and agricultural enterprises due to the durability and low maintenance requirements of these materials. This, combined with the environmental benefits, makes the use of recycled plastics in agricultural pipe production a compelling case for sustainability and efficiency.

Picuno (2014) investigates the innovative material and improved technical design for a sustainable exploitation of agricultural plastic film. One of the main challenges highlighted is the degradation of plastic quality due to repeated recycling processes, which can affect the mechanical properties of the resulting materials. This degradation can lead to reduced strength, flexibility, and increased brittleness, making the recycled plastic less suitable for certain agricultural applications where durability and resistance to environmental stressors are critical. Picuno suggests that the incorporation of compatibilizers, additives that improve the interfacial adhesion between different types of plastics, can mitigate this issue, enhancing the mechanical properties and longevity of recycled plastic products.

Maraveas (2020) addresses the environmental sustainability of plastic in agriculture, focusing on the technical challenges of recycling agricultural plastics, such as mulch films, drip tapes, and greenhouse coverings. The heterogeneous nature of agricultural plastic waste, which often contains a mix of different types of plastics, soil, and organic residues, complicates the recycling process. Maraveas discusses the importance of efficient sorting and cleaning processes to improve the quality of the recycled material. Additionally, the study points to the development of biodegradable agricultural plastics as a complementary solution to traditional recycling, aiming to reduce plastic waste generation in the first place.

2.14. Strategies To Enhance Recycling Efficiency

Both Picuno and Maraveas emphasize the importance of technological innovation and improved recycling methodologies to overcome the challenges associated with using recycled plastics in agriculture. These include:

Advanced Sorting and Cleaning Technologies: Implementing sophisticated sorting technologies, such as near-infrared (NIR) spectroscopy, and enhanced washing processes can significantly improve the purity and quality of recycled plastics, making them more suitable for agricultural applications.

Compatibilization and Material Engineering: The use of compatibilizers and the development of composite materials that combine recycled plastics with other materials (e.g., natural fibers) can enhance the mechanical and physical properties of recycled products.

Biodegradable Alternatives: Research and development of biodegradable plastics specifically designed for agricultural use can provide an alternative route, reducing reliance on recycling and addressing the issue of plastic waste from the outset.

Design for Recycling: Encouraging the design of agricultural plastic products with recycling in mind can simplify the recycling process and improve the quality of recycled materials. This includes minimizing the use of additives and designing for easy disassembly and separation of different plastic types.

Vollmer et al. (2020) explore the prospects of moving beyond mechanical recycling, delving into advanced techniques that can give new life to plastic waste. Their research focuses on chemical recycling methods, such as pyrolysis and gasification, and newer methodologies like solvent-based recycling, which can break down plastics into their molecular components. These technologies not only promise to tackle the issue of mixed and contaminated plastics that are challenging to recycle mechanically but also offer the potential to recover high-quality materials that can be used to produce new plastics with properties equivalent to those made from virgin materials. Additionally, Vollmer et al. highlight the potential for these technologies to improve the energy efficiency of the recycling process, thereby reducing the overall environmental impact.

2.15. Fundamentals Of Heat Exchangers

Heat exchangers are vital components in waste heat recovery systems (WHRS), enabling the efficient transfer of thermal energy from one medium to another. Their design, classification, and operation are central to improving energy efficiency, reducing operational costs, and promoting sustainability in industrial processes. This section explores the fundamentals, classifications, and applications of heat exchangers in WHRS, drawing insights from leading references.

Heat exchangers function by transferring heat between two or more fluids without mixing them, leveraging the principles of conduction and convection. Key parameters in heat exchanger design include heat transfer area, temperature gradients, and flow configurations. The overall heat transfer rate (Q) is described by the equation:

$Q=U \cdot A \cdot \Delta Tm$

Where:

U: Overall heat transfer coefficient ($W/m^2 \cdot K$)

A: Heat transfer area (m^2)

ΔTm: Log mean temperature difference (K)

Optimizing these parameters ensures maximum efficiency and minimal energy losses, as detailed by Shah and Sekulic in *Fundamentals of Heat Exchanger Design* (2003).

Furthermore, the U.S. Department of Energy highlights that modern heat exchangers integrate advanced materials, such as aluminum alloys and composite metals, to enhance thermal conductivity while reducing weight and corrosion risks (*Heat Exchanger Fundamentals*, 2000). These innovations address challenges in high-temperature and corrosive environments commonly encountered in industrial WHRS.

Heat exchangers are classified based on their configuration, flow arrangement, and heat transfer mechanism:

By Configuration:

Shell-and-Tube: Consists of tubes enclosed within a shell, suitable for high-pressure and temperature applications (Kakaç et al., 2012).

Plate: Composed of thin, corrugated plates stacked to create parallel channels, offering high thermal efficiency and compactness (*Heat Exchangers: Classification, Selection, and Thermal Design*, Shah & Sekulic, 2003).

Air-Cooled: Utilizes air as the cooling medium, commonly used in environments with limited water resources (Polley, 2005).

By Flow Arrangement:

Parallel Flow: Fluids flow in the same direction, resulting in smaller temperature gradients.

Counterflow: Fluids flow in opposite directions, maximizing ΔTm often achieving 15–20% higher efficiency than parallel flow (*Waste Heat Recovery: Technology and Opportunities in U.S. Industry*, BCS, Inc., 2008).

Crossflow: Fluids flow perpendicularly, commonly used in compact exchangers like automotive radiators.

By Heat Transfer Mechanism:

Recuperative: Direct heat exchange through solid barriers, widely applicable in industrial settings.

Regenerative: Alternating heat storage and transfer in a matrix, ideal for gas turbines and high-temperature processes (Polley, 2005).

WHRS employ heat exchangers to recover low- to medium-grade waste heat, converting it into useful energy. Applications include:

Preheating Feedstock: Waste heat preheats raw materials, reducing energy demands in subsequent processing stages (Kakaç et al., 2012).

Energy Conversion: Heat exchangers in cogeneration systems convert waste heat into electricity or mechanical energy, demonstrating significant efficiency improvements (*Waste Heat Recovery Methods and Technologies*, Polley, 2005).

The effectiveness of a heat exchanger in WHRS is determined by its efficiency (η\etaη):

η=Qrecovered/Qavailable

BCS, Inc. (2008) reports that advanced WHRS can achieve efficiencies of up to 70%, significantly reducing greenhouse gas emissions and energy costs.

Innovative designs, such as compact plate heat exchangers and regenerative systems, enhance heat recovery efficiency. Polley (2005) discusses the emergence of self-cleaning exchangers to mitigate fouling, a common efficiency barrier. Additionally, Shah and Sekulic (2003) emphasize the role of nanofluids as heat transfer mediums, improving thermal conductivity by 20–50% compared to traditional fluids.

Moreover, the integration of heat exchangers in WHRS aligns with global sustainability goals, minimizing energy wastage and reducing carbon footprints. The U.S. Department of Energy (2000) highlights that these systems have saved industries billions in operational costs while significantly reducing emissions.

3. MATERIALS AND METHODS

3.1. Materials

The primary material used in this study is post-consumer nylon bags, collected from urban environments, primarily streets and local waste sources. These bags underwent a preliminary cleaning and washing process to remove contaminants such as dust, oils, and other impurities. After thorough cleaning, the nylon bags were dried and then mechanically shredded using an industrial grinder machine to produce uniform, manageable fragments suitable for the pelletizing process.

The processed nylon fragments served as the main input material for the pelletizing machine during all experimental phases. The consistency in the source and preparation method of the nylon ensured uniformity in the experimental conditions, thereby minimizing variability in material properties that might affect energy consumption and heat transfer analyses.

Figure 3.1. Pelletizing machine used to convert shredded nylon bags into plastic pellets.

3.2. Methods

This study was conducted to analyze the energy balance of a recycling process that converts waste nylon bags into pellets for subsequent use in agricultural pipe production. The focus was on evaluating the thermal efficiency of the pelletizing machine under two conditions: with and without thermal insulation applied to its barrel.

The thermal insulation material applied to the pelletizing machine's heating elements was a fiberglass wool blanket, purchased from a local supplier in Lebanon. The insulation blanket had a thickness of 2 cm and was manufactured from fiberglass wool, commonly used for industrial thermal insulation applications. A total of 2.5 meters in length and 0.5 meters in width of the insulation blanket were used to cover the heating zones of the extruder barrel.

While the specific brand and origin of the material could not be verified, it conforms to the general specifications of industrial-grade fiberglass wool insulation. Typical properties of this material are presented in Table 3.1. Fiberglass wool is highly durable, resistant to moisture, and provides both thermal and acoustic insulation. The insulation blanket was carefully applied to cover the machine's 14 heating elements, significantly reducing heat loss to the surrounding environment and improving energy efficiency during the pelletizing process.

Table 3.1

Physical Properties of Typical Fiberglass Wool Insulation

Property	Value / Range	Reference
Thermal Conductivity (k)	0.032 – 0.040 W/m·K	Asdrubali et al., 2015; Puri et al., 2018
Density	10 – 100 kg/m³	Asdrubali et al., 2015; Puri et al., 2018
Maximum Service Temperature	450 – 550 °C	Asdrubali et al., 2015; IARC, 2002
Fire Resistance Class	Non-combustible (Euroclass A1)	IARC, 2002; Puri et al., 2018

3.2.1. Experimental setup

The main equipment used in this analysis is an industrial pelletizing machine composed of the following main components:

Material Feeding Unit: Receives the shredded nylon material and delivers it into the extruder barrel by the help of gravity for processing.

Extruder Screw: Transports, compresses, and conveys the nylon material through the extruder barrel. As the material moves along the screw, it is progressively heated and melted by external heating elements.

Heating Elements: The extruder barrel is equipped with 14 electric heating elements, which are strategically distributed along its length to ensure uniform melting and processing of the nylon material. These heating elements are controlled through a series of thermostats designed to regulate and maintain precise temperature settings in different heating zones.

Five pairs of heating elements (10 elements in total) are each monitored and controlled by a separate thermostat. One heating element is controlled individually by its own dedicated thermostat. The remaining three heating elements are jointly monitored and controlled by a single thermostat. Each thermostat allows for manual adjustment of the temperature setpoint, ensuring consistent heat distribution along the extruder barrel. During both insulated and non-insulated test conditions, the temperature settings on all thermostats were maintained consistently to provide comparable data and reliable results.

Extruder Nozzle: Shapes the molten nylon material before it exits the machine and enters the pelletizing stage.

Rotating Blades: Located at the extrusion point, these blades cut the continuous extruded material into uniform-sized pellets.

Air Cooling System: After cutting, the pellets are directed into an air cooling system, which rapidly lowers their temperature to solidify them for collection and further processing.

The pelletizing machine used in this study was powered by an on-site diesel generator system. The generator assembly consisted of a Sincro SK 250 MM AC 3-phase synchronous generator coupled with an IVECO diesel engine and Lister Petter components. The generator was supplied and maintained by Skaini Electro Mechanical, Lebanon.

The Sincro SK 250 MM generator has a maximum continuous power output of 200 kVA (equivalent to 160 kW, at a power factor of 0.8) at 400 V, 50 Hz, and 1500 rpm. It offers a standby output capacity of 220 kVA and is equipped with IP23 enclosure protection and Class H insulation.

The diesel engine driving the generator ensures a stable power supply for the pelletizing machine. The fuel type used was diesel, commonly employed for industrial energy generation due to its efficiency and availability. Given the generator’s age and operational history since 2015, its fuel consumption was estimated at 42 liters per hour at full load. Based on the local diesel price of $0.80 per liter, the cost of producing electricity with this generator was calculated at $0.21 per kWh.

The energy consumption of the pelletizing machine was directly monitored through the digital display on the generator’s control panel, which provided real-time readings of power consumption in kilowatts (kW). This allowed accurate data collection during both the preheating phase and continuous operation, ensuring precise comparison between the insulated and non-insulated experimental conditions.

3.2.2. Temperature measurements

The surface and material temperatures throughout the pelletizing process were measured using an infrared thermometer, model INGCO HIT015501. This device offers a temperature measurement range from -50°C to 550°C, with a distance-to-spot (D:S) ratio of 12:1. The device is equipped with a fixed emissivity setting of 0.95, suitable for accurate temperature readings on metal surfaces, such as the exterior of the extruder barrel. The thermometer provides fast measurements, with a typical response time of approximately 500 milliseconds.

Temperature measurements were taken at three critical points during the experimental procedure:

Extruder Barrel Surface: The external surface temperature of the extruder barrel was measured at multiple locations corresponding to the heating zones. These readings were used to ensure that the barrel temperatures remained consistent during both insulated and non-insulated test runs.

Processed Material Inside the Extruder: The temperature of the molten nylon material was measured through an access opening located at the middle section of the extruder barrel. This allowed for real-time monitoring of the material temperature during processing.

Final Product Temperature After Extrusion: Immediately after pelletizing and before cooling, the temperature of the freshly extruded pellets was measured to confirm uniformity and processing stability across different experimental conditions.

All temperature readings were taken systematically and recorded during both the preheating phase and the continuous operation phase to ensure consistent data collection and enable reliable comparison between test scenarios.

3.2.3. Differential scanning calorimetry (DSC) analysis

Differential Scanning Calorimetry (DSC) testing was performed on the feedstock sample prior to pelletizing. This analysis aimed to determine the material's thermal properties, specifically heat flow (W/g) and heat capacity (J/g°C). This data can be used to calculate the heating requirements during pelletizing according to the following general equation:

$$\Delta H = n \int_{T_{initial}}^{T_{final}} C_P dT \qquad (3.1)$$

Alternatively the heat flow rate during heating the batch from room temperature to the final temperature could be obtained from the measured heat flow rate versus temperature for 3 mg of sample used during the DSC characterization. The average heat flow rate per gram of material was calculated from this figure and then multiplied by the mass flow rate of the material during extrusion to calculate the instantaneous power requirement throughout the extruder from the cold entrance to the hot exit, according to equation 3.2.

$$\begin{aligned} &Average\ power\ requirement\ (mW) = \\ &Average\ heat\ flow\ rate\ per\ gram\ (mJ/g) * \\ &Average\ mass\ flow\ rate\ (34.7 \tfrac{g}{s}) \ldots.. \end{aligned} \qquad (3.2)$$

3.2.4. Heat loss analysis

The temperatures of the outer surface of the extruder were used in the heat loss analysis, applying Fourier’s law of conduction as illustrated in Figure 3.1. The cylindrical extruder, with a diameter of $2R_1$, is assumed to have a uniform barrel thickness of R_2-R_1, constructed from tool steel. In configurations that include insulation, an additional layer of glass-wool insulation with a thickness of R_3-R_2 is considered. The thermal conductivities of these materials are assumed constant: **55** W/m·K for tool steel (Engineering Toolbox, 2024) and 0.04 W/m·K for the glass-wool insulation (Engineering Toolbox, 2024). The heat flux (heat transfer rate per second per unit area) due to conduction through the barrel wall is calculated using Equation 3.3, where the thermal resistance of the wall is a function of its cylindrical geometry, thermal conductivity and convection coefficient, as expressed in Equation 3.4. When the insulation is applied, an additional thermal resistance is introduced, based on the geometry and thermal conductivity of the insulation layer, in accordance with Equation 3.5.

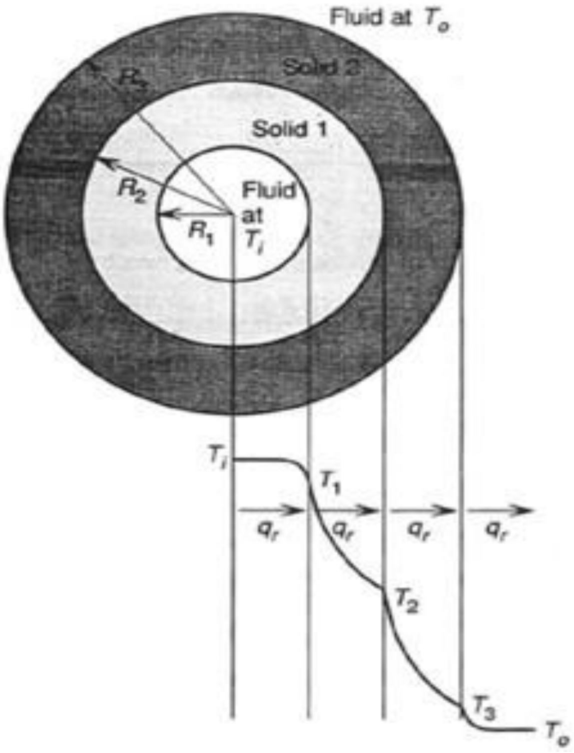

Figure 3.2. Radial heat conduction through a cylindrical extruder barrel with insulation, showing temperature distribution and heat flux across the barrel and insulation layers.

$$q = \frac{T_2 - T_1}{R_1} \tag{3.3}$$

$$R_1 = \frac{\ln R_2/R_1}{2\pi k_1 L} + \frac{1}{2\pi R_3 L h} \tag{3.4}$$

$$q = \frac{T_3 - T_1}{R_{total}} \; where \; R_{total} = \frac{\ln R_2/R_1}{2\pi k_1 L} + \frac{\ln R_3/R_2}{2\pi k_2 L} + \frac{1}{2\pi R_3 L h} \tag{3.5}$$

Barrel Geometry and System Configuration; The barrel has an outer diameter of 20 cm and a wall thickness of 3 cm, resulting in an inner radius of 0.07 m and an outer radius of 0.10 m. The total length of the barrel is 2.54 m. The barrel material has a thermal conductivity of 55 W/m·K (Engineering Toolbox, 2024). In the insulated case, a fiberglass insulation layer, 2 cm thick, is applied over the barrel, increasing the external radius to 0.12 m. The thermal conductivity of the insulation is 0.04 W/m·K (Engineering Toolbox, 2024). Convection heat transfer coefficients were considered based on surface conditions: 25 W/m²·K for the bare metal surface (Yener, Yener, & Mutlu, 2020) and 5 W/m²·K for the insulated surface (ASHRAE, 2019). These values were selected based on standard correlations for natural convection and adjusted for the reduced temperature gradient across the insulated surface.

3.2.5. Data analysis and comparison

The energy consumption data from both test conditions (with and without insulation) were converted into thermal efficiencies and these values were compared to evaluate the energy savings achieved by applying glass wool insulation. The power requirement for the extrusion process was calculated from the calorimeter data using Eqn 3.2. Additionally, the energy required to melt 34.7 g of nylon was added to determine the total power needed to convert the material from solid at room temperature to its molten state. The final temperatures that were measured during operation were different for the two cases which resulted in different power requirements and different efficiencies. Thermal efficiency of the process was calculated according to the following equation:

$$Thermal\ efficiency\ (\eta) = \frac{Average\ power\ requirement}{Power\ supplied\ to\ the\ heaters} \tag{3.6}$$

Specific attention was given to the energy consumed by heaters, overall machine energy consumption, energy consumed by the motor driving the screw and energy usage during the preheating phase. The total power consumption per 34.7 g of the product was also calculated according to the following equation:

$$\text{Total power consumption} = \text{heater and motor power consumption} + \text{preheating power consumption} \qquad (3.7)$$

As an alternative approach, heat loss was directly calculated from the surface temperatures according to Eqns 3.3-3.5. Its ratio to the power supplied to the heaters is calculated as the inverse efficiency that is subtracted from 1.00 to find efficiency:

$$Thermal\ efficiency\ (\eta) = 1 - \frac{Power\ loss}{Power\ supplied\ to\ the\ heaters} \qquad (3.8)$$

The data analysis aimed to quantify energy efficiency improvements and potential cost savings derived from the insulation implementation.

4. RESULTS AND DISCUSSION

4.1. Introduction

This chapter presents the results of the energy consumption measurements and temperature assessments of the pelletizing machine under two operating conditions: with and without the application of glass wool insulation on the machine's heating elements. The data are analyzed and discussed to determine the impact of insulation on thermal efficiency, energy consumption, and potential economic benefits.

4.2. Energy Consumption Measurements

The energy consumption of the pelletizing machine was measured in two distinct phases to evaluate the thermal efficiency improvements resulting from the use of glass wool insulation on the extruder barrel heaters.

4.2.1. Baseline energy consumption (Without insulation)

In the first phase of the experiment, the pelletizing machine was operated without any insulation applied to the heaters. The machine processed transparent nylon bags that were shredded in the grinder machine prior to pelletizing. The heaters were set to specific temperatures along different zones of the extruder barrel as follows:

185°C, 180°C, 155°C, 160°C, 165°C, 175°C, 170°C.

The surface temperatures of the heaters, measured by an infrared laser thermometer, varied significantly, with some heaters registering surface temperatures above 250°C, while others were below 110°C. This discrepancy was attributed to the thermostatic control system, which switched the heaters on and off based on the measured temperature of the extruder screw and material. The measured temperatures on the heater surfaces were as follows (in °C):

Table 4.1. Temperature Settings of the Pelletizing Machine’s Heating Elements (without insulations)

Heater Group	Number of Heaters	Thermostat Temperature (°C)	Surface Temperature Without Insulation at Steady-State (°C)
First group	2	185°C	258.7°C
Second group	2	180°C	177.0°C
Third group	2	155°C	158.6°C
Fourth group	2	160°C	116.4°C
Fifth group	3	165°C	106.4°C
Sixth group	1	175°C	108.7°C
Seventh (last) group	2	170°C	216.0°C

The temperatures of the processed materials inside the extruder were recorded at 157.6°C, while the temperature of the pellets after cooling was 82.1°C. The preheated material entering the machine had a temperature of 69.1°C.

The energy consumption data in this condition were:

Table 4.2. Electrical energy consumption of pelletizing machines and auxiliary systems

Description	Power Consumption (kW)
Preheating phase consumption	33 kW
Machine consumption after preheating (steady-state operation)	35 kW
Engine consumption	24 kW
Cutting and cooling system	2 kW
Lighting and auxiliary systems	2 kW

The power consumption of the pelletizing machine during various operational phases, along with its auxiliary systems, is summarized in Table 4.2.

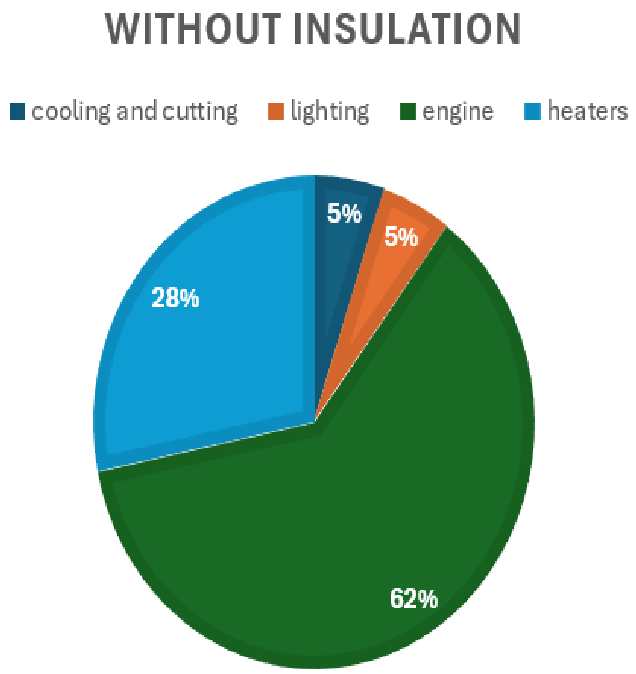

Figure 4.1. Energy consumption distribution of the pelletizing machine before insulation

Energy consumption distribution of different components *without insulation*. The pie chart shows that the engine accounts for the largest share at 62%, followed by heaters at 28%. Both lighting and cooling and cutting contribute 5% each. These percentages represent the proportion of total energy consumption (in kW) by each element before implementing insulation measures.

4.2.2. Modified Energy Consumption (With Glass Wool Insulation)

In the second phase, the 14 heaters on the extruder barrel were wrapped with a 25 mm thick glass wool insulation blanket to reduce heat loss. The heater temperature settings remained the same as the baseline to ensure consistency. The measured surface temperatures of the heaters decreased dramatically due to the insulation, ranging from 15.3°C to 29.6°C, with one reading at 189°C (This heater is not insulated because it is located on the extrusion head).

Table 4.3. Temperature Settings of the Pelletizing Machine's Heating Elements (with insulations)

Heater Group	Number of Heaters	Thermostat Temperature (°C)	Surface Temperature With Insulation (°C)
First group	2	185°C	27.7
Second group	2	180°C	19.0
Third group	2	155°C	15.6
Fourth group	2	160°C	15.3
Fifth group	3	165°C	22.1
Sixth group	1	175°C	29.6
Seventh (last) group	2	170°C	189.0

The temperature of the processed materials inside the extruder increased to 168°C, and the final pellets temperature after cooling was 101.92°C, while the preheated material temperature remained constant at 69.1°C.

The energy consumption data in this condition were:

Table 4. 4. Electrical energy consumption of the pelletizing machine and auxiliary systems (with insulation)

Description	Power Consumption (kW)
Preheating phase consumption	32 kW
Machine consumption after preheating (steady-state operation)	29 kW
Engine consumption	25 kW
Cutting and cooling system	2 kW
Lighting and auxiliary systems	2 kW

This table presents the power consumption when the machine operates with thermal insulation applied, allowing a direct comparison with (Table 4.4).

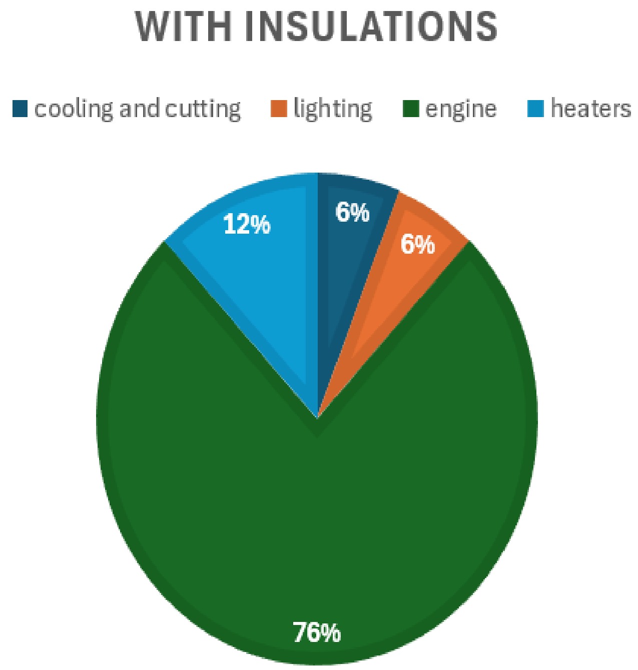

Figure 4.2. Energy consumption distribution of the pelletizing machine after glass wool insulation

Energy consumption distribution of different components *after applying insulation*. The engine remains the largest consumer at 76%, while the heaters' share significantly reduces to 12%. Cooling and cutting and lighting now contribute 6% each. The chart illustrates the impact of insulation in reducing the energy demand of the heaters, thereby improving overall energy efficiency

4.2.3. Thermal Efficiency Explanation (with Reference to DSC)

The thermal efficiency of the extrusion process was calculated by comparing the energy input from the heating system to the heat absorbed by the material, as determined through Differential Scanning Calorimetry (DSC) analysis.

DSC Analysis and Interpretation; The DSC curve (Figure 4.3) illustrates the heat flow behavior of the material as a function of temperature. The X-axis represents temperature (°C), while the Y-axis shows the heat flow per second (mW). The graph highlights two key transitions:

A glass transition or preheat region is observed starting around 69.1°C, corresponding to the material preheat temperature used in the extrusion process.

A distinct endothermic peak is noticeable between 69.1°C and 157.6°C, which matches the temperature rise (ΔT) of 88.5°C during extrusion. This peak represents the melting process, where the material absorbs significant energy to transition from solid to molten form.

The onset and end temperatures, marked by the orange vertical lines on the DSC plot, delineate the boundaries of this transition. The area under the curve within these limits indicates the heat absorbed by the material during the phase change.

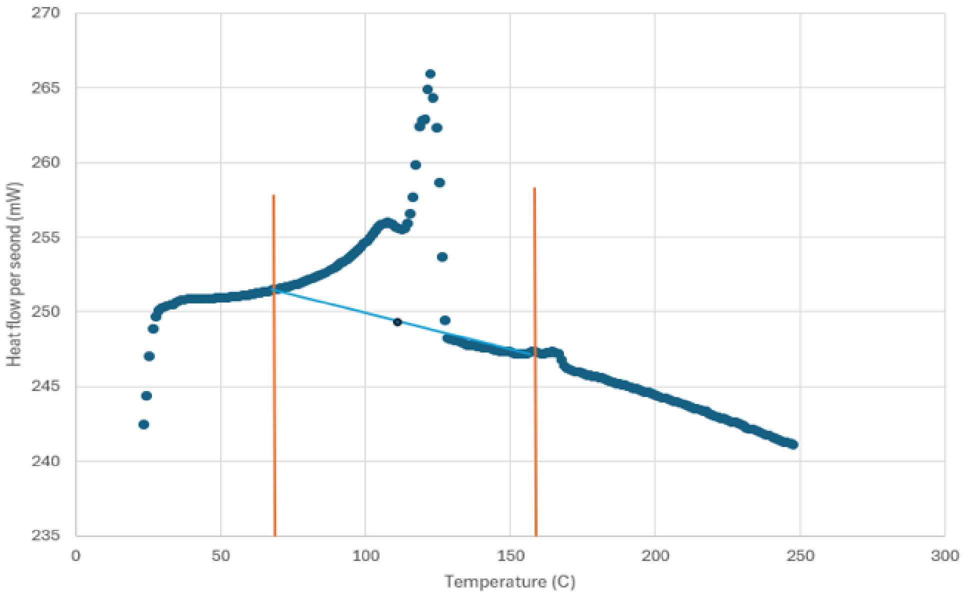

Figure 4.3. DSC Curve of Nylon Material Without Insulation

The total energy per second needed to heat and melt the material was 3.987 kJ/s, based on the material flow rate of 34.7 g/s and the combined heat requirements. The total heat transfer rate to 34.7g/s of melting nylon throughout the length of the extruder includes the heat required to raise the material temperature (82,917 mJ/g), as calculated from the figure. The heat of melting per 34.7 g is obtained as 32,000 mJ/g (Kim, 2006).

The heater energy consumption, measured at 11 kW, far exceeds the energy directly absorbed by the material. This discrepancy highlights losses due to thermal inefficiencies, such as heat dissipation to the surroundings. The calculated thermal efficiency of the heaters is 36.25%.

4.2.4. Thermal Efficiency Analysis with Insulation (with Reference to DSC Figure)

The thermal efficiency of the extrusion process significantly improved after adding insulation, as seen in the energy balance calculations and supported by the Differential Scanning Calorimetry (DSC) data (Figure 4.4).

Figure 4.4 shows the DSC curve of the recycled nylon material, which illustrates the material’s heat absorption behavior during the heating process. The X-axis displays temperature in °C, while the Y-axis indicates heat flow per second (mW). The first orange line marks the onset temperature at 69.1°C, corresponding to the material preheat temperature. The second orange line shows the end temperature at approximately 168°C, matching the material temperature after extrusion in this insulated scenario.

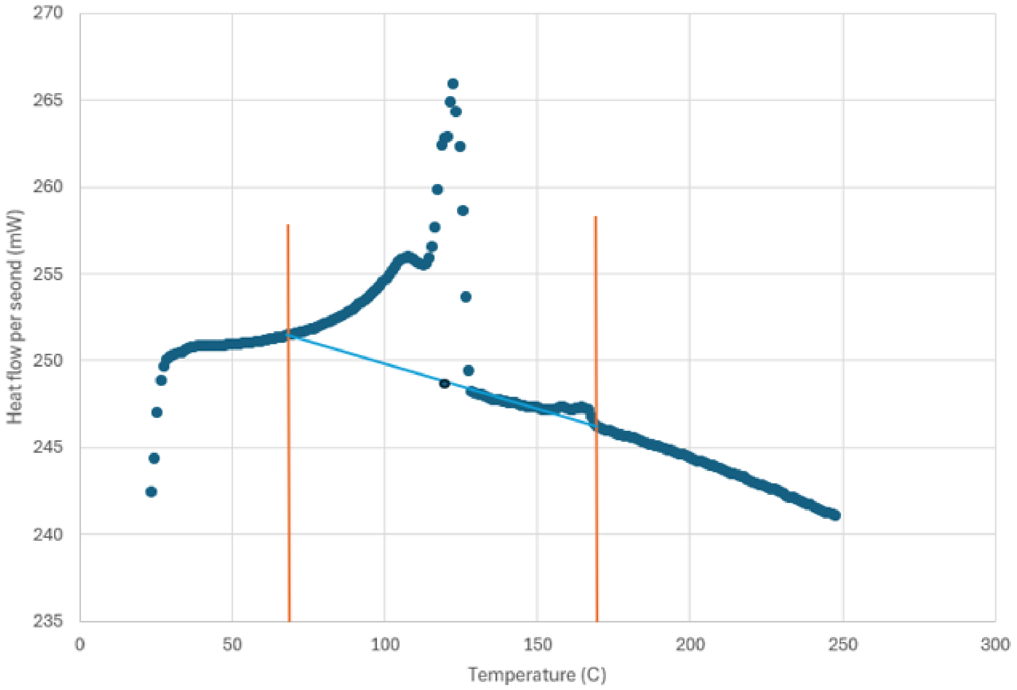

Figure 4.4. DSC Curve of Nylon Material With Insulation

Between these two temperatures, the DSC curve displays a broad endothermic peak, with a more pronounced heat absorption occurring between 100°C and 130°C, indicating the melting phase of the recycled nylon. This behavior is consistent with the heat of melting requirement of 32,000 mJ/g reported by Kim (2006). The area under the curve between the orange lines reflects the total heat absorbed by the material, including both sensible heat (temperature rise) and latent heat (melting).

4.3. Thermal Efficiency Calculations Linked to DSC Data

The ΔT in this insulated system is 98.9°C, which requires 82,584 mJ/g of energy to heat the material from 69.1°C to 168°C. Along with the heat of melting (32,000 mJ/g), the total heat energy absorbed by the material resulted in an energy transfer rate of 3.976 kJ/s, based on the material flow rate of 34.7 g/s. By applying insulation, the heater energy consumption was significantly reduced to 4 kW, compared to 11 kW without insulation. This led to a substantial improvement in thermal efficiency. The efficiency of heaters are found as 99.4%.

4.4. Discussion of Results

The application of glass wool insulation significantly improved the thermal efficiency of the pelletizing machine’s heating system. Key findings include:

- Reduced Surface Temperature Losses

The surface temperatures of the heaters dropped from 258.7°C - 269°C to below 30°C in most areas, indicating a substantial reduction in heat loss to the environment.

- Improved Material Heating

The material temperature inside the extruder increased by 10.4°C, demonstrating improved heat retention and transfer efficiency.

- Energy Savings

Heater energy consumption decreased from 11 kW to 4 kW, representing a 63.6% reduction in heating energy requirements. Total machine consumption (including engines and auxiliaries) dropped from 35 kW to 29 kW, a 17.1% reduction. Preheating consumption decreased slightly from 33 kW to 32 kW, indicating improved initial heating efficiency.

- Enhanced Thermal Efficiency

Thermal efficiency increased from 0.3625 to 0.9940 for the heating system, representing a 174% improvement.

- Process Consistency and Product Quality

The increase in material and pellet temperatures suggests a more stable process with fewer thermal fluctuations, which can positively impact pellet quality and subsequent pipe extrusion processes.

4.5. Summary of Key Findings

Table 4.5. Comparison of Key Operating Parameters of the Pelletizing Machine With and Without Insulation.

Parameter	Without Insulation	With Insulation
Material Temp (Extruder)	157.6°C	168°C
Pellet Temp (After Cooling)	82.1°C	101.92°C
Heater Energy Consumption	11 kW	4 kW
Total Energy Consumption	35 kW	29 kW
Thermal Efficiency (Heaters)	0.3625	0.9940
Heater Surface Temp	258.7°C – 269°C	15.3°C – 29.6°C

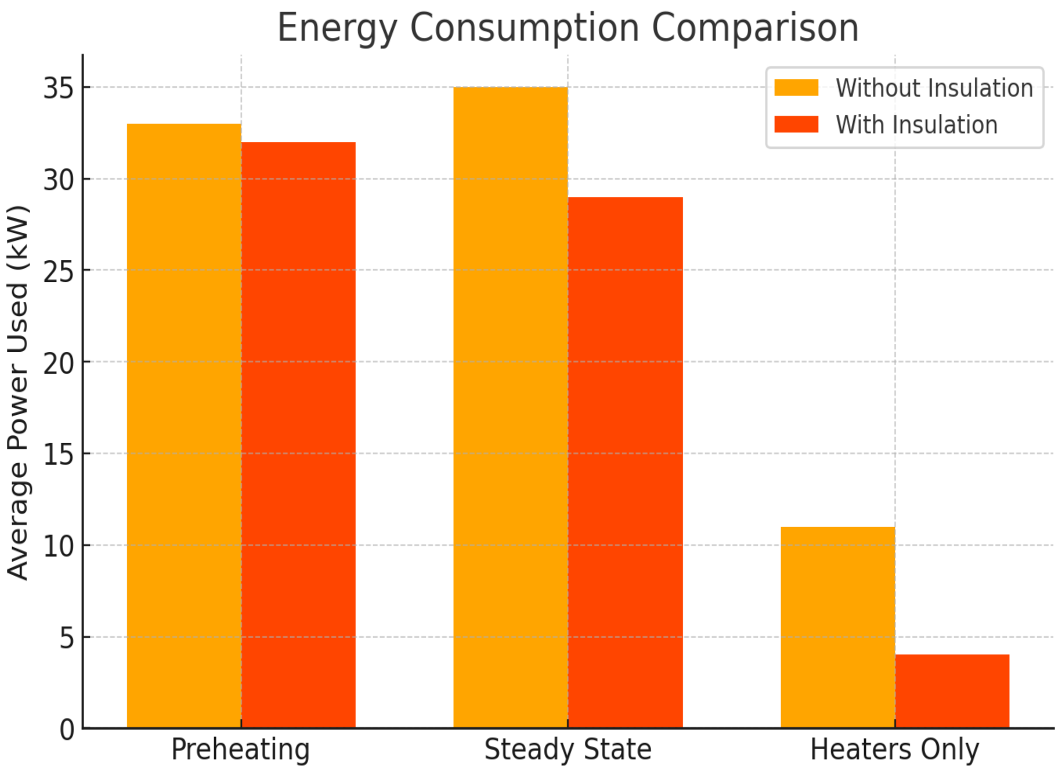

Figure 4.5. Thermal Efficiency Comparison (With and Without Insulation)

Heat Loss and Thermal Efficiency Analysis Based on Thermal Resistance Modeling; To deepen the analysis of the thermal performance improvements achieved through insulation, a theoretical heat transfer model was applied using the thermal resistance equations introduced in Chapter 3.

In the case without insulation, the total thermal resistance of the extruder barrel was calculated using **Equation 3.4**, which considers conduction through the barrel wall and convection from the bare metal surface. Based on the defined thermal and geometric parameters, the total resistance was found to be 0.02547 $m^2 \cdot K/W$. Substituting this value into **Equation 3.3**, the estimated heat loss to the environment was approximately 6,085.6 W. This high rate of energy dissipation highlights the inefficiency of the system when operating without any thermal protection.

For the insulated scenario, the total thermal resistance was calculated using **Equation 3.5**, which incorporates additional resistance due to the fiberglass wool insulation layer. The resulting resistance increased significantly to 0.39044 $m^2 \cdot K/W$. Using this value in **Equation 3.3**, the corresponding heat loss dropped drastically to 397.0 W.

This confirms the effectiveness of the insulation in reducing energy losses by creating a strong thermal barrier.

To assess energy utilization efficiency, thermal efficiency was calculated using **Equation 3.8**, which compares power lost to the environment with the total power supplied to the heaters. For the non-insulated configuration, with 11,000 W of power supplied and 6,085.6 W lost as heat, the efficiency was calculated as 44.7%. In contrast, the insulated system, with a power input of 4,000 W and only 397 W of heat loss, achieved a thermal efficiency of 90.1%. These results clearly demonstrate the insulation's role in optimizing the energy consumption of the pelletizing machine.

Additionally, using the surface area values of the extruder with and without insulation, the heat flux was calculated. For the non-insulated barrel, the heat flux reached 3,813.2 W/m^2, while the insulated surface showed a significantly lower value of 207.3 W/m^2, further validating the insulation’s effectiveness in minimizing surface heat dissipation.

Table 4.6. A comparison of both cases is summarized below

Condition	R_{total} (m^2·K/W)	Heat Loss (W)	Heat Flux (W/m^2)	Power Supplied (W)	Efficiency (%)
Without Insulation	0.02547	6,085.6	3,813.2	11,000	44.7
With Insulation	0.39044	397.0	207.3	4,000	90.1

In conclusion, the theoretical results obtained using **Equations 3.3**, **3.4**, **3.5**, and **3.8** are consistent with the experimental findings. The application of thermal insulation significantly improved thermal resistance, reduced heat loss, and increased energy efficiency—validating the insulation strategy from both practical and theoretical perspectives.

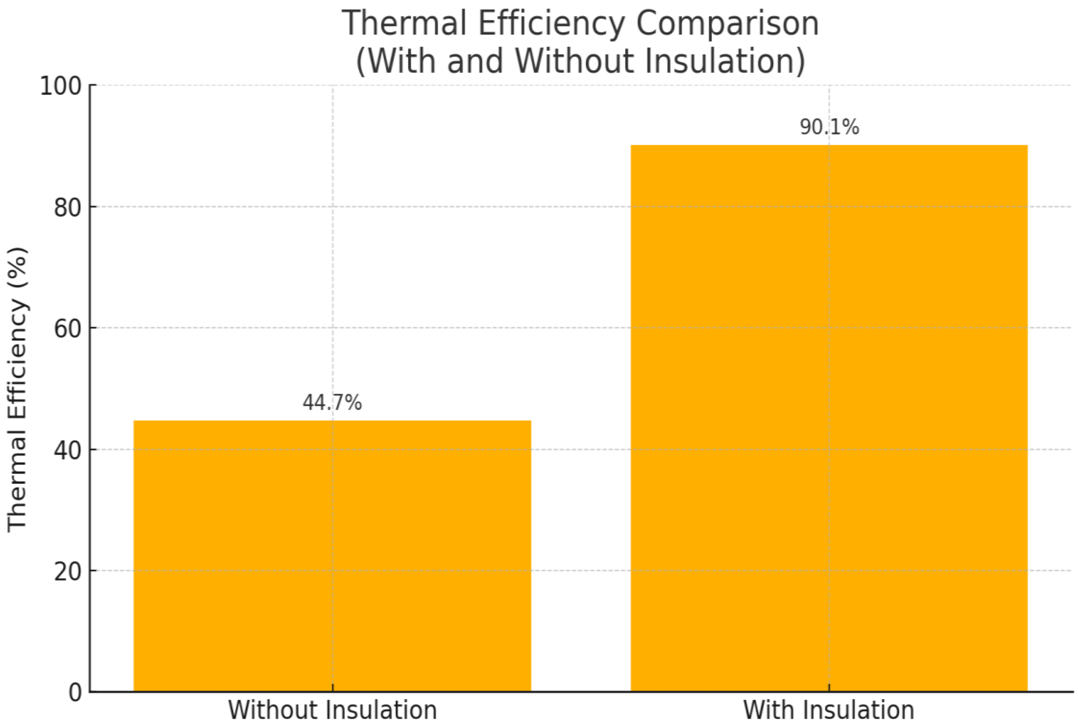

Figure 4.6. Thermal efficiency comparison of the pelletizing machine with and without insulation. The figure shows a significant increase in efficiency from 44.7% to 90.1% after applying thermal insulation.

Comparison Between Heat Loss Analysis and DSC-Based Energy Absorption; To validate the findings obtained from the thermal resistance model, a comparison was conducted with the energy absorption results derived from the Differential Scanning Calorimetry (DSC) analysis. While the model quantifies heat loss based on surface conduction and convection resistances (Equations 3.3 to 3.5), the DSC analysis directly measures the energy absorbed by the nylon material during the heating and melting process.

According to **Equation 3.8**, thermal efficiency was determined by comparing the power lost to the environment with the total power supplied to the heaters. This resulted in a thermal efficiency of **90.1%** for the insulated configuration and **44.7%** for the bare configuration. The corresponding theoretical heat losses were **397.0 W** (with insulation) and **6,085.6 W** (without insulation).

In contrast, the DSC analysis reported in Section 4.3 of the thesis revealed that the energy required to heat and melt the material (at a flow rate of 34.7 g/s) was approximately **3.976 kJ/s (with insulation)** and **3.987 kJ/s (without insulation)**. Heater power input values of **4,000 W** (insulated) and **11,000 W** (non-insulated) were used to determine thermal efficiency based on how much of the input energy was effectively absorbed by the material. This resulted in a DSC-based efficiency of **99.4%** with insulation and **36.25%** without insulation.

Table 4.7. Comparative Summary Table

Condition	Power Supplied (W)	Heat Loss (W)	Efficiency (Thermal Resistance)	Efficiency (DSC-Based)	Heat Absorbed by Material (W)
Without Insulation	11,000	6,085.6	44.7%	36.25%	3,987
With Insulation	4,000	397.0	90.1%	99.4%	3,976

Discussion of Results and Discrepancy; While both approaches confirm that thermal insulation significantly improves energy efficiency, a slight discrepancy is observed between the two methods. The **theoretical analysis** predicts **higher efficiency in the insulated case (90.1%)** compared to the non-insulated one (44.7%), which aligns with the overall trend. However, the **DSC-based analysis** suggests an even higher efficiency of **99.4%**, closely matching the actual energy absorbed by the material.

This difference arises from a few analytical simplifications in the theoretical model:

Idealized Geometry and Constants: The thermal resistance model assumes steady-state conditions, constant material properties, and uniform surface temperatures, which may differ slightly from real dynamic operating conditions.

Surface Heat Loss Only: The model primarily accounts for radial heat loss through the barrel and insulation, potentially underestimating axial and point losses from other parts of the machine.

DSC as Direct Material Absorption: The DSC method directly measures the energy absorbed by the nylon during heating and melting, providing a more material-specific efficiency that excludes other energy-consuming factors like mechanical losses or ambient dissipation.

Despite these minor discrepancies, both approaches strongly agree on the impact of insulation: it significantly reduces heat loss and boosts system efficiency. The combination of theoretical and experimental analyses enhances confidence in the energy performance findings and supports the broader economic and environmental benefits demonstrated throughout the study

4.6. Cost Analysis Before and After Insulation Installation on the Pelletizing Machine

4.6.1. Energy cost calculation from diesel generator

The factory relies on diesel generators for all its energy needs. Below is the breakdown of the energy cost calculation:

Generator Specifications and Performance:

- Rated capacity: 200 kVA
- Power Factor (PF): 0.8
- Real power output: 200 kVA×0.8 PF=160 kW

Fuel Consumption and Cost per Hour:

- Diesel consumption: 42 liters/hour
- Diesel price: $0.80/liter
- Fuel cost per hour: 42 liters×0.80 USD=33.60 USD/hour

Energy Produced Per Hour and Cost Per Kilowatt-Hour:

- Generator output: 160 kWh/hour
- Cost per kilowatt-hour: 33.60 USD160 kWh=0.21 USD

This $0.21 per kWh is the unit cost applied to all energy consumption in the following processes.

Table 4.8. Grinding Process (700 kg Input = 70% of 1 Ton)

Category	Calculation	Value
Energy Consumption	21 kW × 8 hr = 168 kWh × 0.7 = 117.6 kWh × $0.21	$24.70
Labor Cost	$20 × 0.7	$14.00
Maintenance Cost	$1.92 × 0.7	$1.34
Total Daily Process Cost		$40.04

Table 4.9. Pelletizing Process (700 kg Input = 70% of 1 Ton) Preheating and Operation Energy Corrected

Category	Before Insulation	After Insulation
Preheating Energy	33 kW × 1 hr = 33 kWh × 0.7 = 23.1 kWh × $0.21 = $4.85	32 kW × 1 hr = 32kWh × 0.7 = 22.4 kWh × $0.21 = $4.70
Operation Energy	35 kW × 8 hr = 280 kWh × 0.7 = 196 kWh × $0.21 = $41.16	29 kW × 8 hr = 232 kWh × 0.7 = 162.4 kWh × $0.21 = $34.10
Labor Cost	$20 × 0.7 = $14.00	$20 × 0.7 = $14.00
Maintenance Cost	$5.77 × 0.7 = $4.04	$5.77 × 0.7 = $4.04
Glass Wool Blanket	N/A	$2.80
Total Daily Process Cost	$64.05	$59.64

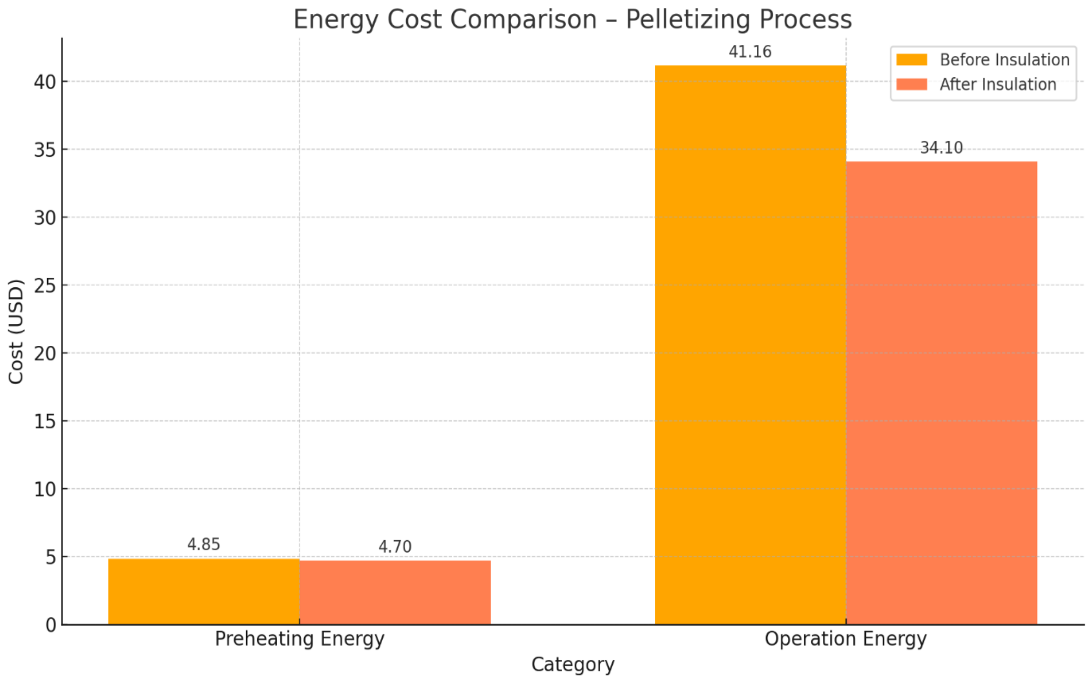

Figure 4.7. Energy cost comparison of the pelletizing process before and after insulation, showing reduced expenses in both preheating and operation stages.

Table 4.10. Pipe Extrusion Process (Full 1 Ton Output, Energy Fixed)

Category	Calculation	Value
Energy Consumption	38 kW × 16 hr = 608 kWh × $0.21	$127.68
Labor Cost (2 operators)	2 × $30	$60.00
Cooling System Cost	$1.37	$1.37
Maintenance Cost	$7.70	$7.70
Packaging Cost	$4.00	$4.00
Total Process Cost		$200.75

Table 4.11. Total Cost Analysis Table (With Material Prices)

Category	Before Insulation	After Insulation
Material Costs	$385 (Nylon Bags) + $195 (Harsh Pellets) = $580	$580
Grinding Process	$40.04	$40.04
Pelletizing Process	$64.05	$59.64
Pipe Extrusion	$200.75	$200.75
Transportation Fee	$11.67	$11.67
Total Cost (Including Materials)	$896.51	$892.10

Table 4.12. Profit Analysis Table (Before and After Insulation)

Description	Before Insulation	After Insulation
Pipe Sales (1 Ton for $1.60/kg)	$1,600.00	$1,600.00
Total Costs	$896.51	$892.10
Profit per Ton	$703.49	$707.90
Daily Energy Savings		$4.41

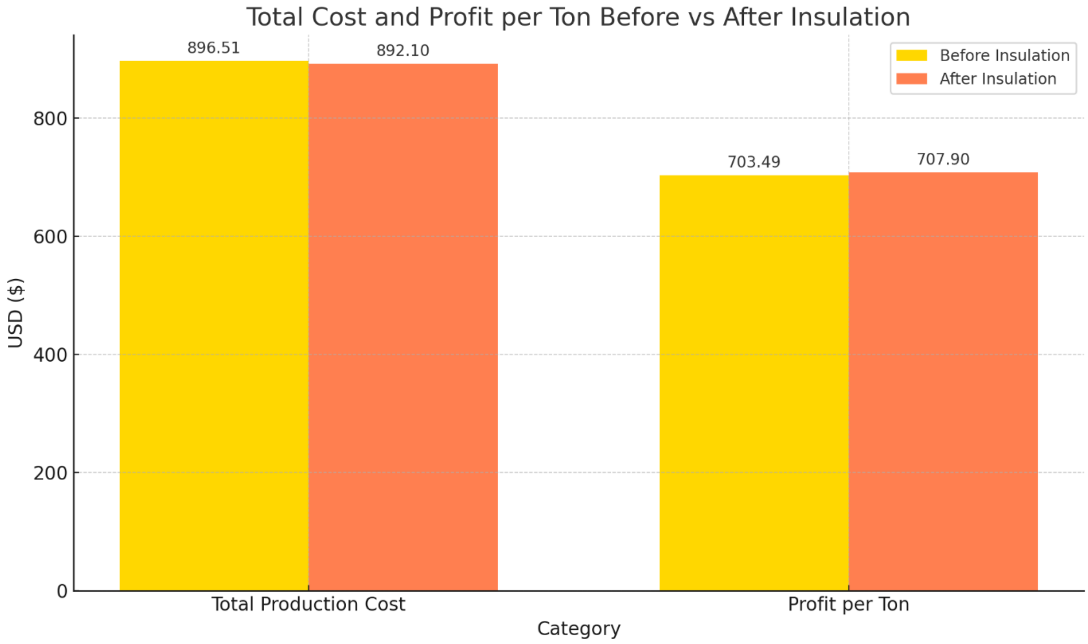

Figure 4. 8. Comparison of total production cost and profit per ton before and after insulation, highlighting increased profitability after energy savings.

Projected Monthly and Annual Profit Increase Due to Insulation Installation; Following the installation of thermal insulation on the pelletizing machine, the process cost was reduced, resulting in an additional profit of $4.41 per ton. Given the factory's daily production rate of 1 ton of pipes, this translates to additional profit of $114.66 per month (26 working days) and $1,376.52 annually (312 working days).

These figures represent direct savings in energy costs, leading to increased profitability without altering production rates or product pricing. In scenarios where daily production exceeds 1 ton, the savings—and consequently, the profits—scale proportionally.

Table 4.13. Insulation Benefits: Increased Profits by Production Volume

Daily Production (Tons)	Monthly Profit Increase (USD)	Annual Profit Increase (USD)
1	$114.66	$1,376.52
2	$229.32	$2,753.04
3	$343.98	$4,129.56
5	$573.30	$6,882.60

Recycled Pellets vs Virgin Raw Material Pellets Comparison

Table 4.14. Pipe Extrusion Process Cost Comparison (Per Ton of Pipes)

Category	Recycled Pellets	Virgin Raw Materials	Difference
Material Cost	$580.00	70% × $1,100 = $770 + 30% × $1,250 = $375 → $1,145.00	$565.00
Grinding Process	$40.04	N/A	–$40.04
Pelletizing Process	$59.64	N/A	–$59.64
Pipe Extrusion Process	$200.75	$200.75	$0.00
Transportation Fee	$11.67	$11.67	$0.00
Total Cost per Ton	$892.10	$1,357.42	$465.32

Table 4.15. Comparison Table - 1 Ton Pipe Production (Before vs After Insulation)

Category	Before Insulation	After Insulation	Difference
Material Cost	$580.00	$580.00	$0.00
Grinding Process	$40.04	$40.04	$0.00
Pelletizing Process	$64.05	$59.64	–$4.41
Pipe Extrusion Process	$200.75	$200.75	$0.00
Transportation Fee	$11.67	$11.67	$0.00
Total Cost	$896.51	$892.10	–$4.41
Revenue (Pipe Sales)	$1,600.00	$1,600.00	$0.00
Profit per Ton	$703.49	$707.90	+$4.41

Final Conclusions;

Energy savings from insulation reduce the pelletizing process cost by $4.41 per ton.

Profit per ton increases by $4.41, from $703.49 to $707.90.

Recycled pellets save $465.32 per ton compared to virgin raw materials.

5. CONCLUSION

This study evaluated the energy efficiency and economic viability of recycling post-consumer nylon bags into pellets for agricultural pipe production. By comparing the performance of an industrial pelletizing machine under two conditions—with and without fiberglass wool insulation—the research provided key insights into energy savings, cost reduction, and process optimization.

5.1. Comparison Between Virgin and Recycled Materials

The analysis confirms a strong economic advantage in using recycled nylon pellets over virgin raw materials. Producing one ton of pipes with recycled pellets costs \$892.10, compared to \$1,357.42 per ton using virgin raw materials. This translates to a cost saving of \$465.32 per ton, mainly driven by lower raw material costs. While the recycling process introduces additional steps such as grinding and pelletizing, these are outweighed by the substantial savings, making recycled pellets a cost-effective alternative.

5.2. Impact of Thermal Insulation on Cost and Energy Savings

Installing a 25 mm fiberglass wool insulation blanket around the extruder's heating elements significantly reduced heat loss and improved thermal efficiency:

Preheating energy consumption decreased from 33 kWh to 32 kWh, reducing cost from \$4.85 to \$4.70.

Operation energy consumption dropped from 35 kWh to 29 kWh, cutting cost from \$41.16 to \$34.10.

Total daily pelletizing cost fell from \$64.05 to \$59.64, generating daily savings of \$4.41.

These savings increased the profit per ton of pipe from \$703.49 to \$707.90, an improvement of \$4.41 per ton.

Over time, these savings scale up to \$114.66 per month and \$1,376.52 annually (based on 1 ton/day and 312 working days/year). Higher production rates would proportionally increase these profits..

5.3. Strategies for Further Profit Increase and Energy Savings

Although the insulation already yielded significant improvements, several additional strategies can further enhance energy savings:

Use of Superior Insulation Materials; Replacing fiberglass wool with materials like aerogels or ceramic fibers (lower thermal conductivity) can reduce heat loss further.

Improve Convective Heat Transfer Control; Optimizing airflow or adding forced convection systems can reduce external surface heat losses and fine-tune the system’s thermal balance.

Use of Industrial Thermal Blankets; Covering other parts of the machine with high-temperature thermal blankets can trap more heat and improve overall system efficiency.

Upgrade Generator Efficiency; Switching to a more fuel-efficient generator can reduce the cost per kWh and improve the factory's energy economics.

Zone-Specific Heater Control; Given the improved internal temperatures with insulation, selective deactivation or power reduction of heating zones can prevent overheating, lower power use, and extend equipment life..

5.4. Final Thoughts

The combination of recycled feedstock and thermal insulation provides a sustainable, cost-effective, and energy-efficient approach for agricultural pipe production. Key achievements include:

Energy consumption reduction (especially in heaters)

Profitability increase by $4.41 per ton

Significant reduction in heat loss, confirmed by both theoretical models and experimental DSC data

Thermal efficiency improvement from:

44.7% to 90.1% (heat loss model)

36.25% to 99.4% (DSC-based analysis)

Although slight discrepancies exist between models due to assumptions like steady-state conditions, both methods validate the effectiveness of the insulation strategy.

By applying additional energy-saving upgrades, the factory can further improve operational efficiency, reduce environmental impact, and enhance long-term profitability..

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