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Transformation of Undifferentiated Urban Solid Waste into Secondary Solid Fuel for Environmental Sustainability

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Abstract

Purpose: the aim of this paper it to face the urgent and more and more increasing problem of urban solid waste (USW) management with a new plant able to convert it into Secondary Solid Fuel (SSF). As sustainability is a very current topic and, due to climate change and other sever connected thematic, it must be taken into account shortly with effective solutions, this research tries to provide a solution to the increasing amount of USW. A key focus is the Circular Economy because, with its recycle and reuse ideas, it is a great concept to follow in order to improve sustainability.
Methods: the first step has been a deep literature review in order to evaluate the existing methods and solutions to face the problem of USW. Then, according to what has been found, a new and innovative solution has been developed and analysed.
Results: this research have proven that USW can be turned successfully into Secondary Solid Fuel (SSF), resulting in an increased overall sustainability.
Conclusions: the problem of USW management needs to be addressed and the solution here provided by the authors is a valid alternative to the existing ones and it is able to increase the sustainability in the macro concept of Circular Economy.

Keywords: *Urban Solid Waste, Secondary Solid Fuel, Recycle, Reuse, Sustainability, Circular Economy*

Introduction

The effective management of urban solid waste (USW) has become one of the most urgent and complex environmental challenges of our time, given the increasing urbanization and large-scale waste production [1]. Rapid urbanization has led to an exponential increase in the daily generation of USW, creating unprecedented pressure on traditional disposal systems. Landfills, which represent the final destination for much of this waste, contribute to the accumulation of non-biodegradable waste and the release of greenhouse gases into the atmosphere, further exacerbating the issue of climate change. This problem is expected to escalate due to the constant growth of the world population, estimated to reach 10 billion people by 2050 [2]. In this critical context, the search for sustainable solutions for USW management has become imperative. The traditional approach based on collection, disposal, and recycling has shown evident limitations, emphasizing the need for innovative strategies that integrate waste reduction with renewable energy production, a very important theme faced in different studies [3]. Various studies focus on this, as discussed in [1], which reports landfilling, thermal treatment, and recycling as the main solutions. Specific examples include the conversion of plastic into diesel [4] and, more broadly, into fuel [5] [6], as well as the use of vegetative waste to create renewable bioenergy [7]. Energy in in fact a very current topic of great impact [8] and it is studied in many different fields [9], [10]. The transformation of undifferentiated USW into Secondary Solid Fuel (SSF) emerges as a promising solution in this landscape, offering a way to convert the combustible fraction of waste into a usable energy resource while simultaneously reducing environmental impact. It is also important to note that by isolating what is needed for SSF from the waste, other materials of primary importance in the context of the circular economy, such as glass, metals, wood, etc., can be recovered. In the perspective of the Circular Economy, this recovery and reuse of waste, even from a single container by citizens, can also reduce the undesirable and hazardous landfills, sources of enormous problems for the ecosystem. The main objective of this research is to explore and critically evaluate the current processes of transforming USW into SSF, studying both the characteristics of the transformation and those necessary for the plants. As this solution represents an innovative strategy to address the waste crisis and contribute to environmental sustainability, understanding the features that such plants require enables the full exploitation of this innovative approach. This not only reduces the amount of waste destined for landfills but also transforms the carbonaceous content of waste into a form of clean energy. The resulting SSF can be used as fuel for energy production, providing a sustainable and renewable source.

Problem Statement

Sustainability is a major concern worldwide as the environment needs to be protected. Pollution is a sever problem and urban solid waste (USW) is one of the causes. The management of this kind of waste is a key factor in protecting environment. However, there is still a lack of valuable solutions to face this issue. Even if is mandatory to find a way to reuse and recycle USW, deep studies on the conversion into Secondary Solid Fuel (SSF) are missing and it must be powered the literature on this topic.

Research Questions

In order to better address the Problem Statement and try to better solve it, it has been translated into 3 research questions:

1) What are the current main methodologies to face the increase of urban solid waste (USW)?
2) Is it possible to convert USW into Secondary Solid Fuel (SSF) and how can it be done?
3) What are the benefits of this solution in the optic of Circular Economy and Sustainability?

The choice of these RQs follows a clear logical path. At first, the current solutions are evaluated. Then, the focus is set on SSF and, finally, the whole work is associated with Circular Economy and Sustainability.

Methodology

A comprehensive review of existing literature has been conducted by using the database Scopus. The used strings of keywords are: ("Urban Solid Waste" OR "solid waste") AND ("Secondary Solid Fuel" OR "SSF" OR "Recycle" OR "reuse") AND ("Circular Economy" OR "Sustainability"). Each string of keywords follows a clear logical reasoning. The first is chosen to focus solely on solid waste domain. Subsequently, the second string has been selected to investigate the reuse of solid waste as a fuel. Finally, the third string provides the focus on circular economy and sustainability. This yielded a total of 108 papers. To refine the search results, filters in cascade have been applied. Firstly, aiming to ensure maximum relevance and novelty, the date range was restricted to 2015-2023, reducing the number of documents to 90. Subsequently, subject areas of interest have been limited to "Environmental Science", "Economics, Econometrics and Finance", "Engineering", "Business, management and accounting", and "Energy", obtaining 85 papers. Finally, as objective filters, only the 63 articles in English have been considered. Of these, 60 were available to read. Upon careful analysis, 10 articles were found to be outside the scope of the study, resulting in a final sample size of 50 records. To this amount, other 32 papers known by authors have been added to furtherly increase the quality of the paper and state its novelty.

With the software VOSviewer a map based on bibliographic data is created. An analysis of co-occurrence, using the full counting method and considering all keywords is conducted. The minimum number of occurrences is set to 6. Reducing the minimum strength of the link to 5 yields to the map shown in Fig1.

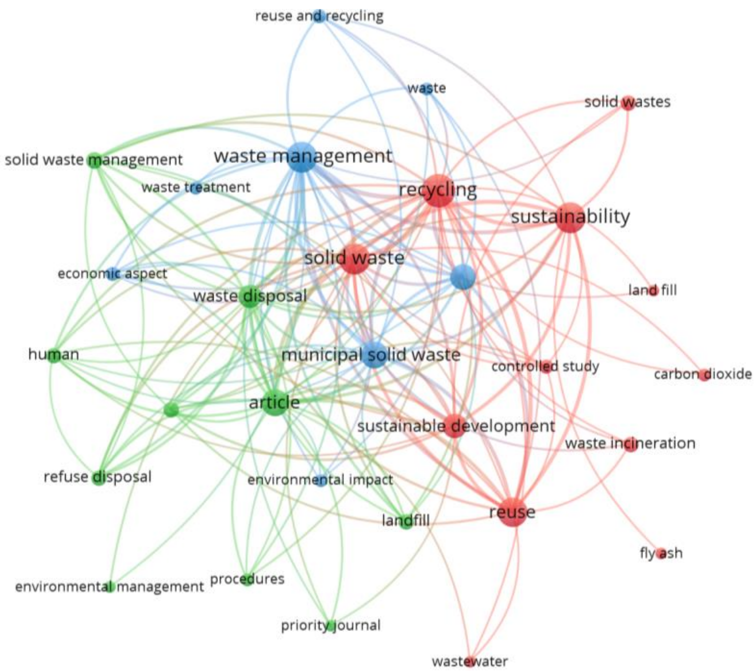

Fig1.Co-occurence map.

From the map emerges the strong link between “solid waste” and “municipal solid waste” to “waste management” and “recycling”, confirming the current interest in the topic of this paper. Moreover “sustainability” has a link with many of the other keywords, supporting the relevance of this thematic and the importance of good waste management to achieve the targets of circular economy. Eventually, “economic aspect” stands out, reaffirming the importance of the economical factors in the field of waste management.

The methodology adopted for the drafting of this paper followed a well-defined research structure, aimed at exploring the state of the art in the transformation of Urban Solid Waste (USW) into Secondary Solid Fuel (SSF) and identifying current innovations, both technologically and in terms of plant infrastructure, as well as those lacking for widespread use.

Literature Review Phase: The first phase of our approach was dedicated to an in-depth search of existing literature in the field of USW management and technologies associated with the transformation into SSF. This process, consisting of cascading filters presented and explained thoroughly in the full article, allowed the acquisition of a significant quantity of articles on the current state of research, with the objective of identifying traditional methodologies and challenges still unresolved in the sector.

Analysis of the State of the Art: The next phase involved a detailed analysis of the state of the art, highlighting existing processes, emerging trends, knowledge gaps, and innovation opportunities, as well as the needs for the widespread adoption of this solution in response to the increase in USW. This critical analysis was fundamental to establish a solid foundation on which to build the unique and innovative contribution of this paper, emphasizing current shortcomings and the characteristics required by plants of this type, and assessing the necessary modifications and improvements compared to existing methodologies.

Identification of Innovative Aspects: Subsequently, efforts focused on identifying current shortcomings and evaluating the resulting modifications and improvements needed compared to existing methodologies, both to enable widespread use of these plants and to make them technologically innovative. This phase of the study involved the exploration of new emerging technologies, the analysis of successful case studies, and the consideration of alternative plant approaches to better evaluate their characteristics. The authors sought to overcome the limitations identified in the literature, seeking potential solutions capable of improving the performance and sustainability of the entire transformation process.

Synthesis of Innovative Proposals: A crucial step was the synthesis of innovative proposals arising from the study phase. The authors clearly outlined the necessary modifications and improvements, highlighting how these could contribute to the progress of USW transformation into SSF. This synthesis phase was guided by the desire to offer tangible contributions to the scientific community and industry operators for the creation of better plants.

Validation of Contributions: Finally, the authors validated the proposed contributions through critical examination and comparison with results obtained in previous studies. This validation was crucial to ensure the solidity and reliability of the identified needs and the proposed innovations, providing a confident basis for the practical implementation of the suggested innovations. In conclusion, the method followed in drafting this paper was characterized by rigorous literature review, in-depth analysis of the state of the art, and the proposal of innovative solutions through a careful and considered study phase. This targeted approach allowed the authors to contribute significantly to the field of sustainable USW management through transformation into SSF, rigorously showcasing both the needs and possible innovative solutions to address them. After completing the work, artificial intelligence algorithms were finally utilized to improve the linguistic translation from Italian to English.

Literature Review

Circular economy involves a production approach that departs from the traditional linear model, promoting the production of goods without escalating raw material usage and eliminating generated waste [11] . Therefore, the circular economy represent a novel paradigm in sustainable production and green development, aiming for resource efficiency, robust economic prosperity, and balanced environmental and social progress to maximize economic gains while minimizing resource and energy consumption and pollution emissions [12] [13] [14]. Thus, reuse and recycling are the two most important strategies involved in the practical implementation of the circular economy [15] [16] [17] [18] because they place emphasis on economic waste value potentials [19] [20] and job creation potentials [21] [22]. Creating value necessitates a multifaceted approach, entailing collaboration among a range of actors as well as cultivation of new knowledge and business competencies [23]. In fact, the linear model has led to environmental challenges such as diminishing landfill space, marine, and urban littering [24]. Furthermore, waste management is both a great challenge in today's scenario [25] and a key element of moving towards a circular economy, in fact if solid waste isn't properly managed, it can lead to considerable resource losses and cause serious environmental damage [26] [27] [28]. Urban waste primarily came from anthropogenic activities such as industrial activities, urban household consumption, sanitation services and food production [29] [30]. Since improper waste disposal practices have a detrimental impact on the environment, health and economy, states and local governments must embrace and encourage all aspects of the Circular Economy to ensure a satisfactory urban waste management [31]. In particular, in developing countries, the challenges of urban waste management are increased by the rapid population arising primarily due to the migration from rural to urban areas [32], the infrastructure deficit to dispense fundamental services, the lack of legislation and policies [31], economic boom, and rising living standards [33] [34]. Establishing an effective waste management framework depends on high support, time, and money, that are scarce commodities in many developing countries [35]. A direct consequence of a bad waste management is the growth, in the past few decades, of marine litter in the ocean with detrimental effects on the environment, human activities and health [36] [37]. Presently, landfills remain a prevalent method for waste disposal, particularly in developing countries where waste is not perceived as a valuable resource [38], presenting both an immediate and future environmental pollution challenges [39] [40] [41]. The conventional urban solid waste management is therefore not tailored to handle this complexity [42]. In fact, other things being equal, the amount of waste generated is generally proportional to the population [43], but it increases faster if the household income increases [44]. Thus, particular attention must be paid to the collection of waste, the first step of waste management, as it is one of the key levers to achieve the targets on waste [45]. In fact in developing countries there are many informal recycling activities and few environmental laws to regulate waste management [46] [47]. In particular, construction waste management is one of the challenges faced by rapidly developing countries due to large increases in population [48]. In the EU, on the other hand, Member States must progressive reduce the disposal of municipal waste to landfill [49]. Moreover recent economic and geopolitical developments have underscored the importance of prioritizing waste reuse and recycling to safeguard the availability of raw materials [50]. Furthermore, landfills are a relevant source of greenhouse emission [51], having become the third largest source of CH_4 emissions in the United States and having accounted for 18% of the total methane emissions there [52]. On the other hand, the concept of a circular economy still raises a variety of questions regarding the incineration of waste; in fact, only non-recyclable waste should be incinerated [53]. Furthermore, Municipal solid waste incineration generate high concentrations of heavy metals, therefore requires treatment to make it environmentally safe before disposal [54] [55]. In literature are proposed various solutions. For example, from an economic point of view, the replacement of the conventional lime used in cementitious materials with solid wastes would yield an important cost savings [56]. A solution to reuse the construction waste is to convert it in the form of aggregates in roller-compacted concrete pavements, green concrete, mortar using recycled aggregates, interlocked concrete pavement and concrete blocks [57]. If it's possible to differentiate the urban waste, wood pallets, glass and plastic bottles, tires, and cardboard tubes could be reused for the realizations of building structures needed in urban areas close to the landfills where these materials are available [58]. A valuable solution is the conversion of urban waste to energy [59]. In fact Waste to Energy combustion processes contribute to lower consumption of raw materials and fossil fuels, whilst keeping the environment and material cycles in the circular economy toxic free and ensuring the safe and irreversible removal of materials and substances that are unsuitable for reuse or recycling [60].

Current Market Status and Offer

Several plants capable of converting municipal solid waste (MSW), or Solid Urban Waste (SUW), into solid recovered fuel (SRF) are already present in the market. These plants, manufactured by various builders, follow a precise transformation cycle that is divided into well-defined phases to ensure efficiency and compliance with environmental regulations. The process typically begins with the collection and transportation of waste to the plant, followed by shredding to reduce volume and facilitate subsequent stages. After shredding, the material undergoes drying, separation, and purification processes to remove contaminants and recover recyclable materials. The final stages include mixing the treated materials to achieve a homogeneous composition and extrusion to form the SRF, which can be used as an alternative fuel. These plants represent a key solution for sustainable waste management, significantly contributing to the reduction of natural resource consumption and environmental impact.

Shredding of Urban and Industrial Solid Waste

Industrial shredders are essential for reducing the volume of bulky waste such as tires, paper bales, and bumpers, as well as various materials like scrap metal. These machines are crucial in recycling centers, landfills, and demolition sites, optimizing the processing of municipal solid waste (MSW) and waste from electrical and electronic equipment (WEEE). A wide range of models is available to adapt to various needs, with a cutting system that facilitates preliminary processing and sorting.

Screening and ballistic separation

Waste separation is carried out using technologies such as ballistic separators and screening systems, which isolate recyclable materials or residues. Drum and ballistic screens separate waste based on size and physical properties, improving the collection of different materials such as paper, plastic, wood, metals, and glass, which can be recycled or resold. This process not only recovers valuable materials but also reduces environmental impact.

Refrigerator and WEEE Recycling

Refrigerator recycling, post-shredding, allows for the recovery of materials such as plastic, iron, aluminum, and refrigerant gases, with a recovery rate exceeding 85% of high-quality materials.
The specific separation line for WEEE processes various types of household appliances, allowing for the efficient recovery of components such as plastic, metals, and glass."

Semi-finished Transport

The use of modular belt conveyors and hoppers simplifies the movement of semi-finished products between different stages of the process."

Dryers

The dryers available on the market allow for the reuse of waste and scraps, improving environmental sustainability. They play a fundamental role in the production of combustible solid secondary (SSF), which can be converted into energy through combustion.

Proposed Plant by the Authors

The plant takes an innovative approach, distinguishing itself from other market solutions both by the addition of a phase and by cutting-edge controls. These controls, the subject of parallel studies detailed in a document, along with the additional phase, not only contribute to optimizing production performance and increasing process efficiency, but also ensure the quality of the Solid Secondary Fuel (SSF). In fact, SSF quality must be high to be considered as an efficient alternative by big consumers which, otherwise, would keep using primary fuel. The importance of sustainable, renewable energy sources is increasingly recognized in efforts to reduce environmental pollution and enhance energy security [61]. Various types of SSF vary in quality depending on the calorific value, and the goal is to obtain a high-quality SSF consistently from mixed municipal solid waste. In this phase of the project it is also important to make an accurate analysis of the investment to protect the capital. Integrated risk management strategies, including contingency planning, enhance plant operations by ensuring economic resilience against unforeseen costs [62]. The analysis of investments through Monte Carlo simulation provides a robust framework for assessing economic and financial risks associated with these projects [63].

Description of the Plant Proposed by the Authors

The plant conceived by the Authors is directly powered by compactors that collect urban MSW, without these wastes undergoing preliminary storage, thus avoiding environmental issues such as odors and leachate. Unfortunately, it resulted in quite an expansive practice to process big volumes of MSW efficiently while keeping

high quality standards. A future improvement will be investigated by the Authors, generalizing, and adopting a methodology used in healthcare, where process optimizations via discrete event simulation demonstrate a potential for significant cost reductions while maintaining high standards of quality and efficiency [64]. Probabilistic modelling, such as Monte Carlo Simulation, is crucial for accurately estimating project costs and managing financial risks in construction projects [65].
The plant consists of six processing stations connected in series via a conveyor belt. The arrangement of the stations is as follows:
1) Instant loading
2) Shredding
3) Drying
4) Separation and recovery of recyclable materials
5) Allocation and mixing
6) Extrusion of residual waste
This process transforms MSW into standardized SSF (Solid Secondary Fuel) with a Lower Heating Value (LHV) of 5500 KCal/kg, similar to fossil coal which has an LHV of 7000-8500 KCal/kg. The produced SSF is classified as EoW (End of Waste), meaning it is no longer considered waste and can be legally stored and transported.

Innovations of the Plant and Controls Proposed by the Authors

The plant proposed by the Authors stands out for the following innovations compared to competitors:

- Allocation and Mixing (Fig2., Phase 5): This station allows for the control of SSF component percentages, ensuring consistent quality of the final product (introduced in 2017).
- Controls: Integration of advanced control technologies at both Industry 3.0 (introduced in 2017) and Industry 4.0 (introduced in 2022) levels. These advanced control systems enhance the quality of recycled materials and the compliance of SSF with regulatory standards. The integration of a stochastic model in process control is currently under implementation, with the scope to facilitate a more dynamic adjustment of operational parameters, ensuring both efficiency and compliance [66].

The Authors specify that they will not engage in the direct production of these plants, but have focused on the functional layout and control system, both proposed for adoption by other manufacturers in the sector. This approach facilitates the adoption of their innovations, improving the efficiency and effectiveness of waste treatment plants globally.

Fig2.Functional layout of the plant.

Meaning and Importance of the Allocation and Mixing Phase

The allocation and mixing phase plays a crucial role in the process of transforming urban solid waste into solid secondary fuel (SSF). This phase occurs after the initial four treatment phases, which include loading, shredding, drying, and separation, and precedes the final phase of SSF extrusion. In this critical stage, the treated waste is accumulated in dedicated silos. This phase is a key step that directly impacts the quality and effectiveness of the produced SSF, supporting the goal of turning waste into a valuable and sustainable resource.

Silo Storage and Quantitative Selection

Silo storage offers several advantages. Primarily, it enables flexible material flow management, as processed waste can be stored awaiting the next phase. The availability of materials in silos allows plant operators to precisely select and dose the quantities needed for SSF production. This precise selection is essential for maintaining the consistency of the final mixture.

Control of Component Percentages

The ability to control the percentages of different components that go into SSF production is essential for ensuring the quality of the finished product. Through the allocation and mixing phase, it is possible to adjust the proportions of various materials (such as plastic, paper, metals, and other inert materials) to meet specific quality and regulatory standards. Standardizing the composition of SSF is critical not only to meet energy requirements but also to ensure that the fuel possesses consistent combustion characteristics.

Consistent Quality Assurance

The process of accurate mixing ensures that each batch of produced SSF maintains the same physical and chemical properties, significantly reducing quality variations between batches. This not only enhances the effectiveness of SSF as a fuel but also ensures that end-users—such as power plants and other facilities utilizing SSF as an energy source—can rely on a consistent and reliable product of uniform quality.

Long-Term Implications

Effectively implementing this phase in the SSF production process has long-term positive implications for environmental sustainability and the circular economy. The employment of modern methodologies that incorporate both traditional data analysis and real-time adjustments can significantly enhance the operational accuracy and responsiveness, crucial for achieving long-term sustainability goals in industrial operations [67]. Accurate control of components not only optimizes waste utilization as resources but also minimizes the release of harmful emissions during combustion, thus contributing to reduced environmental impact.

Innovations in Controls: Impacts on Processes and SSF Quality

The innovative controls introduced by the authors, operating according to the paradigms of Industry 3.0 and 4.0, play a fundamental role in optimizing the production process of solid secondary fuel (SSF). As demonstrated in related research, the application of advanced control systems enhances operational efficiencies and compliance in production environments [68]. These advanced controls are not merely functional; they are designed to adapt and self-configure based on the specific conditions of the process, making the entire system more efficient and responsive. The innovative controls introduced by the authors represent a significant breakthrough in the management and effectiveness of waste transformation plants, with significant impacts not only on the quality of the final product but also on overall sustainability and operational efficiency of the plant. A future innovation could consist in a System Dynamics (SD) approach which helps in modelling activities to efficiently manage operations under various scenarios, utilizing a decision cockpit for real-time data management and decision-making [69].

Adaptability and Self-Configuration of Controls

The adaptive and self-configuring approach of the controls allows for continuous monitoring and adjustment of plant operations in real-time. This means that every phase of the process, from waste reception to the final production of SSF, is optimized for current conditions rather than relying solely on predefined settings. This flexibility ensures that the process is always aligned with best operational practices, maximizing the effectiveness of waste transformation and the quality of the produced SSF.

Standardization and Product Consistency

Advanced controls ensure the standardization and consistency of standardized SSF. Through constant monitoring and adaptation of process variables, a uniform quality of SSF is maintained, meeting the required energy and environmental standards. This precision in process control reduces variability in the final product, ensuring that each batch of SSF meets specifications.

Improvement in Maintenance and Extension of Plant Operating Life

By implementing control systems that include predictive maintenance and timely intervention procedures, plant maintenance is significantly improved. The ability to anticipate problems before they occur reduces machine downtime and prolongs the life cycle of components and the entire system. This not only reduces maintenance costs but also improves the availability and reliability of the plant.

Sustainability: Environmental, Political, and Social Perspectives

Advanced controls significantly contribute to the sustainability of the plant on various fronts. On one hand, they optimize energy and resource consumption, minimizing the environmental impact of daily operations. On the other hand, they enhance control over atmospheric emissions, reducing pollution and facilitating compliance with stricter environmental regulations. These improvements not only benefit the environment but also strengthen the political and social sustainability of the plant, promoting greater acceptance from local communities and stakeholders.

Resilience and Problem Anticipation

Finally, the adoption of advanced self-diagnostic principles based on statistical process control allows the plant to anticipate problems before they cause significant disruptions. The ability to proactively identify and resolve potential failures or inefficiencies means that the plant can operate with greater continuity and resilience, essential for maintaining constant and reliable SSF production.

Safety and Health 4.0

As a final aspect, but not less important, the adoption of "Safety and Health 4.0" technologies enhance plant safety and health by integrating advanced digital tools like IoT sensors and AI, which dynamically manage safety and health protocols. AI in particular can provide great value in forecasting [70], in both public and private sector [71] . This system detects irregularities and potential hazards, allowing for immediate response and adjustment of safety measures in line with operational changes [72], especially when it comes of hazardous substances [73]. Intelligent sensors placed in critical areas help pre-empt risks, thus preventing accidents. This proactive approach not only strengthens the plant's safety and health infrastructure but also fosters a pervasive safety and health culture across all organizational levels, ensuring a secure environment for all employees. [74], [75], [76], [77] highlight the application of Industry 4.0 to enhance safety and efficiency in industrial settings. Moreover, also maintenance of the system is improved with modelling [78] and data science [79].

Importance of Recycled Materials in the Context of the Circular Economy

The recycling process implemented in the described plant, involving materials such as metals, glass, wood, paper, inert materials, and high-value plastics, proves crucial for adhering to the principles of the Circular Economy. In [80] Pinna et. al highlight the importance guaranteeing material efficiency, reduction of raw material, increase usage of renewable material and waste reduction. This approach not only allows for the recovery of precious resources that are dwindling on the planet due to excessive and often irrational exploitation but also creates a secondary business opportunity through the resale of recycled materials. This activity not only benefits the ecosystem but also incentivizes SSF producers to value this phase of the process. In addition to this, another option to improve energy consumption and decrease waste materials is to prioritize the SSF batches in production, according to the mix available in the silos. For example, using advanced scheduling models incorporating energy-aware objectives, which offer significant enhancements in sustainable manufacturing, supporting a more efficient allocation and use of resources [81].

The Special Case of Glass

The treatment of glass in the proposed plant deserves thorough analysis. Initially, glass is shredded and then sent to landfills or glassworks to be transformed into bubbles, which are used as insulating materials in construction (e.g., in bricks) or tiles. Glass processing is complex and expensive: about 120 kg of raw materials are needed to produce 100 kg of glass, and the process requires melting temperatures above 1500 degrees Celsius, as well as half a kilo of oil for every kilo of glass produced. Separate collection by color and type (such as glass and Pyrex) is essential to allow targeted reselection and optimal use of each type of glass, including scrap. The latter, if mixed 80% with raw materials, can significantly reduce the melting temperature, saving up to 20% of oil.

Environmental Impact of Untreated Glass

It is important to emphasize the environmental impact of untreated post-consumer glass: a bottle abandoned in the sea can take up to 1000 years to decompose, while if buried in the ground it can take hundreds of years. Therefore, post-consumer glass treatment becomes crucial, not only for saving raw materials and oil but also for minimizing environmental damage. Effective end-of-life management of materials, through de-manufacturing and recycling, is vital for sustainable development and reducing environmental impact, facilitating a transition to a circular economy [82].

This understanding highlights the need for a more sustainable and responsible approach in the treatment of recyclable materials, especially for those with long degradation times and significant resource requirements for their production.

Results

The results of the literature review underscore the importance of the applying principles of circular economy, particularly reuse and recycling, to create value and employment opportunities from waste, aiming to achieve economic prosperity and social and environmental progress. Indeed, bad waste management has negative effects on environment, health, and economy. Moreover, waste management poses significant challenges, particularly in developing countries where population growth outpaces, and infrastructure and political consensus is lacking. The last result indicate that landfilling remains the predominant method of waste disposal despite, as incineration, presents environmental challenges. Nevertheless, there exist innovative solutions for sustainable waste management, such as the utilization in construction sector or energy generation. The results obtained from studies and simulations highlight the needs of facilities for transforming Urban Solid Waste (USW) into Secondary Solid Fuel (SSF), their feasibility and effectiveness, and possible solutions for improvement. Quantitative and qualitative data regarding the percentage of successfully converted waste, the composition of the resulting SSF, and associated environmental impacts will also be presented. This section will further illustrate the energy efficiency of SSF compared to other conventional energy sources.

Discussion

The discussion will focus on interpreting the obtained results, highlighting the practical and theoretical implications of transforming Urban Solid Waste (USW) into Secondary Solid Fuel (SSF). The challenges encountered during the large-scale implementation of this technology will be explored, along with the opportunities and benefits arising from it. Themes related to the long-term sustainability of SSF will also be addressed, considering economic, social, and environmental aspects.

Conclusions

In this section, the main conclusions drawn from the research will be synthesized. The implications of the findings in terms of necessary-solution linkages and their impact on waste management, environmental sustainability, and energy efficiency will be discussed. It will be emphasized how the conversion of Urban Solid Waste (USW) into Secondary Solid Fuel (SSF) can contribute to a broader transition toward a circular economy, where waste becomes a resource, and the very concept of waste is redefined. This transformation not only provides immediate environmental benefits but can also play a key role in building a more sustainable and resilient society in the face of global environmental challenges. From this perspective, research and implementation of USW transformation into SSF emerge as a fundamental priority for efforts aimed at creating a future where waste management is harmonized with environmental protection. Finally, recommendations for future developments and implementations will be provided, underscoring the importance of SSF as a crucial component of an integrated approach to waste management.

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The References section will provide a comprehensive list of sources cited in the document, including scientific publications, regulatory documents, and case studies related to the transformation of Urban Solid Waste (USW) into Secondary Solid Fuel (SSF) and sustainable urban waste management.

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