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EDITOR-IN-CHIEF'S WORD

Dear Readers,

It is a privilege to introduce our new issue of Engineering Power, which focuses on innovative approaches to energy efficiency and sustainability. The global transition towards cleaner and more efficient energy solutions has become a key priority, driven by the need to reduce our reliance on fossil fuels and mitigate environmental impacts. Achieving this transition requires continuous advancements in renewable energy integration, energy storage, and sustainable resource management. This issue highlights emerging technologies and methodologies that support energy transition goals. The research featured here underscores the importance of efficiency, sustainability, and technological innovation in shaping the future of energy systems. I hope that these insights will inspire further exploration and development in this vital field.

Editor-in-Chief
Vedran Mornar, President of the Croatian Academy of Engineering

EDITOR'S WORD

Dear readers,

I am pleased to present to you a new issue of the journal Engineering Power, again edited by Prof. Sandro Nižetić, PhD, and Assoc. Prof. Goran Krajačić, PhD. This issue covers topics related to energy efficiency and sustainability through three papers dealing with the principles of circular economy in biowaste management, numerical simulation of asynchronous e-motor and recovery of aviation oil from organic solid waste. I hope you enjoy reading.

Editor
Bruno Zelić, Vice-President of the Croatian Academy of Engineering

FOREWORD

Nowadays, there is high demand for novel and advanced technological solutions in the field of energy to meet desired energy transition goals. The key goal is to minimize and finally to completely abandon the utilization of fossil fuels that are causing serious environmental issues worldwide. The rise in renewable energy capacities followed by efficient energy storage technologies and progress in energy efficiency are key research areas that are driving energy transition in an effective way. The key request for each novel developed technology is environmental suitability, therefore, besides the request for the performance and economic improvement of specific energy technologies, the sustainability aspect is one that should be considered to secure long-term viable solutions that would effectively contribute energy transition efforts.

This special issue brings new knowledge in the field of energy efficiency and sustainability, it consists of overall three published papers. In the work, Application of circular economy principles in biowaste management, the current market issues were discussed, as well as techno-economic trends in biowaste management. The novel approach was proposed and focused on sorting of biowaste in three different categories and that was followed by identification of their suitable treatment methods. Study contributed to the better understanding of the circular economy aspects in the case of biowaste. Work Numerical Simulation of Asynchronous E-motor with Field-Circuit Coupling was related on the comparative analysis of the two numerical methods that were applied on the asynchronous electric motor (Siemens squirrel cage induction motor). The first numerical approach was obtained using the Ansys Maxwell for finite element method, while second AVL FIRE M for finite volume method. Both applied numerical approaches demonstrated well agreement between numerical simulations and data from the manufacturer. Moreover, the finite element method showed faster convergence time. Overall, proposed work demonstrated effectiveness of the demonstrated numerical approaches and that could be used to analyze performance of the asynchronous electric motors. The mechanisms of microwave heating were analyzed in work Sustainable high-quality aviation oil recovery from organic solid wastes through microwave-assisted heating technology by comparing electrical heating in the case of high-quality aviation oil recovery from organic solid waste. Study revealed the highest energy efficiency for proposed approach of 97%, while highest total energy efficiency was 63%, in the case of microwave power of 650 W and pyrolysis temperature 460 °C. Proposed approach showed promising and effective strategy for aviation oil recovery. Previously briefly elaborated papers in this special issue provided novel approaches that are contributing to the energy efficiency and sustainability aspects.

The Guest Editors would like to thank the authors for their contribution as well as to the anonymous reviewers who have helped to improve the quality of published papers. Finally, we would like to thank Prof. Bruno Zelić, PhD for providing us with technical support for managing of this special issue.

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CONTENT

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Application of circular economy principles in biowaste management

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Abstract

In developed countries, biowaste management legislation is changing rapidly over the last 2 decades due to the growing environmental awareness in society. The main benefits from changes in biowaste processing pathways for corporations come from the improvement of the corporate social responsibility (CSR) image. In developing countries, the search for suitable technology is driven primarily by efforts to minimize processing costs. This paper summarizes the current global market situation and techno-economically assesses some promising trends. It is firstly proposed to sort biowaste into 3 different categories and to combine different wastes and methods of their treatment with each other. Applying circular principles and respecting conventional financial indicators seems to be more reasonable that maximizing the added value of products obtained. It is pointed out that applying circular principles and respecting conventional financial indicators seems to be more reasonable that maximizing the added value of products obtained.

Keywords*: circular economy; biowaste; techno-economic assessment; valuation*

1. Introduction

The amount of biowaste is growing globally as more households move from low–income to lower– and middle–income class (Turkadze, 2021). Based on historical data, even 2 decades ago it was possible to generalize that large quantity of biowaste was linked to the lifestyles of the most affluent EU (Ignat and Constantin, 2021) and USA citizens (Awasthi et al., 2021), whereas in the USA the main emitter of greenhouse gases was the entire middle class (Goldstein et al., 2020). However, the sharp dynamics of population curves in developing countries (Kircher et al., 2023) and the increased pressure on the energy utilization of biowaste in the EU (Maurya and Misra, 2023) have caused that India and China tend to be the main producers of biowaste at the moment (Gul et al., 2022). In heavily populated countries, underdevelopment, poverty and corrupted public authorities are often cited as the main reason for irrational biowaste management (Mutatkar, 2020; Wang, 2020). The identification of new and perspective technologies that could minimize negative environmental impacts and turn the costs associated with biowaste management into profits are thus intensively in demand all over the world (Marousek et al., 2023a). However, most of the technologies proposed recently focus rather on obtaining products with the highest possible added value, without assessing the entire economics of the process and the technical context, including water and energy consumption. For the sake of clarity, this review paper divides biowaste into 3 basic types: type (A) (biowaste composed mainly easily biodegradable organic matter with substances based on sugars, starch, easily hydrolysable hemicellulose etc.); type (B) (liquids rich in phosphate and nitrogen substances) and type (C) (hardly biodegradable organic matter composed of cellulose with a higher degree of crystallization, lignin, etc.).

Biowaste is still unsorted in most countries and the overall mixture obtained contains type (A) biowaste the range from 1 to 40 %; type (B) biowaste usually only in a concentration up to 1% and the type (C) biowaste in the range of 1 to 70%. The type (A) biowaste represents a valuable intake for most microorganisms and thus its level in the biowaste is almost constantly decreasing over time. Type (A) biowaste includes mainly food waste and post-harvest residues (straw, corn cobs, etc.). The type (A) is often refined into sugary hydrolysates which are subsequently used in the feed industry and, with an increased degree of hygiene, also in the food industry. Concept of these procedures was reviewed by Zhou et al. (2021). It is worth pointing out that sugar solutions can be fermented into a whole range of organic compounds (such as alcohols) that can be used as fuels (Wang et al., 2020). However, current research and development in this direction does not yet inspire hope for price competitiveness with fossil fuels.

The type (B) biowastes with reasonable levels of nutrients are hard to find as concentrations of key substances tend to be variable and chemically unstable. Most often, these are digestates, slurry, fermentation residues, whey and the like. These can be refined into ammonium sulfate; phosphate fertilizers; complex fertilizers; seed coating products and others. As recently reviewed by Deng and Dhar (2023), many alternatives to precipitation technologies can be used to capture phosphorous compounds, but emerging sorption technologies have an advantage in that the captured nutrients are more easily accessible to plant nutrition (Kopecky et al., 2020). As reviewed by Wu and Vaneeckhaute (2022), ammonia stripping is among the most frequently investigated ways to recycle nitrogen from wastewater, but the economic viability of this technological pathway is problematic. To make matters worse, (B) is often present in complex molecules at low concentrations which often require high energy cost for their release (Skare et al., 2021).

As far as type (C) biowaste is concerned, these are usually bulky and their processing can be energy–intensive (Zheng et al., 2021) which makes the products obtained problematically price-competitive (Akbari et al., 2021). Common type (C) biowastes include bark; sawdust; pruning; waste wood and similar waste materials with a high proportion of lignocellulose. The most common method of refining is pyrolysis, which transforms these feedstocks into gaseous, liquid and solid residues. In addition to energy use, the usual products include charcoal; tar; technical gases and biochar, while each of these outputs can be further refined into a spectrum of products with higher added value. Following the above, the development of conventional biowaste technologies is thus linked with public incentives into acquisition of modern technologies (Simkova et al., 2022); encouraging of corporate social responsibility (Habek et al., 2019); subsidizing energy prices (Yao et al., 2022) and legislation tightening (Gavurova et al., 2019).

The exponential growth of humanity, coupled with volatility of global economy and escalating trade tensions, underscores the urgent need for heightened food production and innovative solutions at the nexus of the food industry and biowaste management (Zeller et al., 2020). Increasing recognition of biowaste valorization's pivotal role in environmental sustainability is driving the implementation of stringent regulations and financial incentives to promote environmental protection, albeit met with reluctance from major economic powers fearing competitive disadvantage (Delgado et al., 2020). Addressing such challenges necessitates an interdisciplinary approach, with recent advancements in self-learning algorithms poised to substantially contribute to solving techno-economic issues (Kliestik et al., 2023). While agricultural subsidies dominate the environmental policy landscape in developing countries, environmental legislation in developing countries remains nascent. This dynamic necessitates the development of biowaste valuation technologies that are both ecologically sound and economically viable (Dvorsky et al., 2023). Achieving exceptional financial performance in this arena demands surpassing established technologies and leveraging synergies, with emphasis on consistent biowaste quality and access to cost-effective waste energy sources. Stakeholders are actively pursuing economically viable technologies to enhance biowaste's value, focusing on nutrient recovery and organic matter enrichment. In connection with the above, the application of circular economy principles in biowaste management is a high priority of contemporary engineering.

2. Methodology

Patent (European Patent Office, United States Patent and Trademark Office, Japan Patent Office and Google Patent search tools) and Research (Cambridge Journals, EBSCOhost, Emerald Premier, Encyclopedia Britannica, IEEE Xplore, IOPscience, nature.com, Oxford English Dictionary, Oxford Journals, ProQuest Central, ProQuest EBook Central and ScienceDirect search tools) databases were searched via indexing tools for the following keywords (and its combinations): organic matter; hydrolysis; biowaste; nutrient regeneration; biowaste; circularity and valuation. Top 20 papers and patents from each database were reviewed for relevance. The identified technologies were subject to legislative and techno-economic considerations.

3. Results and Discussion

3.1. Established valorization methods

Over the past century, advancements in agricultural practices have led to a remarkable 3 fold increase in crop yields across various commodities. The increments in animal and fish production are two to four times more efficient than those reported a century ago. The remarkable advancements in agricultural productivity owe their success to a multifaceted approach encompassing traditional agricultural fields such as breeding, agrotechnics, and agrochemistry, particularly combined with applications stemming from industrialization; automation and robotization which are lately even booted by use of artificial intelligence (Kliestik et al., 2024). Despite remarkable advancements, global food systems still face significant challenges (Stehel et al., 2018). In developed countries, around 5% of fruits and 2% of vegetables are wasted, a figure that doubles or triples in developing regions. When it comes to animal products, the waste issue is almost consistent globally. It's estimated that over 2% of meat from livestock and poultry is wasted, along with nearly 3% of fish products. This waste is largely attributed to limited markets for byproducts like tongue, wings, lungs, heart, runners, kidneys, fins, or spleen for human consumption, particularly in developed countries.

The cost affordability of food varies extensively among countries as never before in extant records (Strunecky et al., 2021). As a result, health systems in rich countries face problems linked with obesity and related diseases while other countries cry for help because of malnutrition from food deprivation (Kopecky et al., 2020). However, intensive agricultural production that is driven by short-term profit is being accompanied by deforestation; a decrease in wildlife; soil erosion and loss of fertility;

contamination of water bodies with agrochemicals, and the release of greenhouse gases. Following the above, there is a general consensus that global food demand will further increase by more than 40 % in 2050 relative to 2020 (Tian et al., 2021). However, limited water and land resources altogether with climate change impacts do not match with increased food demands. Existing models indicate that the growth rate of crop production will slow down, the yield of main crops will stagnate, and biodiversity losses and environmental degradation will intensify. Critical situations can be expected, particularly in protein supply for human nutrition. It seems that the meat production (particularly poultry; pig; veal and fish) would not be able to increase sufficiently in the future to fill the meat gap demand due to lacking feed production and insufficient land area even though abandoned farmland is used in developed countries (Hall, 2018). In addition, to crops and livestock, the oceans are the critical source of protein, supplying one third of global meat demand. However, its overexploitation would probably take its toll and limit further accessibility of ocean protein. Finite food sources necessitate both to find out the alternative means of production as well as decrease its wasting. Higher efficiency in animal husbandry amended by the progress in genetic engineering of livestock (Lee et al., 2020) or production of artificial meat might solve the meat demand only partially because, in the end, all of them have a high demand for energy and nutrients.

The overwhelming majority of reviewed documents agrees that the main schism is that the contemporary food production industry has deeply incorporated unsustainable elements into its daily operations in the pursuit of increased profits (Habek, et al., 2019). On the other hand, given that plethora of unsustainable moments have been incorporated into the daily activities of all mankind, there are several options with untapped potential. Better processing of biodegradable waste (including that from landfills or sewage treatment plants) is widely agreed to be the biggest opportunity with many technological solutions available and under development. The increasing wealth simultaneously with natural humankind's greed to gather resources is, most probably, not to decrease in coming years. Currently, over 52 % of the overall global municipal waste is food waste, whereas, calculated per person, the vast majority of waste is mainly produced by less technologically developed countries (Xue et al., 2017). Avoidable losses occur due to inefficient food processing, inadequate preparation techniques, suboptimal logistics, and improper storage, including the expiration of shelf life and similar factors. It was highlighted that in undeveloped retail and consumer stages of developed countries, over 41% of food is wasted. In contrast, developing countries generate eight times more food waste in the early stages of the food supply chain compared to developed nations (Dvorak et al., 2018). It is anticipated that in the coming years, Asia will generate more than 520 million tons of biowaste. Consequently, the valorization of biowaste presents a colossal economic and environmental challenge, its resolution jeopardized by various socio-economic factors, particularly in developing countries.

There is a broad consensus regarding the high energy potential of food waste. However, when selecting the appropriate technology, three key concerns should be considered based on the current state of knowledge. Firstly, it is crucial to distinguish between easily and less easily decomposable organic matter. Secondly, one should bear in mind that certain technologies might hinder the subsequent regeneration of nutrients. When it comes to processing more easily biodegradable waste, t numerous technological options exist. In developed countries, biowaste is commonly processed through anaerobic digestion, which produces biogas for electricity, or it undergoes composting to create a soil conditioner (distinct from fertilizer due to its low levels of nitrogen and phosphorus readily available for plant nutrition). However, both of these publicly supported technologies come with significant drawbacks. In many countries, the residual material from anaerobic digestion of biowaste is subject to stringent regulations, and its disposal onto arable land is often economically unfeasible. The alternative, aerobic composting, entails converting food waste into humic compounds or stabilizing it with a soil mixture to create organo-mineral associates. Nevertheless, composting has substantial disadvantages, including significant loss of organic carbon as CO_2 (Svajlenka and Marouskova, 2023) and substantial nitrogen loss, which amount to as much as 62%, during the composting process. Moreover, the resulting compost contains minimal quantities of labile organic compounds strongly impairing its fertilizing properties. The primary advantage of compost lies in its ability to enhance the qualitative aspects of soil organic matter and improve soil's air and water management. However, the economic evaluation of these benefits can be challenging. In developed countries, farmers' demand for compost is generally low because achieving a demonstrably quantifiable fertilizing effect requires the application of substantial quantities of compost to the fields, resulting in disproportionately high costs. Although the obligation to operate sewage treatment plants has significantly improved the quality of water bodies in developed countries, the related legislation has set the rules so controversially that the management of sewage sludge is not sustainable. In its present state, critical phosphorus is mostly precipitated by iron or aluminum salts into minerals such as struvite or vivianite, which is the cheapest way of its capture. However, these minerals integrate phosphorus so firmly into their crystals that it is difficult for living organisms to access. A better way is when phosphorus is captured by sorption processes on charred waste, but current legislation is still not adapted to this technological leap. In addition to minerals, sewage sludge still contains significant amounts of hardly biodegradable organic matter (Brabenec et al., 2021). Its decomposability can be increased physically (intracellular disintegration) or thermochemically (steam explosion) so that it can be used by anaerobic digestion consortia for additional biogas production or, for example, by insects.

However, recent literature and patent documents suggest that the most profitable method for evaluating biowaste with higher labile organic matter content is through insect utilization that can be turned into valuable source of protein and fat. The attention is currently turned to growing insects for mass consumption (van Huis et al., 2013). The idea of insect utilization is old, honeybees (*Apis melifera*) and silkworms (*Bombix mori*) supply mankind for more than three thousand years. Larvae and adult insects are part of diet in many communities at the Africa and Asia due to high energetic content value. The high nutritional value and exceptionally high protein content (Rumpold and Schluter, 2013) connected with high resource efficiency to convert organic matter into protein (Nakagaki and DeFoliart, 1991). The efficiency of protein production via insect might be higher than that of any recently cultivated livestock. This approach offers a promising solution to counter pessimistic forecasts of future protein shortages (Wang et al., 2020) especially considering the projected doubling of protein consumption (by 196 %) by 2050 (Berners-Lee et al., 2018). While the previous solution was seen in lowering the protein consumption and adjusting the diet structure with a preference for a plant-based diet, the new option would be to use insects as feed or directly for human consumption (Marousek et al., 2023b). The necessary change in biowaste utilization might be its management by biological means.

Mass intensive insect rearing will be needed for large-scale production at levels dwarfing the current wild-harvest and small-scale production (Berggren et al. 2019). Food safety agencies all around the world tends to allow production of yellow mealworm (*Tenebrio molitor*), locusts (*Locusta migratoria*) and house crickets (*Acheta domesticus*) for human consumption lately. Including these ones, many other insects such as black soldier fly (*Hermetia illucens*), common housefly (*Musca domestica*), lesser mealworm (*Alphitobius diaperinus*), banded cricket (*Gryllodes sigillatus*) and field cricket (*Gryllus assimilis*) are being approved as feed especially for poultry, aquaculture, pets and pigs. The mealworm beetle (*Tenebrio molitor*) is commonly used for research purposes, and its larvae, yellow mealworm has the reputation of promising feed for majority of farmed animals. Mealworm cultivation is well established on a semi-industrial scale, being easily reared on oat flakes. Every 1 kg of raw mealworm larvae contains some 8.8 kJ, nearly 210 g of protein and 230 g of fat respectively (EFSA, 2021a). Commercial projects produce between 110 and 460 g of insects per 1 kg of biowaste, with conversion efficiency correlating most strongly with the nutritional value of the biowaste (Vochozka and Marouskova, 2018). Vast number of substrates was assessed for the production of mealworm, however, as its name suggests, larvae prefer similar food sources to humans. Flakes of various compositions showed the highest efficiency with a conversion ratio around 11 % (Rumbos et al., 2020). Beer yeast, pastry remains, spent grains and potato steam peelings showed the best efficiency (nearly 29 % conversion) in mealworm rearing (van Broekhoven et al., 2015). Other studies revealed that mealworm larvae fed on low-energy biowaste had the conversion feed efficiency below 1 % (Tan et al., 2018). The mean larvae development time ranged between 95 and 122 days independently on the diet. Migratory locust (*Locusta migratoria*) is infamously known to make huge swarms affecting extensive areas in warm climates, particularly in Africa. Locusts in nature feed on green parts of graminoids as different grass species, reeds, and cereals. However, as their population grows, they transition from a solitary phase to a gregarious phase, leading to insect plagues that can devastate not only legumes but also other plants. Products from locust larvae have high crude protein content between 43% and 54%, a well-balanced amino acid profile (EFSA, 2021b) and a production cycle within 21 days. Moreover, existing know-how on rearing and commercial scale for pet food or even human nutrition is well established. House crickets (*Acheta domesticus*) are spread worldwide in warmer areas. At 30–35 °C crickets can pass the entire cultivation cycle within 20 days (Clifford and Woodring, 1990). House crickets are omnivorous, feeding on leaves, seeds, fruit, other live or dead insects, including cannibalization (Sorjonen et al., (2019). House cricket rearing shows to be the techno-economical optimum for valorization of soya byproducts and barley leftovers. Two other crickets (banded cricket - *Gryllodes sigillatus* and field cricket *Gryllus assimilis*) of tropical origin might be used in feed production. The other species of crickets are currently accepted for feed production. Common housefly (*Musca domestica*) is a commensal insect associated with humans worldwide. Its larvae can thrive on a wide range of decaying biowaste. Housefly larvae are considered as a solution to process manure produced by concentrated animal facilities around the globe (Miranda et al. 2019). Housefly rearing can reduce nitrogen concentration in manure by 23 up to 77% and recover up to 25%, of dry matter (Roffeis et al., 2015). Lesser mealworm (*Alphitobius diaperinus*) is a tropical insect that thrives in warm, humid environments. It is one of the most common insect pests in commercial poultry farms feeding on poultry manure, spilled feed, and other organic material. However, mealworm might serve as a vector for many pathogens that cause serious diseases, such as *salmonella*, *escherichia*, and various viruses. Nevertheless, mealworm can also be used as an aquafeed ingredient, turning the insect from a noxious pest to a valuable nutrient source (van Broekhoven et al., 2015).

All the reviewed literature agrees that the black soldier fly (*Hermetia illucens*) has currently the highest industrial potential for mass rearing because its larvae are the easiest to separate from biowaste on a commercial scale. The larvae of black soldier fly are capable to develop on various biowaste (preferably fermented cereals; manure and food waste) while converting 15 up to 48 % of it into its body in usually less than 5 weeks (Ganda et al., 2019; Rehman et al., 2017). The metabolic residues of black soldier fly larvae are called frass and there is a big demand for these on the decorative flower market (Gligorescu et al. 2020). Converting 1 kg of biowaste into black soldier fly and frass to reduces release of NH_3 nearly 205 times and N_2O over 980 times in comparison to composting (Pang et al. 2020). The high efficiency of biowaste conversion into insects is usually influenced by optimal feedstock composition, particularly crude protein in formulas was between 30-40%, which is rare even in some of the most energy-rich types of biowaste. The highest efficiency of biowaste conversion (above 41 %) was reported for mealworms. The black soldier fly larvae maximal biowaste conversion match to most efficient insects. Gärttling and Schulz (2022) summarized the nutrient content in frass from literature and industrial producers of black soldier fly products. Data from 24 sources (dry matter of frass ranged from 67 to 79 %) showed that total nitrogen (N_{tot}) was on average 3 % of dry matter, with C_{tot} : N_{tot} ratio of 14.7.

The level of phosphorus P was usually between 1 and 2%, while the potassium level was usually half of that. The magnesium and calcium content are usually around 1%. These values are close to old manure, and it can be argued that frass from black soldier fly can be understood as soil improver with some long-term fertilization capabilities (Schreefel et al., 2020). As low as the content of mineralized nutrient is in frass is (in comparison to established mineral fertilizers) given the current societal trends, frass is a highly marketable commodity and many commercial projects are finding success with it in the hobby and gardening segment (Anyega et al. 2021).

The other promising alternative are fungi. Fungi are considered a viable alternative to produce high-quality protein that can be further used to substitute meat (Bonny et al. 2017). However, producing stable-quality fungal protein from biowaste appears to be extremely challenging. The main constrain is the quality assurance due to natural fungal inoculum in biowaste that would produce harmful mycotoxins due to inconsistencies in feedstock properties which are a common source of contamination vectors (Xing et al. 2019). To evade this issue, all the food waste must be deeply sterilized with high energetic costs. Regarding pyrolysis, all the economic and technological considerations across the reviewed documents indicate that the potential of pyrolysis processes remains largely untapped, particularly if it is part of a complex refining process. There is a broad consensus that the production of char or biochar represents the viable technology for treating hardly degradable solid biowaste. Nevertheless, from an economic point of view, it should be noted that it is necessary to look for biochar applications that are more lucrative than its energy use otherwise producers will prefer to sell it as energy commodity. Pyrolysis of biowaste often needs significant energy investment since many biowaste feedstocks are excessively wet or contain high levels of minerals, necessitating external energy sources. Currently, the most cost-effective method for producing biochar is based on the approach proposed by Stehel et al. (2020), which involves pyrolyzing fermentation residues from biogas plants and utilizing waste heat from a cogeneration unit that burns biogas for electricity. This concept involves using the low-potential waste heat from the combustion engine and the pyrolysis chamber to dry the mechanically dewatered fermentation residues, while the hot flue gas from biogas combustion contributes to the energy balance of the pyrolysis chamber.

The resulting biochar consists of crumbly pyrolytic structures with a carbonaceous nature, intended for use in plant production, soil enhancement, nutrient recovery, and environmental engineering in general. In addition to its agronomic benefits and soil improvement characteristics, all the reviewed documents have consistently concluded that the properties of biochar make it an outstanding tool for carbon sequestration. Its high porosity reduces material density, making it suitable as a substitute for sand in the production of lightweight concrete (Marousek et al., 2023a). The substantial porosity of biochar also makes it an excellent sorbent, capable of filtering microorganisms present in liquid forms of organic matter without further treatment. However, it should be noted that during the pyrolysis process, the majority of nitrogen is converted into a mixture of pyrolytic gases, and no economically sustainable technology has yet been defined for regenerating these gases into chemical forms suitable for fertilizing agricultural crops. Therefore, it is recommended to recover nitrogen into ammonium nitrate or sulfate before using the feedstock as raw material for the pyrolysis process (Menkveld and Broeders, 2018). From an environmental perspective, equipping the chimney of the pyrolysis unit with a water filter is advantageous, as it captures the finest soot particles and allows them to be further used for special applications.

Following the biochar production, it can be employed to recover phosphorus. To enhance the sorption capacity of biochar while maintaining cost-effectiveness, it is advisable to activate biochar using calcium fertilizers (Figure 2). As far as activation by calcium fertilizers, the highest phosphorus sorption rates are reported for biochars made from coconut shells and hardwoods, which are materials where high porosity can be expected. However, taking into account the economic side of the matter, the best results are nowadays achieved with feedstocks such as digestates or distillery stillages, the production price of which is many times lower. The cost of this activation is negligible, as calcium is an essential component for crop production. Subsequently, the modified biochar can effectively capture phosphorus in forms readily accessible for plant nutrition.

3.2 Assessment of type (A) biowaste management methods

As far as the processing of type (A) biotaste (containing rather organic matter that is more easily hydrolyzable by usual enzymes at normal conditions) is concerned, anaerobic digestion is the dominant technology in the field for several decades already (Bencoova et al., 2021), whereas biomethane (purified biogas) is the latest trend which expands the possibilities of biogas use into transport, industry and other sectors, including injection into ordinary gas pipelines. The European biogas sector is the fastest growing in the world and currently generates more than 21 billion m^3 of gas (both biogas and biomethane) and nearly 300 000 jobs (europeanbiogas.eu). For the year 2030, a target of 35 trillion m^3 has been set. Nevertheless, if mainly the purposefully grown phytomass was used to produce such a high amount of biogas, this could have negative environmental and economic consequences in the long term. It seems advantageous to diversify the feedstock and also process the type (A) biowaste so that less agrochemicals are used. However, biowaste of type (A) is most often based on lignocellulose, whose natural biological decomposition in an anaerobic environment usually takes more than 2 months. Nevertheless, the residence time in the fermenter is a key technical indicator that demonstrates direct financial implications since it can prolong the return on investment payback period of usual biogas station (1 MW of electricity + 0.8 MW of heat; investment of 2 M€) by 1 up to 3 years (Vochozka et al., 2018). For economic reasons, biogas stations processing biowaste of type (A) most often install technologies of deep disintegration of plant matter such as steam-explosion, milling,

Fig. 1: *Jean pain composting represents an low-cost method of heat production whereas a pile (4x4x4m) of type (B) biowaste can serve for family home or small business all winter long. The right section of the image shows an infrared image, where scan "A" indicates temperatures in the center of the pile (discharged to the house) are satisfactorily above 40°C and scan "B" indicates that after coming from the house heating circuit, the process fluid is returning at a temperature below 20° C.*

pressure shockwaves or enzymatic hydrolysis (Marousek et al., 2013a, b). Repeated attempts were made to use (A) in composting. However, the demand for composts is low and allows only minimalist profits (Murindangabo et al., 2023). A wide range of fermentation technologies can be found in the literature, which demonstrated the possibility of turning type (A) biowaste into hydrogen (Sarangi and Nanda, 2020); alcohols (De Buck at al., 2020); organic acids (Tsapekos et al., 2020) and other reactants such as aldehydes. Although all these products are usually of high value, the whole concept is hardly economically viable (costly reactants, high energy requirements etc.) which casts a negative light on other biorefining technologies in general (Pavolova et al., 2021). Groeneveld et al. (2021) pointed out that the biotransformation of type (A) biowaste via insect rearing has promising financial potential. The obtained larvae can be used not only as feed with a high content of valuable feed substances but can also be processed into a whole range of products based on protein and fat (Marousek et al., 2023c). Jean pain composting (Fig. 1) of type (A) biowaste has an ever-growing fan base since it allows to produce low-potential heat (40 to 70 °C) for 2 up to 5 months and is thus one of the cheapest sources of heat in the temperate and climatic cold zones. A summary of the above findings is shown in Table 1.

3.3 Assessment of type (B) biowaste management methods

Regarding the valuation of biowaste with a significant share (B), it is worth noting that there is currently a shift from precipitation technologies (such as production of struvite, vivianite and like) that were designed in the last century to modern sorption-based technologies (Priya et al., 2022). Modern sorption technologies most often use biochar as a sorbent, which is usually made from biowaste type (C), so there are different synergies between different wastes. It is worth remembering that biochar is a way of carbon sequestration, which can represent additional economic synergies. Even the modern sorption technologies for (B) type biowaste processing, however, do not show good profitability (Bartos et al., 2021), because as regards phosphorus, they compete with imports of fossil minerals (Simkova et al., 2019) and as regards the regeneration of nitrogenous substances, they compete with Fischer–Tropsch synthesis (Chen et al., 2021), whose production costs depend primarily on the prices of catalysts (Novakova et al., 2022; Rowland et al., 2021) and especially energy (Vochozka et al., 2020a).

3.4 Assessment of type (C) biowaste management methods

Incineration is the traditional way to deal with the type (C) biowaste. Although the demand for energy is constantly growing (Vochozka et al., 2020b), modern methods of type (C) biowaste regeneration are also coming to the fore. Recently, many research activities have been devoted to pyrolysis and torrefaction, especially in connection with use in agriculture (Ghorbani et al., 2023) and civil engineering (Marousek et al., 2023b). In this segment as well, countless technologies can be found that allow the type (C) biowaste to be refined into a whole constellation of commodities with high added value, such as Bishenol A (Shah et al., 2021); furfural (Sherif et al., 2021), pigments for pains (Bhakare et al., 2020); sorbents (Binh et al., 2022) and many others. However, simulation modeling by digital twins of material and energy flows (Valaskova et al., 2024) indicate that such refining pathways do not tend to improve the corporate performance (Valaskova et al., 2023). However, customers remains skeptical of biowaste refining because, unlike fossil fuels, the type (A) biowaste is hardly available in constant quality throughout the year.

Table 1. *A simplified summary of economic and environmental perspectives with regard to the current state of the global market.*

Feedstock	Technology	Products	Economic sustainability	Environmental sustainability
A	hydrolysis	sugars	good	high
A	fermentation	alcohols	unsustainable	N/A
A	fermentation	biogas	good	good
A	biocatalysis	aldehydes	good	good
A	composting	compost	low	good
A	pyrolysis	biodiesel	unsustainable	N/A
A	fermentation	hydrogen	unsustainable	N/A
A	Jean Pain	heat	good	high
A	fermentation	organic acids	good	high
A	rearing	insects	high	high
B	precipitation	phosphate minerals	unsustainable	N/A
B	sorption	phosphates	good	high
B	mixing	ammonium sulfate	low	high
B	mixing	ammonium nitrate	good	high
C	pyrolysis	charcoal	low	high
C	pyrolysis	tar products	low	good
C	combustion	energy	low	good
C	pyrolysis	gases	low	low
C	pyrolysis	biochar	good	high
C	combustion	ash	low	good
C	pyrolysis	cement substitutes	good	high

4. Conclusions

In order to improve the economy of biowaste management it is proposed to sort biowaste according to the quality of organic matter and nutrient content into several basic categories (analogous to solid waste, where metals, paper, plastics, etc. are sorted, for example). Furthermore, it is advisable to deviate from the complex refining of products with the highest possible added value and choose refining pathways with regard to the variability and year-round availability of biowaste with established indicators of financial performance in mind.

Insect rearing and Jean Pain composting appears to be the most efficient methods of the type (A) biowaste management at the moment. Fungi cultivation hold promising potential for the near future, yet the challenge lies in mastering the technology to ensure both robustness and the elimination of toxic metabolites in mass fungi production. Regarding the type (B) biowaste, sorption of phosphate on biochar and refining of ammonium nitrated seems to be the most promising at the moment. However, both technologies still face some challenges as far as mass commercialization is concerned.

Regarding type (C) biowaste, the most reasonable valorization technology is pyrolysis, whereas use of the most profitable use seems to be production of specialized biochar applications and cement substitutes.

5. Literature

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Numerical Simulation of Asynchronous E-motor with Field-Circuit Coupling

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Abstract

The focus of this work is a comparative analysis of two numerical methods for asynchronous electric motor simulations. Magnetic potential formulation is employed in each method separately, using Ansys Maxwell for finite element method and AVL FIRE M for finite volume method. 2D simulations are conducted on a Siemens squirrel cage induction motor validating the simulation results on the datasheet information form the manufacturer. Although axial symmetry is exploited for a 2D approach, 3D effects of a rotor cage are considered coupling the field and circuit equations. End ring resistance and inductance are fed directly into the solver which has been proven to increase the accuracy of the results from the regular 2D approach and is feasible in both methods. Torque results for both methods incorporating field-circuit coupling show discrepancies of less than 5% compared to the data from the manufacturer. Conversely, simulations omitting field-circuit coupling show higher torque discrepancies of more than 10%. Two initialization strategies are used to demonstrate the superior speed of the torque output with frequency domain initialization compared to the steady state case. Numerical results show excellent agreement between the numerical simulations and the data from the manufacturer. Also, convergence time is investigated varying mesh sizes for the finite volume method. Finally, it is shown that a faster convergence time is achieved employing the finite element method mainly since it was running with a coarser mesh not containing boundary layers.

***Keywords**: Squirrel cage induction motor; magnetic potential; 2D simulations; finite volume method; frequency domain simulation*

1. Introduction

Electrification of the transport sector in the last decades has sparked the development and research of electric motors. It is well established that numerical analysis of electrical machinery is the essential tool in the field of electrical engineering. Regarding the market representation, the most prevailing motor in the world is still the squirrel cage induction motor (SCIM), due to its simplicity and robustness, making it a subject of design optimization and performance evaluation in the engineering community.

The industry standard for the analysis of electromagnetic phenomena in electric machines is the Finite Element Method (FEM). Numerous FEM-based software packages have been employed to perform electromagnetic simulations enabling engineers to predict the behavior of SCIMs [1]. These simulations provide valuable insights into motor performance under different operating conditions and aid in the design and optimization process. FEM-based simulations are also used as a starting point for prototyping and testing of electric motors for electric vehicles applications, reducing the price of the design process [2]. Due to a good accuracy-computational efficiency trade-off, 2D electromagnetic analysis is often employed on radial machines instead of a full-scale 3D analysis [3]. Moreover, field results gathered from a 2D geometry simulation can be used as an input for a thermal analysis accounting for electromagnetic losses as heat sources in thermal analysis [4]. To increase the accuracy of a 2D FEM model, 3D effects are considered via field-circuit coupling [5]. Herein, stator winding and rotor cage end regions are modelled by resistance and inductance circuit elements [6]. Such coupled models are employed in time-stepping finite element analysis to calculate stator and rotor core hysteresis losses [7]. Regarding the time discretization of a 2D FEM field-circuit model, time-periodic finite element method can be employed to reduce computational effort compared to a classical time-stepping method [8]. Moreover, additional 3D effects such as radial ventilation ducts can be considered through use of equivalent permeability in stator and rotor cores, accounting for permeabilities of air and steel separately [9].

While FEM is the go-to numerical method for electric machinery simulations, researchers have been exploring alternative methods with comparable accuracy and computational efficiency. Here, Finite Volume Methods (FVM) comes in play as an established method in computational fluid dynamics and increasingly applied in electromagnetic simulations in recent years. FVM has been employed to simulate the behavior of an induction motor in 2D geometry on a test case from COMPUMAG conferences i.e., TEAM problem 30a [10]. Obtained results are in good agreement with analytical results confirming the accuracy of the method [11]. Further development of FVM for SCIM applications in 2D geometry was undertaken by Petranović et al. to couple the external circuit and field equations for rotor bars currents, incorporating 3D effects of a short-circuited squirrel cage rotor in a 2D model [12]. Rotor end ring currents are directly coupled with magnetic potential field equation through potential gradient term i.e., voltage, which leads to an altered system matrix. The influence of additional terms is practically included in the simulation assigning the amount of end ring inductance and resistance. Recent development of finite volume framework for SCIM applications has raised the question of this approach comparability with the traditional finite element framework.

On that account, 2D analysis of a three-phase squirrel cage induction motor with external circuit coupling is conducted employing two different numerical approaches. Finite element analysis is conducted using Ansys Maxwell, while the finite volume analysis uses AVL's Fire M. Both software packages are using $\vec{A}$-Φ formulation to describe electric and magnetic fields which is an advantage regarding the comparability of methods. To the best of the author's knowledge, there haven't been any publications regarding 2D simulations of SCIM with field-circuit coupling applied on an existing SCIM in the finite volume framework. Therefore, this paper is focused on investigating a real Siemens SCIM employing a 2D approach with field-circuit coupling offering a possibility of results validation on the data from the manufacturer. Both methods are using transient simulations, assisted with frequency/eddy current solutions for shorter initialization time, and a more rapid convergence. Transient simulations with steady state initialization are also conducted to show the influence of initialization techniques on convergence time. Complexity of use and computational efficiency are compared for both methods and mesh sensitivity analysis is conducted.

2. Model assumptions and equations

Before the equation overview, some model assumptions and clarifications are stated here.

1. All simulations carried out in the scope of this paper are in 2D geometries spanning the x-y plane on a radial machine which implies the following. Current density vector and magnetic potential vector both have only one component which is in z direction. Similarly, magnetic flux density and field intensity have components in x and y direction.
2. Eddy effects are omitted in both stator and rotor cores considering the lamination of both parts. Stacking factor is equal to one.
3. Stator edge effects are neglected and modelled with zero magnetic potential boundary condition.
4. 3D effects are considered only in rotor accounting for the end ring resistance and inductance coupling the field equations with external circuit equations. Stator winding 3D effect are not considered.

Field equation solved numerically is derived expressing Ampère's circuital law through magnetic vector potential. Quasistatic equation omitting the displacement current term in $\vec{A} - \Phi$ formulation is defined in (1).

$$\nabla \times \frac{1}{\mu}(\nabla \times \vec{A}) = \sigma\left(-\frac{\partial \vec{A}}{\partial t}\nabla\Phi + \vec{v} \times (\nabla \times \vec{A})\right) \quad (1)$$

The double curl term on the left-hand sign can be rewritten as diffusion term, while the right-hand side amounts to a current source density term and a total time derivative encompassing a partial derivative of and a motional term for the induced current calculation as show in (2).

$$\nabla \cdot \frac{1}{\mu}(\nabla \vec{A}) = \sigma\left(-\frac{d\vec{A}}{dt} - \nabla\Phi\right) \quad (2)$$

$-\nabla\Phi$ term is not explicitly calculated but is instead imposed as a source current density in the stator winding to describe the differences in electric potential. $-\nabla\Phi$ term in rotor bars is used to couple the field-circuit equations, but electric potential is once again not explicitly solved. Therefore, electric potential calculation is not explicitly calculated anywhere in discretized space. Instead, rotor bar current in 2D geometry exists because of a changing magnetic flux density (magnetic potential), to which the $-\nabla\Phi$ term is contributing through end ring inductance and resistance. v×(∇×A) term is present in the rotor domain which is separated from stator domain at the half distance of air gap length.

Since this work also encompasses frequency domain solution initialization, an equation for this solution type is given in (3). Unlike the transient simulations, which are solved in multiple time steps using backwards Euler to discretize the time derivative, field equations are solved in a single step like magnetostatic simulations. The difference is that here, magnetic vector potential is solved in a complex space assuming harmonic magnetic field due to harmonic source excitations. Field equation then looks like:

$$\nabla \cdot \frac{1}{\mu_{eff}}(\nabla \vec{A}_C) = \sigma\left(-j\omega\vec{A}_C - \nabla\Phi_C + \vec{v} \times (\nabla \times \vec{A}_C)\right) \quad (3)$$

Where μ_{eff} is an effective permeability, and ω is an angular frequency [13]. $\vec{A}_C$ and Φ_C are complex values of a magnetic and electric potential written through their real and imaginary part as:

$$\vec{A}_C = \vec{A}_R + j\vec{A}_I \quad (4)$$

$$\Phi_C = \Phi_R + j\Phi_I \quad (5)$$

In the finite volume approach used by Fire M, equations (1) and (3) are discretized in time and space occupied by mesh consisting of finite volumes. Magnetic potential equation is then solved for each finite volume yielding the value of magnetic potential in the center of the volume i.e., approach is cell centered. Conversely, the finite element approach employed by Ansys Maxwell for solving the Ampère's equation is edge/node based using tetrahedra/triangles for space discretization [14]. Ansys Maxwell employs the first order edge elements for the magnetic vector potential and second order nodal elements for the electric potential. Magnetic potential in one finite element is defined as:

$$\vec{A} = \sum_{k=1}^{Ne} a_k \vec{N}_k \quad (6)$$

where a_k is the circulation of the magnetic potential along a finite element edge, and $\vec{N}_k$ is the edge shape function associated with kth edge. $\vec{N}_k$ is defined as:

$$\vec{N}_k = n_n \nabla n_m - n_m \nabla n_n \quad (7)$$

3. Induction Motor Design

The electric motor chosen for software comparison is an asynchronous 36/26 Siemens motor with squirrel cage rotor. Electrical data is acquired from the manufacturer's datasheet [15]. Motor geometry is measured from the actual motor and drawn in CAD-software which is used to feed the meshers of both software. Important geometrical and electrical data are shown in table 1.

Table 1. *Geometrical and electrical data*

Geometrical data		Electrical data	
Outer stator diameter	125 mm	Rated power	0.75 kW
Rotor diameter	75 mm	Rated speed	1395 rpm
Shaft diameter	32 mm	Rated torque	5.1 Nm
Air gap length	1 mm	Frequency	50 Hz
Axial length	70 mm	Rated current	1.88 A (VY)
Stator slots	36	Number of phases	3
Number of strands	91	End ring inductance	$4.7 \cdot 10^{-9}$ H
Rotor slots	26	End ring resistance	$1.565 \cdot 10^{-6}\,\Omega$

End ring resistance and inductance are calculated analytically and used as an input in both software [16].

The value of phase resistance necessary for end ring resistance calculation is computed assuming the rotor bar temperature to be 75 °C. Calculated resistance is subsequently used to couple the external circuit of the rotor edge with field equations. Motor layout is shown in Fig. 1.

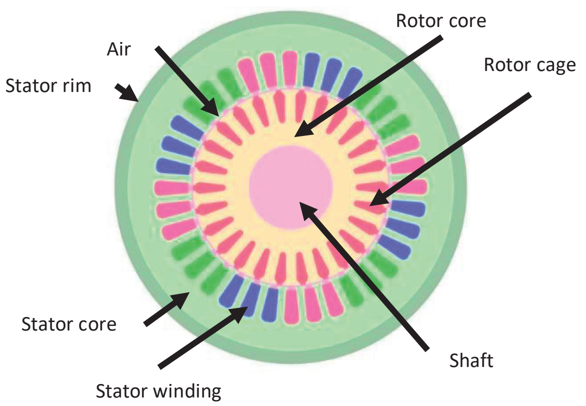

Fig. 1. Induction motor layout

4. Mesh and Numerical Setup Mesh

Once all the necessary geometrical data is acquired, 2D meshes are generated in both software. Tetrahedral Mesh in Ansys Maxwell is on a 2D sheet, while Fire M uses a different approach due to the finite volume-based formulation which requires a physical volume to discretize the space. This is achieved by having a one cell depth in the 3rd dimension, so the mesh technically has an arbitrary long third dimension. Meshes are shown in figure 2.

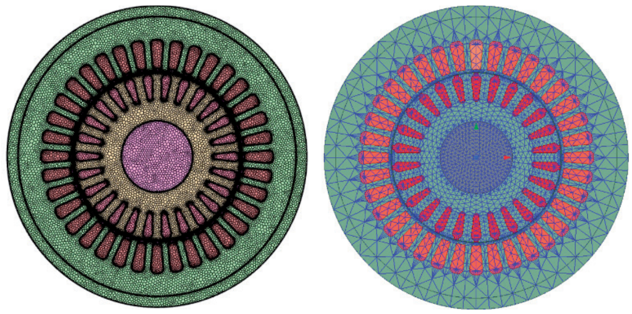

Fig. 2. Computational mesh: Fire M (left), Ansys Maxwell (right)

It is apparent that Maxwell is using a much smaller mesh consisting of 8780 tetrahedral elements, while the mesh in Fire M is consisted of 91562 cells, most of which are polyhedral. Finite element mesh is much smaller since Maxwell uses proprietary adaptive mesh refinement algorithms by default, which are automatically designed to detect and refine the mesh in regions with the largest field error. The mesh is initially created for the magnetostatic case using the adaptive refinement with the energy error parameter set to 1% and after that fed to the transient simulation [14]. Regarding the complexity of use, it is important to state that both software come with automated tools for mesh and model assembly requiring minimal input of geometrical and electric data, which also generate the meshes. The software then takes advantage of axial symmetry and solves only half the domain reducing computational effort. However, in this case, author created the full mesh by hand, employing the default setup from each software. Taking the movement of rotor into account, special care needs to be taken when creating the mesh in Fire M which uses a more complex approach opposed to Ansys Maxwell. Here, rotor and stator need to be physically disjointed in the middle of the airgap to allow for the use of mesh deformation formula which manages the rotation of each rotor cell in a time-marching scheme [17]. Note: Mesh deformation is just the name of the utility in Fire M which is in charge of mesh manipulation by user. Since the cell nodes in the air gap, although identically positioned are disjointed, no mesh deformation takes place. Instead, only the rotation is occurring. On the other hand, Ansys Maxwell uses the motion band feature to set up rotation of the rotor which is applied to a circle in the airgap previously assigned during geometry manipulation. Rotational speed is kept constant amounting to 1395 revolutions per minute.

Time dependency

Both software run transient simulations with a duration of 1 second and a time step of 1 millisecond, or 1000 time steps. When considering the sinusoidal dependence of winding sources with phase angle shifts for the B and C phase, source terms setup in both approaches is quite similar. Furthermore, the excitation method used employs stranded configuration, which ignores the eddy effects (skin and proximity effects) in the winding domain. The only domain where the eddy effects are calculated is the rotor bars because electrical steel lamination also causes them to be ignored in the rotor and stator core.

Boundary conditions

Boundary conditions are the same in both software with the default boundary condition on every multi-material interface where the direction of the magnetic field is prescribed in equation 8. The outer edge of the domain surrounded by air has the zero magnetic potential prescribed as $\vec{A} = (0,0,0)$.

$$\vec{n}x\vec{H} = \vec{0} \tag{8}$$

Initial conditions

Two different simulations are run to highlight the significance of proper initialization from the perspective of the initial conditions. To provide the solver with the magnetic potential result in the first simulation, steady state initial conditions were used. The frequency/eddy current solver is used in the second simulation as the initial solution in the zeroth time step. Simulations converge much faster than in the steady state initialization case, demonstrating significant time savings for the same configuration because the frequency solver also calculates induced current in the rotor bars.

Solver and other differences

The two software also differ in the type of solver used for calculating the linearized system of equations. Ansys Maxwell uses a direct solver by default, while Fire M employs an iterative solver, in this case a generalized minimal residual. The relative residual tolerance for an iterative solver is set to . Solution obtained from the direct solver is considered as an exact solution within the limits of numerical precision.

Frequency/eddy current solver

Instead of using the moving mesh with a sinusoidal excitation, slip frequency and phase angles are assigned to the winding domain. Slip frequency is set as =3.5 Hz and the phase angles are set to 0° for phase A, 120° for phase B, and 240° for phase C.

5. Result analysis

Displayed results are divided in two parts. Firstly, steady state initialization results are presented alongside the simulation time and mesh sensitivity analysis. After that, frequency domain initialization is shown.

Steady state initialization

Regarding the steady state initialization, it takes the simulations at least 20 stator electrical periods to approach the steady state value. Convergence plot of torque values for both software is shown in figure 3. Curves are almost identical and follow the same trend with a minor peak in value in the beginning of simulation. Simulations are carried out in no load condition.

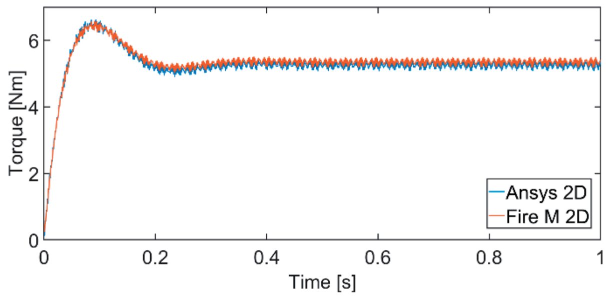

Fig. 3. Torque convergence, steady state initialization

Averaged values over the last two stator electrical periods are shown in table 2 and compared with a reference torque. Results overshoot the reference value by approximately 5%. Values of torque obtained with exact simulations in table 2, but without end ring coupling are shown to emphasize the importance of rotor edge effects. Discrepancies are undershooting the reference value by 10%.

Table 2. *Torque results*

	Datasheet	Fire M	Ansys Maxwell
Torque with end ring	5.1 Nm	5.34 Nm	5.27 Nm
Torque without end ring	-	4.68 Nm	4.65 Nm

Field plots for magnetic potential and magnetic flux density are shown in figures 4 and 5. It is apparent they are almost in perfect agreement.

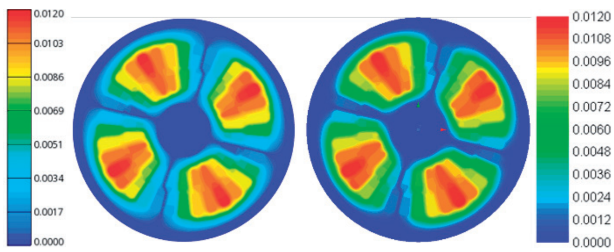

Fig. 4. Magnetic potential field: Fire M (left), Ansys Maxwell (right)

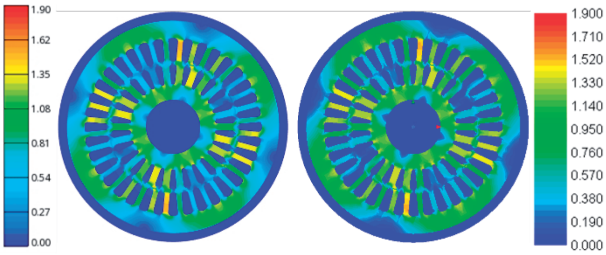

Fig. 5. Magnetic flux density field: Fire M (left), Ansys Maxwell (right)

Considering rotor bars are the only domain where eddy effects are calculated, induced current from an arbitrary rotor bar is examined and compared between the two software. Results are shown in figure 6. Once again, the curves are almost overlapping verifying the validity of an alternative finite volume approach.

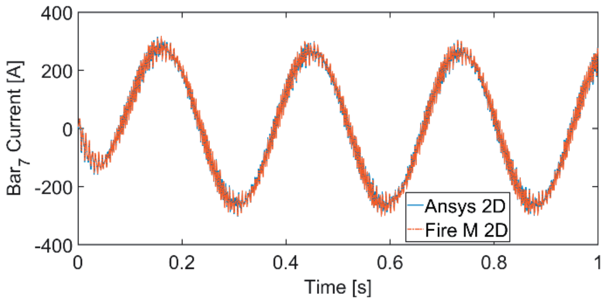

Fig. 6. Induced current in Rotor bar 7, steady state initialization

Simulation Time

For comparability purposes, both simulations incorporating steady state initialization with initial meshes are run on 4-CPUs on an Intel Xeon CPU E4-2650 processor. According to expectations, Fire M simulation on a much larger mesh takes longer to complete. One of the reasons is the use of boundary layer as a default setup in 2D polymesher which substantially increases the number of cells. Therefore, a mesh sensitivity analysis is carried out generating 3 additional meshes with fewer cells. Comparison of CPU time is shown in table 3.

Table 3. *Computational time comparison*

	Average WCT	Torque
Ansys Maxwell	45 min	5.27 Nm
Fire M - 91562	169.1 min	5.34 Nm
Fire M - 48970	127.3 min	5.33 Nm
Fire M - 32908	119 min	5.36 Nm
Fire M - 12015	80.2 min	5.17 Nm

Reducing the mesh size in finite volume approach by factor of 8 has decreased the computational time by a factor of 2 with limited impact on the accuracy of solution. Torque in the smallest mesh shows minor difference considering no boundary layers are used in the air gap where the torque is calculated. Induced current shape in smaller meshes is also well described. It is important to state that both software have output all available field plots for each time step which has increased the simulation time significantly. This is once again done for comparability purposes since Ansys Maxwell integrates the current density over the surface of a rotor bar to get a plot shown in figure 6. Incorporating that additional time for results output, makes the total time to 62 minutes. On the other hand, this time is incorporated into Fire M's WCT, since the user needs to manually add all integral results and field plots necessary for results evaluation before the simulation. This just proves simulation time heavily depends on the wanted output result, which makes it difficult to properly compare simulation time from both methods. Comparing the smallest polyhedral mesh with tetrahedral mesh gives similar accuracy, with slightly higher computational time. Therefore, it is concluded that employing a coarse mesh in finite volume approach offers a viable alternative for 2D approach for SCIM numerical analysis.

Frequency domain initialization

Initialization with frequency domain solver offers the advantage of faster convergence to a steady state solution compared to steady state initialization approach. Main cause of this is the consideration of the induced currents in rotor bars, which in turn give different results of the magnetic field and subsequently, magnetic potential. Figure 7 shows the comparison of current density field in frequency/eddy current solver. It is noticeable that induced currents are homogenous within each rotor bar.

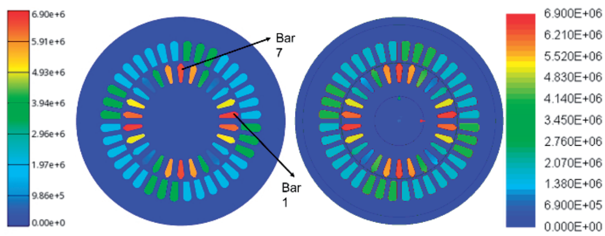

Fig. 7. Current density field: Fire M (left), Ansys Maxwell (right)

Comparison of calculated torques and induced currents in selected bars is shown in table 4. Results are in very good agreement and the discrepancies are almost non-existent. Torque prediction is very close to the reference value from the manufacturer with a discrepancy of less than 4%.

Table 4. *Frequency domain results*

	Ansys Maxwell	Fire M
Torque	5.30 Nm	5.29 Nm
Bar 1 Current	265.53 A	265.45 A
Bar 7 Current	-260.71 A	-259.92 A

Once the simulations in the frequency domain are finished, results for the magnetic potential are fed to the transient solver in a similar manner for both software. Simulations are also run for 1 s. Figure 8 shows the convergence of frequency/eddy current initialization compared to a steady state initialization. It is shown that convergence of both transient solvers is very similar to each other with small discrepancy following the trend from steady state initialization convergence. It is also apparent that the simulation converges in the first few time steps so the end time of the simulation beyond this comparison could be significantly reduced depending on the wanted output quantity.

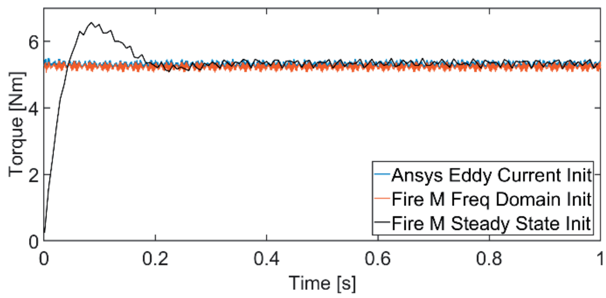

Fig. 8. Torque convergence, frequency domain initialization

Figure 9 shows the convergence of the same bar current as figure 6, but with frequency initialization. It is visible that the current is starting from the values shown in table 4., unlike the steady state initialized solution where the current starts from zero. Overall computational time is almost identical to steady state approach for 1000 timesteps (excluding the short time it takes the frequency solver to converge), but in practice can be shortened. To describe a one electrical period of a rotor bar current it is sufficient to run the simulation for 0.286 seconds in which time this motor makes more than 6 revolutions around its axis for the current slip frequency.

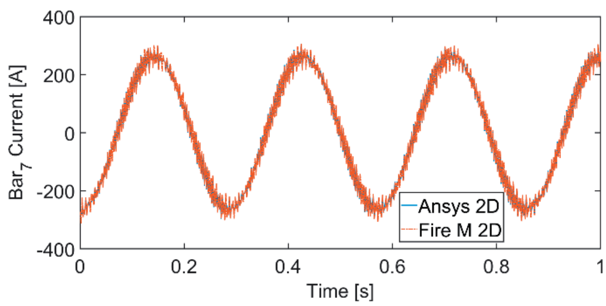

Fig. 9. Induced current in rotor bar 7, frequency domain initialization

6. Conclusion

Finite element and finite volume method performance are compared analyzing the behavior of a squirrel cage induction motor employing commercial software. Ansys Maxwell and Fire M show almost identical results for relevant field quantities, as well as for torque, which is in good agreement with the reference value deviating less than 5 %. Mesh sensitivity analysis has shown that similar computational time can be achieved in both software when the finite volume mesh is coarsened by removing boundary layers from the mesh with minor influence on accuracy. Moreover, the frequency and the quantity of output results for a time-marching scheme heavily influence the computational time which can be doubled if the fields are written for every time step. Although exact comparability of computational time is hard to assess due to the fundamental differences between FEM and FVM, Ansys Maxwell still offers 30% faster converges for similar load when comparing the coarsest finite volume mesh with finite element mesh. However, this percentage is influenced by the file output frequency and the difference between direct and iterative solver operations. Regarding the complexity of use, Ansys Maxwell has proven to be faster to use and more user friendly, but Fire M allows for more user control e.g., linear solver tolerance, underrelaxation parameters manipulation and has better overview of the solver performance. Furthermore, frequency domain initialization has proven to significantly decrease the calculation time opposed to steady state initialization. Torque output from the frequency domain solver is sufficient even without the subsequent transient analysis and has less than 4% discrepancy with reference value. If the complete field results for every rotor angle position are required, computational time can be shortened running the simulation for one rotor electrical period. Future work will be reserved for the expansion of the current 2D model to incorporate the stator edge effect within the FVM simulations.

Acknowledgment

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Sustainable high-quality aviation oil recovery from organic solid wastes through microwave-assisted heating technology

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Abstract

Organic solid wastes are booming as society and industry rapidly develop, and it is necessary to reuse and recycle organic solid wastes to embrace a green and sustainable future. In this study, the mechanisms of microwave heating by comparing electrical heating were illustrated, the oil recovery performance during the microwave-assisted pyrolysis process of organic solid wastes was detailed, and the blueprint for sustainable high-quality aviation oil recovery from organic solid waste through using microwave-assisted heating technology was drafted. Microwave heating technology has the advantages of less reaction time, more rapid product formation, and lower reaction activation energy compared with electrical heating technology. The oil yields of the biomasses are below 50 wt. %, much lower than plastics (99, 78, 40, 98, and 79 wt. %). The oil components of organic solid wastes are hydrocarbons and oxygenated derivatives hydrocarbons, and the carbon numbers are mainly from C7 to C16. The highest recovered energy efficiency is 97% with the highest total energy efficiency of 63% when the microwave power is 650 W and the pyrolysis temperature is 460 ^{o}C for the polystyrene by using SiC. The unitary cost and unitary energy economic cost of the sustainable high-quality aviation oil recovery from organic solid wastes were 3.2×10^4 CNY/t and 779 CNY/GJ, respectively. The microwave-assisted pyrolysis has a good production on the oil yield and quality, and embraces good economic benefits and industrialization prospects. The aviation oil recovery blueprint can be drafted as: the organic solid wastes are recycled by the treatment plant, decomposed in the microwave pyrolysis factory, processed with some additives in the aviation fuel factory, and finally used in airplanes and filling stations.

Keywords*: High-quality aviation oil; organic solid waste; microwave-assisted heating technology; electrical heating technology*

Nomenclature

CRF	Capital recovery factor
C_{ED}	Cost of energy dissipation (CNY)
C_{oven}	Microwave oven price (CNY)
EC_{fuel}	Unitary energy economic cost of fuel (CNY/GJ)
EC_{oil}	Unitary energy economic cost of the oil (CNY/GJ)
EC_{waste}	Unitary energy economic cost of the organic solid waste (CNY/GJ)
f_{EC}	Energy economic factor
HHV_{oil}	Higher heating value of the oil (GJ/kg)
HHV_{waste}	Higher heating value of the organic solid waste (GJ/kg)
i	Interest rate
L	Microwave oven lifespan
m_{oil}	Mass or weight of the oil (kg)
m_{waste}	Mass or weight of the organic solid waste (kg)
N	Number of annual batches
q_{oil}	Specific energy of the oil (CNY/GJ)
q_{waste}	Specific energy of the organic solid waste (CNY/GJ)
Q	Energy value of the microwave power consumption (GJ/kg)
$Q_{electricity}$	Energy value of the electricity (GJ/kg)
Q_{ED}	Energy value of the dissipation (GJ/kg)
Q_{oil}	Energy value of the oil (GJ/kg)
Q_{waste}	Energy value of the organic solid waste (GJ/kg)
r_{EC}	Relative cost difference
UC_{oil}	Unitary cost of the oil (CNY/t)
UC_{waste}	Unitary cost of the organic solid waste (CNY/t)
φ	Maintenance factor
η_r	Recovered energy efficiency
η_t	Total energy efficiency

1. Introduction

Organic solid waste is mainly defined as biodegradable abandoned materials or by-products from humans, plants, or animals [1]. It mainly includes agricultural waste (rice husk, wheat straw, corn cob, bean nut, etc.), forest waste (branch, leave, weed, etc.), domestic waste (food scraps, paper, plastic products, etc.), industrial waste (waste from food processing plants, waste cloth from textile mills, etc.). Organic solid waste contains nutrient substances like lipids, carbohydrates, proteins, and minerals, and these nutrient substances ensure the organic solid waste can be biodegradable or recyclable as bio-based products such as bio-fertilizer, bio-oil, bio-gas, and bio-plastics [2-4].

The global generation of organic solid waste is difficult to estimate, and municipal solid waste production can reflect the organic solid waste to some extent. The annual generations of municipal solid waste are 1.3, 2.2, and 3.4 million tons in 2015, 2025, and 2050, respectively [5], and organic solid waste is more than 70% of the municipal solid waste including food waste, paper, textile, garden waste, and plastic [6]. Plastic waste is typical organic solid waste, and it increased from 353 million tons to 467 million tons during 2019 ~ 2030 (Figure 1). The plastic waste was recycled, incinerated, landfilled, and mismanaged in the amounts of 33, 67, 174, and 79 million tons in 2019. Nearly half of the plastic waste is landfilled, 19% of the plastic waste is incinerated, and recycled plastic slowly increased from 9% to 12% when the time changed from 2019 to 2030 [7].

Organic solid waste is usually incinerated or landfilled, whereas these two disposal ways are both harmful to the environment [8]. If these huge amounts of organic solid wastes are burned in the open air or incinerated in a furnace, a great amount of emissions and pollution (NO_x, SO_x, CO_2, etc.) will be released into the environment, deteriorating the environment and ecology we people and animals live in [9]. Meanwhile, landfilling needs plenty of land, and it significantly pollutes the soil, air, and water [10]. Therefore, it is crucial to consider environmentally friendly converting techniques by using organic solid waste to obtain valuable resources.

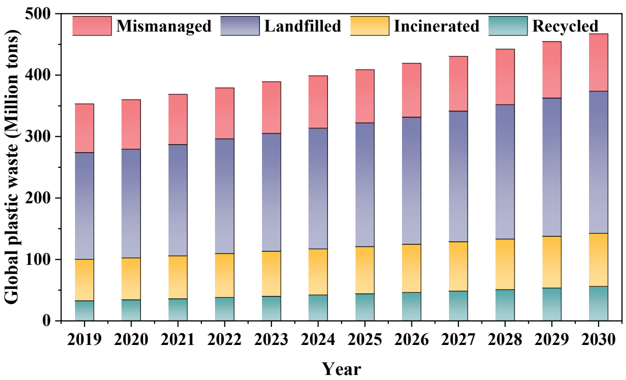


Figure 1 Plastic waste annual generation and disposal conditions [7].

An environmentally friendly treatment method for organic solid wastes is to convert them into valuable energy sources such as syngas, oil, and char. As compared with raw organic waste, the produced products (biorefineries or bio-based products) generally have high values and qualities [11]. Furthermore, bio-based products can minimize the CO_2 emission in the atmosphere [12]. There are many bioconversion techniques such as landfilling, composting, anaerobic digestion, and pyrolysis [12, 13]. The landfilling technology emits greenhouse gases and may pollute the soil, being forbidden in some countries [13]. The composting technology produces bio-fertilizer, bio-methane, and bio-pesticide with the advantages of non-chemical, low-cost, and soil protection, whereas this technology needs large land space, regular monitoring, and a long operation period. Also, this technology generates an obnoxious odor and may carry heavy metal [14, 15]. The anaerobic digestion technology can produce bio-gas and bio-fertilizer (digestion) via simple, less-emission, cheap, and easy operation, however, this technology also has a long operation period and requires accurate temperature. Moreover, this technology needs pretreatment and has a low-processing capacity [16, 17]. The pyrolysis technology is one of the most important thermochemical conversion routes to convert organic solid waste into high-value gas, oil, or char to resolve environmental concerns and protect energy safety [18, 19]. Microwave-assisted pyrolysis technology has the advantages of less reaction time, more rapid product formation, and lower reaction activation energy compared with conventional pyrolysis [12, 20].

The microwave-assisted heating technique is a promising technology among all kinds of pyrolysis technologies due to its advantages of less reaction time, more rapid product formation, and lower reaction activation energy. Yue et al. [21] studied the microwave-assisted pyrolysis corn straw to produce hydrogen enhanced by the catalyst and absorbent. Sun et al. [22] indicated that the bimetallic catalysts have a good performance in the pine wood pyrolysis process assisted by the microwave to produce oil and gas. Mahfud et al. [23] optimized the microwave-assisted pyrolysis oil generation process from the microalgae through response surface methodology. Oh et al. [24] estimated the microwave-assisted pyrolysis performance for sewage sludge, food waste, and livestock manure. Mohamed et al. [25] studied the switchgrass pyrolysis process for producing oil and char assisted by the microwave and catalytic. Other studies also analyzed the microwave-assisted pyrolysis performance of oil palm shell waste [26], empty fruit bunch [27], walnut shell [28], and rice husk [29].

The results from our previous studies indicated that some organic solid wastes can be converted into high-quality clean aviation oil, and the oil yield can be as high as 99 wt. % [30]. These supply a very good way to effectively reuse and recycle organic solid waste, reduce pollution emissions, and develop a circular economy. However, the processing processes and results were significantly varied by many factors, i.e., feedstock screened, furnaces used, conditions set, etc. Up to now, the heating fundamentals were still not well illustrated, and the conditions were still not well summarized.

In this study, coal, biomass, and plastic were selected to analyze the oil recovery performance through microwave-assisted pyrolysis technology due to the wide variety of organic solid waste. Based on the literature review, the economic analysis for the microwave-assisted pyrolysis process of organic solid waste was lacking, especially using plastics. The unitary cost, unitary energy economic cost, relative cost difference, and energy economic factor were applied as the economic parameters to assess the economic performance, based on the oil yield, oil component, and energy analysis.

The main objective of this study was to address the sustainability of high-quality aviation oil recovery from organic solid waste by using microwave-assisted heating technology. The specific objectives were to (a) illustrate the mechanisms of microwave heating by comparing electrical heating, (b) to detail and assess the oil recovery performance during the microwave-assisted pyrolysis process of organic solid wastes, and (c) to draft a blueprint for sustainable high-quality aviation oil recovery from organic solid waste through using microwave-assisted heating technology.

2. Electrical heating and microwave heating

2.1 Equipment

Figure 2 shows the typical furnaces used for electrical heating and microwave heating. Figure 2 (a) is a picture of a typical electrical furnace which is mainly named a Muffle furnace. The furnace is composed of a furnace body, electrical resistance, furnace door, flue, and control system. The core part is the electrical resistance located around the inner wall of the furnace. When the furnace is turned on, current flows through the electrical resistance, making the electrical resistance become hotter and even red. The furnace body is usually made of refractory material that can withstand high temperatures, while the shell is made of steel plate or other metal material to protect the internal structure of the furnace body. The furnace door is used to open and close the furnace body to allow materials to enter and exit. A flue is used to discharge smoke and exhaust gases. The control system is mainly used to control the temperature, pressure, and gas flow parameters in the furnace to ensure that the furnace can run normally and

(a) Electrical furnace (b) Microwave furnace

Figure 2 Typical furnaces for electrical heating and microwave heating.

achieve the required heating effect. The furnace applications are wide, including water quality analysis, environmental analysis, and other fields of sample treatment, hot processing, industrial workpiece treatment, cement, building materials industry of small workpiece hot processing or treatment.

Figure 2 (b) is a picture of a typical microwave heating furnace. The microwave heating furnace usually includes a magnetron, waveguide, high-voltage transformer, and cooling fan. Magnetrons are the most common microwave generators and they are made of vacuum tubes, applied to consistently produce microwave irradiation in the wave band [31]. A waveguide serves as a hollow metallic conduit utilized for guiding microwaves. It facilitates the transmission of microwave signals through the mechanism of continuous reflections from the inner walls of the cylindrical tube. The high-voltage transformer is used to generate high voltage to meet the effective operation of the magnetron [32]. The cooling fan is applied to reduce the system temperature to avoid the condition of overheating. The microwave heating furnace has more advantages than the electrical heating method, such as (a) non-contact heating, (b) homogeneous temperature distribution, (c) rapid heating rate, and (d) volumetric heating pattern. Therefore, microwave heating furnaces have been applied in the food, construction, chemistry industries, and so on.

2.2 Heating mechanism

For the materials put in the furnaces, the heating mechanisms would be significantly difference. Figure 3 shows the heating mechanisms of electrical heating and microwave heating. Figure 3 (a) presents the electrical heating mechanism. The electrical heating pattern delivers the heat from the outside of the object target by conduction, convection, and even radiation. The electrical heating pattern easily causes the skin effect, and the water on the external surface of the object target rapidly evaporates, demonstrating that the conventional heating pattern is efficient for surface heating, non-uniform for object heating, and wasteful for the energy utilization because of the high thermal gradient and heat conduction or convection [34].

Figure 3 (b) shows the microwave heating mechanism. The microwave was first applied to dielectric heating in the 1970s as a novel heating technology, and microwave heating technology has the advantages of less reaction time, more rapid product formation, and lower reaction activation energy compared with electrical heating technology [35]. The microwave heating pattern produces heat in the inside of the object target by fractions of the polar particles or molecules. Microwave heating is uniform volumetric heating due to the polar particles or molecule's fraction heat generated from the core to the outside of the object target [36].

2.3 Heating performance

The heating performance comparison between electrical heating and microwave heating is presented in Figure 4. The heating material was wheat straw with a weight of 10 g and a size of 4 mm, and the absorbing material was SiC with a weight of 30 g and a size of 2-3 mm. The material was heated by two powers of 686 W and 984 W, and three different experimental groups were conducted: (a) the wheat straw by the electrical heating, named as Group I, (b) the wheat straw by the microwave heating, named as Group II, and (c) the wheat straw and SiC by the microwave heating, named as Group III. For Group I, the material temperature slowly increased in the first four minutes and then rapidly climbed with average heating rates of 33 ^oC/min for 686 W and 37 ^oC/min for 984 W. For Group II, the material temperature rapidly climbed in the first two minutes and then slowly increased with average heating rates of 16 ^oC/min for 686 W and 18 ^oC/min for 984 W. For Group III, the material temperature rapidly climbed with average heating rates of 82 ^oC/min for 686 W and 91 ^oC/min for 984 W. Microwave heating has a higher heating rate at the initial period than electrical heating, and the microwave heating assisted by the absorbing material (SiC) can have a 2.5 times heating rate compared with the electrical heating. This indicated that the microwave heating can effectively improve the heating rate compared with the electrical heating. The experimental reactant, apparatus, and procedure of the microwave-assisted pyrolysis process in references [43-46].

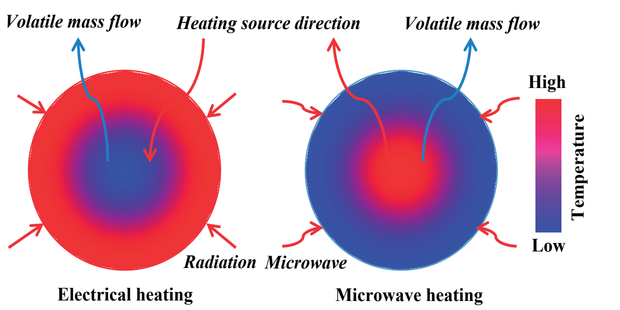


Figure 3 Heating mechanisms of electrical and microwave [33].

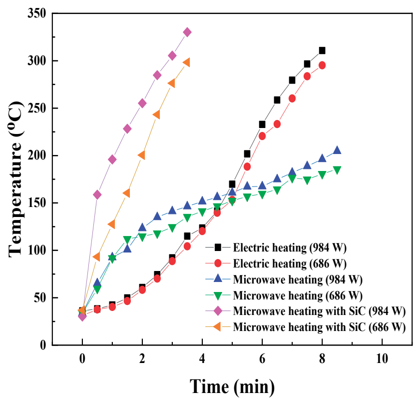


Figure 4 Heating performance comparison between the electrical heating and microwave heating.

2.4 Energy and economic criteria

Energy efficiency is an essential indicator to reflect the system's energy conservation or utilization state, and it also affects the performance, stability, and sustainable development of the system. The energy and economic flows can be found in reference [46]. For the sustainable high-quality aviation oil recovery process from the organic solid wastes through microwave-assisted heating technology, the recovered and total energy efficiencies can be calculated by following equations [46].

$$\eta_r = \frac{Q_{oil}}{Q_{waste}} \times 100\% \tag{1}$$

$$\eta_t = \frac{Q_{oil}}{Q_{waste} + Q_{electricity}} \times 100\% \tag{2}$$

$$Q_{oil} = m_{oil} \times \mathrm{HHV}_{oil} \tag{3}$$

$$Q_{waste} = m_{waste} \times \mathrm{HHV}_{waste} \tag{4}$$

$$Q_{electricity} = Q \times 3600 \times 10^{-6} \tag{5}$$

where η_r and η_t indicate recovered and total energy efficiencies, Q, Q_{oil}, Q_{waste}, and $Q_{electricity}$ are energy values of the microwave power consumption, oil, organic solid waste, and electricity (GJ/kg), m_{oil} and m_{waste} denote masses or weights of the oil and organic solid waste (kg), HHV_{oil} and HHV_{waste} mean the higher heating values of the oil and organic solid waste (GJ/kg), respectively.

The economic analysis during the aviation oil production process can be conducted by following equations [46].

$$EC_{oil} = \frac{UC_{oil}}{q_{oil}} \tag{6}$$

$$EC_{waste} = \frac{UC_{waste}}{q_{waste}} \tag{7}$$

where EC_{oil} and EC_{waste} denote unitary energy economic costs of the oil and organic solid waste (CNY/GJ), UC_{oil} and UC_{waste} are unitary costs of the oil and organic solid waste (CNY/t), q_{oil} and q_{waste} means specific energies of the oil and organic solid waste (CNY/GJ), respectively.

$$C_{oil} = EC_{oil} \times Q_{oil} \tag{8}$$

$$C_{waste} = EC_{waste} \times Q_{waste} \tag{9}$$

where C_{oil} and C_{waste} mean costs of the oil and organic solid waste (CNY), respectively.

$$C_M = \frac{C_{oven} \times CRF \times \varphi}{N} \tag{10}$$

$$CRF = \frac{i \times (1+i)^L}{(1+i)^L - 1} \tag{11}$$

where C_{oven} is the microwave oven price (CNY), CRF denotes the capital recovery factor, φ indicates the maintenance factor, N means the number of annual batches, i is the interest rate, L indicates the microwave oven lifespan.

The unitary energy economic cost of fuel and the cost of energy dissipation can be calculated by Eq (12) and Eq (13):

$$EC_{fuel} = \frac{EC_{waste} \times Q_{waste} + EC_{electricity} \times Q_{electricity}}{Q_{waste} + Q_{electricity}} \tag{12}$$

$$C_{ED} = EC_{fuel} \times Q_{ED} \tag{13}$$

$$Q_{ED} = Q_{oil} - Q_{waste} - Q_{electricity} \tag{14}$$

where EC_{fuel} means the unitary energy economic cost of fuel (CNY/GJ), C_{ED} indicates the cost of energy dissipation (CNY), Q_{ED} is the energy value of the dissipation (GJ/kg).

The energy economic factor (f_{EC}) and relative cost difference (r_{EC}) can be calculated as follows.

$$f_{EC} = \frac{C_M}{C_M + C_{ED}} \tag{15}$$

$$r_{EC} = \frac{EC_{oil} - EC_{fuel}}{EC_{fuel}} \tag{16}$$

3. Oil recovery from microwave-assisted pyrolysis of organic solid wastes

3.1 Oil yields

Table 1 presented oil yields of several organic solid wastes (coal, biomass, and plastic) at different microwave-assisted pyrolysis conditions. The feedstocks include Indian coal, Indonesian coal, brown coal, brown coal and corn stover mixture (1:1), corn stover, wheat straw, microalgae, aspen pellet, solar panel, polystyrene, polypropylene, and polycarbonate. The oil yield is in the range of 7 ~ 99 wt. % with different microwave heating powers, pyrolysis temperatures, heating times, material sizes, and absorbents. The pyrolysis types have (a) flash pyrolysis, (b) fast pyrolysis, and (c) slow pyrolysis based on different reaction conditions. The flash pyrolysis has a high microwave power, high pyrolysis temperature, and high heating rate, leading to a high gas yield. Fast pyrolysis adopts medium microwave power, medium pyrolysis temperature, and medium heating rate, causing a high oil yield. The slow pyrolysis adopts the low microwave power, low pyrolysis temperature, and low heating rate, obtaining a high solid yield [12]. The pyrolysis conditions in Table 1 are: the heating power of 480 ~ 1250 W, pyrolysis temperature of 350 ~ 800 °C, and most conditions belong to fast pyrolysis. The pyrolysis conditions are conducive to oil production.

Figure 5 presents the oil yields of several organic solid wastes (coal, biomass, and plastic) at different microwave-assisted pyrolysis conditions. The oil yields of the coal and biomass are below 50 wt. %, much lower than plastics (99, 78, 40, 98, and 79 wt. %). The oil yield of polycarbonate is far lower than other plastics because of the generation of wax. The oil yield of brown coal is the lowest (average of 7 wt. %), whereas the oil yield of polystyrene is the highest (99 wt. %).

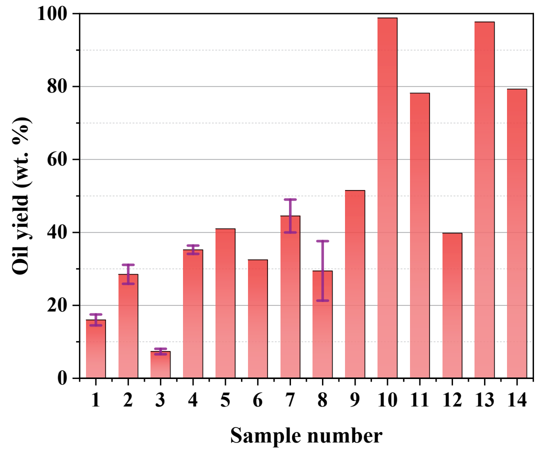


Figure 5 Oil yields of different organic solid wastes.

Table 1 *Oil yields of different organic solid wastes at different conditions.*

No.	Feedstock	Oil yield (wt.%)	Conditions	Ref.
1	Indian coal	16±2	Heating powers of 480 W and 640 W, coal sizes of 0.3 mm and 2.8~3.5 mm, maximum pyrolysis temperature of 800 °C, graphite as the susceptor	[37]
2	Indonesian coal	29±3		
3	Brown coal	7~8	Pyrolysis temperature of 500~600 °C, heating time of 20 min, absorbent of SiC	[38]
4	Brown coal and corn stover mixture (1:1)	34~36		
5	Corn stover	41	Heating power of 700 W, heating time of 15 min, pyrolysis temperature of 600 °C, Na_2CO_3 as a catalyst	[39]
6	Wheat straw	33	Pyrolysis temperature of 600 °C	[40]
7	Microalgae	40~49	Heating power of 500~1250 W, pyrolysis temperature of 462~627 °C	[41]
8	Aspen pellet	21~38	Heating power of 700 W, pyrolysis temperature of 350 °C and 500 °C, molecular sieve-based zirconium oxide catalysts	[42]
9	Solar panel	52	Heating power of 600 W, pyrolysis temperature of 550 °C, panel sheet size 20×20 mm^2	[43]
10	Polystyrene	99		
11	Polypropylene	78	Heating power of 650 W, pyrolysis temperature of 460 °C, absorbent of SiC	[30]
12	Polycarbonate	40		
13	Polystyrene	98	Heating power of 650 W, pyrolysis temperature of 460 °C, iron-based absorbent	[44]
14	Polypropylene	79	Heating power of 600 W, pyrolysis temperature of 450 °C, absorbent of SiC	[45]

3.2 Oil components

The oil components are important to decide the physical and chemical properties of oil, and they can be applied to estimate the quality of aviation oil. Table 2 shows the main oil components of different organic solid wastes. The oil components of different organic solid wastes are various. The oil components for the solar panel are: aliphatic hydrocarbons (44 area%) > aromatic hydrocarbons (16 area%) > oxygenated derivatives of hydrocarbons (31 area%). The hydrocarbons for the polystyrene mixed with SiC are: monocyclic aromatic hydrocarbons (54 area%) and polycyclic aromatic hydrocarbons (4 area%). The oil components for the polypropylene in [30] are mainly composed of cycloalkane (40 area%), and olefin (16 area%). The oil components for the polycarbonate are: monocyclic aromatic hydrocarbons (1 area%), polycyclic aromatic hydrocarbons (1 area%), and olefin (84 area%). The oil components for the same organic solid waste (for example, the polypropylene in [30] and [45]) are different, and the carbon number of oil components is also various because the experimental conditions of [30] and [45] are not exactly the same. This indicates that the oil components can be controlled by changing the experimental conditions. The oil components of organic solid wastes are hydrocarbons and oxygenated derivatives hydrocarbons.

The oil component yields based on the carbon number for various organic solid wastes are shown in Figure 6. The carbon numbers are mainly from C7 to C16, and only polycarbonate has the component C6 and solar panel has the component C19. For various organic solid wastes and various experimental conditions, the carbon distributions and yields are different. For example, the yield of polystyrene in [30] intensively appears in C8 (46 area%), whereas the yields of polystyrene in [44] focus on C8 (37 area%), C9 (12 area%), and C15 (9 area%). This is because the absorbents are different: (a) SiC is used as the absorbent in [30] and (b) Fe is adopted as the absorbent in [44]. This demonstrates that the absorbent has an important effect on the oil components.

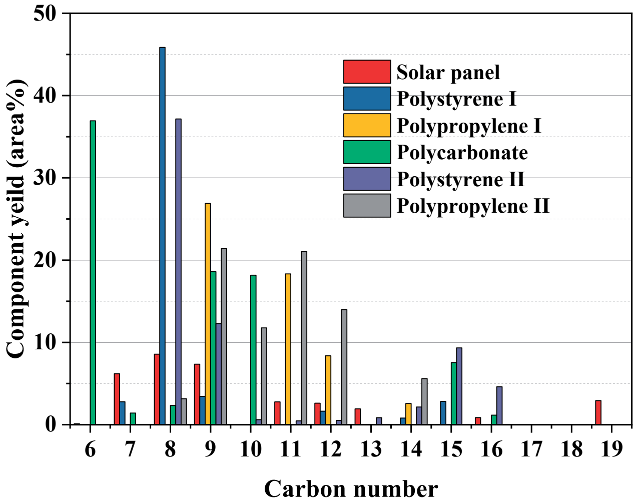


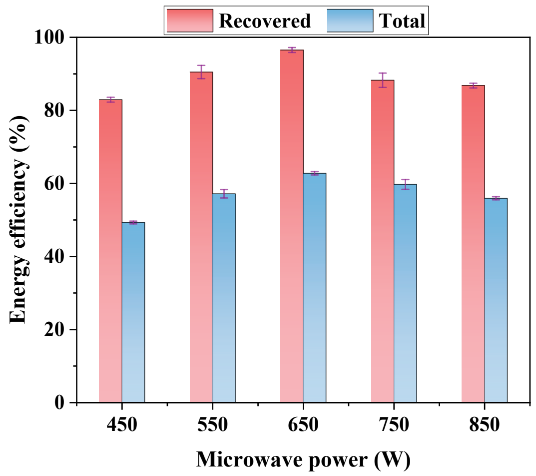
Figure 6 Yields at different carbon number for various organic solid wastes.

3.3 Energy analysis

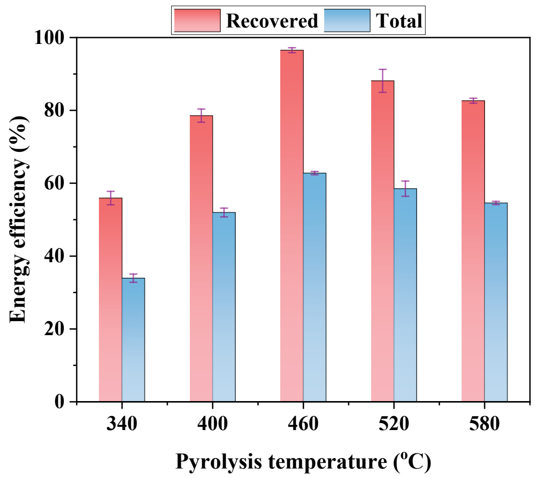
The energy analysis for sustainable high-quality aviation oil recovery from organic solid wastes is still not widely studied. The recovered and total energy efficiencies from references [43] and [46] are discussed. The recovered and total energy efficiencies in [43] were in the ranges of 24% ~ 75% and 12% ~ 46%, respectively. The recovered and total energy efficiencies in [46] are presented at different conditions in Figure 7. The recovered and total energy efficiencies in [46] were in the ranges of 56% ~ 97% and 34% ~ 63%, respectively. The recovered and total energy efficiencies in [46] were much higher than the efficiencies in [43], indicating that plastics have a good energy conversion performance. Furthermore, plastics have a high oil yield and good components, therefore, plastics recycling to produce aviation oil is a potential technique to address the energy crisis and embrace a sustainable future.

Table 2 *Main oil components of different organic solid wastes.*

No.	Feedstock	Components (area%)	Carbon range	Ref.
1	Solar panel	Aliphatic hydrocarbons (44), aromatic hydrocarbons (16), and oxygenated derivatives of hydrocarbons (31)	C6 ~ C19	[43]
2	Polystyrene	Monocyclic aromatic hydrocarbons (54) and polycyclic aromatic hydrocarbons (4)	C7 ~ C15	[30]
3	Polypropylene	Cycloalkane (40) and olefin (16)	C9 ~ C14	[30]
4	Polycarbonate	Monocyclic aromatic hydrocarbons (1), polycyclic aromatic hydrocarbons (1), and olefin (84)	C6 ~ C16	[30]
5	Polystyrene	Monocyclic aromatic hydrocarbons (62), polycyclic aromatic hydrocarbons (21), and others (17)	C8 ~ C16	[44]
6	Polypropylene	Alkanes (7), alkenes (18), and cyclanes (53)	C8 ~ C14	[45]



(a) Energy efficiencies at different microwave powers.



(b) Energy efficiencies at different pyrolysis temperatures.

Figure 7 Recovered and total energy efficiencies at different conditions [46].

The best microwave power and pyrolysis temperature can be found in Figure 7. The recovered energy efficiency is the highest (97%) with the highest total energy efficiency of 63% when the microwave power is 650 W and the pyrolysis temperature is 460 °C. Also, the highest recovered energy efficiency of 75% and the highest total energy efficiency of 46% are obtained when the microwave power is 600 W and the pyrolysis temperature is 550 °C in [43]. This indicates that the reaction conditions control is significant to obtain good aviation oil.

3.4 Economic analysis

The optimal economic performance was achieved under the conditions of a microwave power of 650 W, a pyrolysis temperature of 460 °C, and a SiC loading of 2 t. The corresponding values for the key performance indicators were as follows: unitary cost of 3.2×10^4 CNY/t, unitary energy economic cost of 779 CNY/GJ, relative cost difference of 1.5, and an energy economic factor of 71% [46]. Figure 8 presents the unitary energy economic costs and relative cost differences at different microwave powers. The unitary costs of aviation oil (UC_{oil}) decreased from 3.9×10^4 CNY/t to 3.2×10^4 CNY/t when the microwave power increased from 450 W to 650 W, and then increased to 3.6×10^4 CNY/t as the microwave power climbed to 850 W. The relative cost difference (r_{EC}) changed in similar way, decreasing from 1.8 to 1.5 and then increasing to 1.8 with the microwave power increasing. Conversely, The energy economic factor (f_{EC}) increased from 61% to 71% and decreased to 67%.

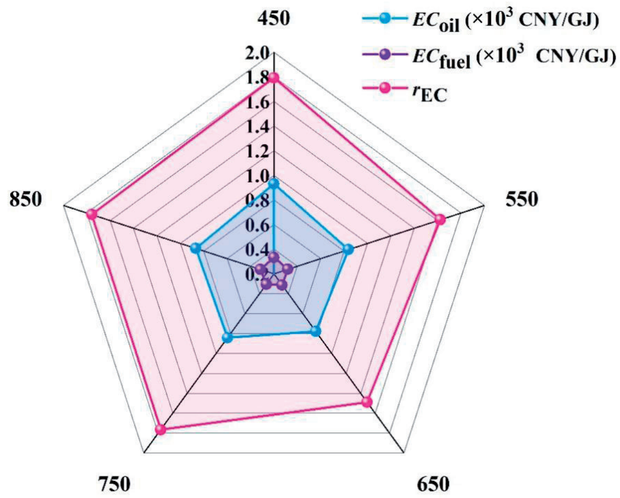


Figure 8 Unitary energy economic costs and relative cost differences at different microwave powers [46].

4. Aviation oil recovery blueprint

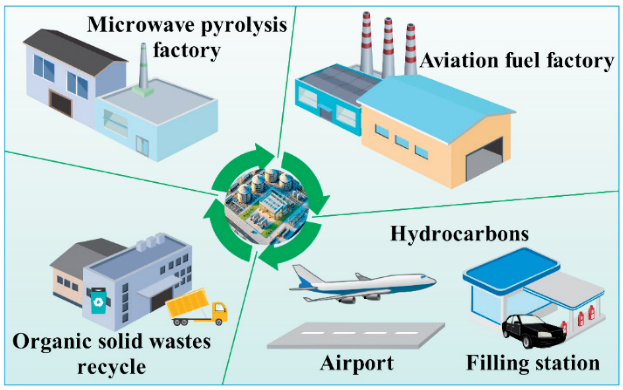


Figure 9 Aviation oil recovery blueprint.

Sustainable high-quality aviation oil recovery from organic solid wastes through microwave-assisted heating technology can be produced by controlling the reaction conditions, such as microwave power, pyrolysis temperature, and absorbent. The unitary cost and unitary energy economic cost of the sustainable high-quality aviation oil recovery from organic solid wastes were 3.2×10^4 CNY/t and 779 CNY/GJ, respectively [46]. The energy and economic benefits contribute to the aviation oil recovery applications of organic solid wastes, and the industrial production of sustainable high-quality aviation oil can be expected. Therefore, the aviation oil recovery blueprint can be drafted as: the organic solid wastes are recycled by the treatment plant to be classified and pretreated, and then the organic solid wastes are decomposed in the microwave pyrolysis factory to produce the raw oil. The raw oil is processed with some additives in the aviation fuel factory, and finally, the hydrocarbon fuel can be used in airplanes and filling stations, as shown in Figure 9.

5. Conclusions

In this study, the sustainability of high-quality aviation oil recovery from organic solid waste through using microwave-assisted heating technology is conducted. Some conclusions are obtained.

The microwave heating technology has more advantages than the electrical heating method, such as (a) non-contact heating, (b) homogeneous temperature distribution, (c) rapid heating rate, and (d) volumetric heating pattern. The microwave heating assisted by the absorbing material (SiC) can have a 2.5 times heating rate compared with the electrical heating.

The oil yield is in the range of 7 ~ 99 wt. % with different microwave heating powers, pyrolysis temperatures, heating times, material sizes, and absorbents. The oil yields of the biomasses are below 50 wt. %, much lower than plastics (99, 78, 40, 98, and 79 wt. %).

The oil components of organic solid wastes are hydrocarbons and oxygenated derivatives hydrocarbons, and the carbon numbers are mainly from C7 to C16. However, the carbon distributions and yields are different for various organic solid wastes and various experimental conditions.

The highest recovered energy efficiency is 97% with the highest total energy efficiency of 63% when the microwave power is 650 W and the pyrolysis temperature is 460 ^{o}C for the polystyrene by using SiC.

The aviation oil recovery blueprint can be drafted as: the organic solid wastes are recycled by the treatment plant to be classified and pretreated, and then the organic solid wastes are decomposed in the microwave pyrolysis factory to produce the raw oil. The raw oil is processed with some additives in the aviation fuel factory, and finally, the hydrocarbon fuel can be used in airplanes and filling stations.

Although microwave irradiation heating methods are more effective than conventional heating methods, its applications are still limited. One of the biggest challenges is that the energy conversion efficiency from electricity to microwave energy (50% ~ 65%) is considerably lower than the conventional electric heat conversion (90%) [47, 48]. Also, thermal damage emerges in the microwave heating process caused by abnormal temperature gradients induced by uneven material properties or non-uniform microwave irradiations [49]. Furthermore, most studies on microwave irradiation are conducted in laboratory settings and microwave leakage remains a serious concern due to its harmful effects on humans [50].

6. Acknowledgments

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