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Potential of Industrial Symbiosis in Emerging Clusters: A Case Study of Hassia, Syria

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Sustainable development goals (SDGs) aim to create a sustainable future, and industrial symbiosis is a critical pathway towards sustainably. Industrial symbiosis involves the exchange and utilization of waste materials, energy, and water across industries, enhancing resource efficiency and promoting a circular economy. Industrial symbiosis may provide a lot of benefits for industrial clusters including increasing profitability and competiveness through reducing the cost of raw materials. This would help eliminate environmental problems and, hence, promote sustainability. However, the investigation of industrial interdependence in Syria faces significant challenges,

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including a lack of prior studies, bureaucratic obstacles, and limited documentation of input and output flows. This study proposes solutions to enhance industrial symbiosis in the industrial city of Hassia, Syria, utilizing insights from previous studies in other countries. The findings reveal a dearth of evidence for industrial symbiosis practices, with limited efforts focusing on the sale of by-products. Currently, Hassia Industrial Cluster shows limited industrial symbiosis (IS). It mainly involves partial water recycling to optimize resources and selling by-products to reduce waste and support a circular economy. Some by-products are also used in other production processes. However, the cluster lacks procedures for energy recovery, needing further exploration. Through the implementation of the proposed solutions, substantial recovery of cooling and heating capacity, as well as the utilization of by-products in the cement, concrete, and ceramics industries were achieved. The importance of industrial diversification within the industrial city was also highlighted, as it may contribute towards a crucial role in optimizing the potential for industrial symbiosis in Hassia and other industrial cities in the region.

Keywords: Sustainable development goals; industrial symbiosis; industrial cluster; circular economy; waste and energy recovery.

1. INTRODUCTION

Industrial symbiosis may largely contribute to sustainability in both developing and developed countries with various environmental, social and economic benefits [1]. Industrial symbiosis can be explained using two key concepts encompassing eco-industrial environment (IE) and circular economy (CE) [2]. Despite their recognition, their relationship is unclear, and no integrated framework has been established [3,4].

Eco-industrial parks (EIPs) are complex socio-technical systems with many stakeholders. They consist of geographically concentrated, interconnected enterprises, suppliers, and institutions. This setup can enhance company productivity, foster innovation, and induce new projects. Benefits include supply chain optimization, shared utilities and services, and the exchange of by-products and waste materials [5]. Recently, industrial symbiosis is a popular term describing industrial activities which promotes the idea that a waste or by-product of one sector could be a resource for another industrial sector [6]. This may enhance resource efficiency, reduce environmental impact, eliminate environmental damage and risk, create economic and social value and achieve efficient industrial production [7,8,9,10,11] It involves traditionally separate industries collaborating to exchange materials, energy, water, and by-products, thus, reducing their environmental footprint [12,13].

The core principles of industrial symbiosis revolve around the imperative of cooperation among geographically proximate industrial facilities to unlock both economic and environmental benefits [14]. While the evolution of the industrial symbiosis system aligns with the course of sustainable industrial development [15], the initial consideration when implementing an industrial symbiosis framework lies in the comprehensive assessment of the genuine potential for exchanging waste materials and energy [16]. Notably, in evaluating the viability of industrial symbiosis, the majority of studies have primarily focused on inter-plant exchanges [17] or exchanges occurring among firms [18]. Chertow identified three key dimensions of resource exchange in industrial symbiosis: (1) reusing by-products as substitutes for products or raw materials, (2) sharing infrastructure and efficiently using resources like energy, water, and wastewater, and (3) collaboratively providing services such as transportation, food, and shared power plants [14].

Despite global efforts to enhance industrial symbiosis, it remains a niche strategy facing many challenges. These include regulatory, financial and governance issues. Jacobsen's 2021 study identified challenges in economics, systems, resources, cooperation, knowledge, technology, locations, and management. Melissa Demartini's systematic review analyzed prevalent analytical approaches in industrial integration, focusing on simulation methods, interaction mechanisms, and software. The study found the agent-based dynamic system approach effective for designing and analyzing industrial integration. It also presented a theoretical framework to guide researchers and practitioners and proposed a comprehensive research agenda for future exploration [19]. In 2021, Henriques studied the enabling factors and barriers in various economic sectors. The study used a two-stage evaluation methodology: first, analyzing key dimensions of each sector, and second, assessing the impact of these factors on each sector. The study resulted in recommendations to foster integration and overcome obstacles in each sector [4].

Uusikartano and others analyzed 20 eco-industrial parks (EIPs) worldwide. They identified six roles of public actors in emergency investment plans: operator, regulator, sponsor, supporter, policy maker, and legislator [20]. The study highlighted the organizational frameworks and mechanisms for each role, emphasizing the importance of public participation in the successful operation of EIPs. Ferreira's 2020 literature review explored using waste materials as internal resources in manufacturing and resource exchanges in industrial symbiosis. The main goal was to show how waste materials can be integrated into manufacturing and identify resource exchanges in industrial symbiosis [21].

Al-Quradaghi and others proposed a framework for designing environmental industrial parks, focusing on environmental, economic, social and management performance [22]. Key criteria for transitioning from traditional to environmental parks may include: (1) fostering company cooperation, (2) establishing regulatory frameworks, (3) considering financial and economic factors, (4) promoting information exchange and transparency and (5) providing technical facilitation. Lütje and Wohlgemuth studied industrial solidarity systems in Germany, focusing on methods and engineering requirements. They aimed to analyze and simulate the transformation of these systems through goal-setting [23]. In 2020, a project has been conducted to analyze the latest findings on the reuse and recycling of by-products within the steelmaking cycle, as well as the utilization of by-products from other activities outside the steel production process, such as alternative carbon sources [24]. Hamid Afshari developed a mixed-integer linear programming model for designing energy integration networks, considering seasonal energy demand fluctuations. Applied to a real-world case, the model proved practical for companies promoting energy symbiosis. The study showed that economic and environmental goals are crucial for developing energy exchange networks [25].

Several studies have explored by-product exchanges in industrial complexes and the role of industrial parks in sustainable development implementation. This study focused on the Syrian Arab region, aiming to develop a plan for exchanging by-products within the industrial activities and firms. It sought to provide new insights and a pioneering approach for the region.

The paper was structured as follows. The introduction focused on different aspects of industrial symbiosis, its profitability, sharing infrastructure and reduced environmental implications. In section two, a brief description of the case study was presented. This included industrial cluster in Hassia, Syria, road networks, central geographical location and resources supply for various plants and firms. Methodology, in section three, included data collection, calculation and waste and by-products recovery. The next section presented results and discussion. The last section included the conclusion section with some final remarks.

2. CASE STUDY

The iron and steel production industry is experiencing substantial growth and is recognized as one of the most energy-intensive sectors. Unfortunately, this growth also contributes to the generation of various pollutants, including air, water, and soil contaminants [26]. In response to economic pressures and carbon taxation targeting energy-intensive sectors in Europe, the iron and steel industries have sought to relocate operations to countries with less stringent regulations [27]. The status of industrial symbiosis (IS) within iron and steel production clusters has been examined and confirmed by Pinto and others in their study [28]. Their project highlights the environmental and economic advantages of implementing IS practices within the iron and steel industry, emphasizing the importance of achieving sustainability through collaboration between steel mills and urban centers. Furthermore, Wu and others highlighted the crucial role of energy exchange in mitigating carbon dioxide emissions [29]. Yu and others identified potential IS connections that could lead to a reduction in CO_2 emissions [30]. Moreover, Dong and others emphasized the economic benefits derived from material exchanges within iron and steel production clusters [18].

Industrialization has been proved crucial for economic development, adding value and helping countries achieve their goals. To this regard, the Syrian government has prioritized fostering industrial clusters for several reasons: promoting progress, addressing environmental issues, integrating diverse industries, encouraging competition, and reducing pollution. Syria has established four major industrial clusters: Hassia in Homs, Adra in Damascus Countryside, Sheikh Najjar in Aleppo, and Deir Ezzor, currently non-operational due to the crises.

2.1 The industrial cluster in Hassia

The field of industrial symbiosis (IS) in Syria, especially in the Middle East, is underexplored. Despite several industrial clusters, there's a lack of research on IS in Syria, highlighting the need for comprehensive studies and further investigation. The Hassia Industrial Cluster in southern Homs, established in 2004, is a well-developed industrial and urban center covering nearly 2,500 hectares. It offers several facilities and can accommodate about 70,000 people, with plans to expand to 12,500 hectares for 350,000 residents. Centrally located, it has excellent connectivity to transportation networks and seaports via the Great Homs highway networks, enhancing its economic growth potential.

2.2 Highways Connectivity

The Hassia Industrial Cluster benefits from excellent highway connectivity, providing convenient access to various key destinations: 1) The capital city of Damascus is located approximately 110 km away, while its international airport is situated at a distance of approximately 150 km. 2) The vibrant city of Beirut is approximately 230 km from the cluster. 3) The Jordanian capital, Amman, can be reached within a distance of approximately 350 km. 4) In addition, the cluster is approximately 500 km away from Iraq to the east.

2.2.1 Proximity to seaports

A key advantage of the Hassia Industrial Cluster is its proximity to major seaports, enhancing maritime trade connections: 1) Tartous port: 100 km away. 2) Lattakia port: 180 km away. 3) Tripoli port (Lebanon): 150 km away. These geographical benefits boost trade opportunities and economic growth, providing easy access to domestic and international markets via well-connected highways and seaports.

2.2.2 Water supply and infrastructure

Hassia Industrial Cluster benefits from a reliable water supply sourced from Al-Qalamoun Basin, which possesses the capacity to provide the cluster with 8 million cubic meters of water annually, with the potential to expand to 14 million cubic meters. To secure this water supply, approximately 20 wells have been drilled, yielding 8 million cubic meters of fresh groundwater. The water is channeled to the cluster through an interconnected system of collection tanks, which are linked via a traction line to distribution tanks within the cluster network. Additionally, ongoing studies are being conducted to implement a dedicated pipeline that will draw water from the Euphrates River, significantly increasing the water supply by providing over 30 million cubic meters per year.

2.2.3 Industrial plants and facilities

Hassia Industrial Cluster is home to numerous plants and firms specializing in the smelting and production of iron and steel, with additional plants currently in the construction phase. Table 1 provides a comprehensive overview of the active iron and steel plants operating within the cluster. For the purpose of this paper, four operational plants have been selected as representative case studies, effectively encapsulating the diverse industrial activities within the cluster.

Table 1. Iron and steel plants operating within the cluster

Plants	Code	products	Capacity t/y
Emaar Al-Ghad Metal Smelting Company	EMS	Iron billet	900,000
International Iron Rolling Company	IIR	Reinforcing rebars	750,000
Al-Tak Aluminum Industry Company	TAI	Aluminium ingot	95,000
Sheikh Zain Company	SHZ	Aluminium ingot, Aluminum profiles	76,000

2.2.4 Industrial symbiosis and resource recovery

Hassia Industrial Cluster shows limited industrial symbiosis (IS). IS mainly involves partial water recycling to optimize resources and selling by-products to reduce waste and support a circular economy. Some by-products are also used in other production processes. However, the cluster lacks procedures for energy recovery, needing further exploration.

3. METHODOLOGY

This study employs a bottom-up approach, to investigate the industrial symbiosis (IS) dynamics within the selected case study, as discussed in Section 2. The methodology encompasses several distinct stages, each one is playing a crucial role in the analysis.

First stage: Identification and Analysis of core plants: Core plants were identified and their input/output specifications were analyzed.

Second stage: Analysis of Inputs, Outputs, and resource flows - Material and energy inputs/outputs for each plant were charted, with a focus on waste streams and pre-disposal processes like cooling, separation, and mixing.

Third stage: Assessment of Industrial Symbiosis Potential - The current status of industrial symbiosis (IS) was estimated by matching waste sinks with resource sources, providing insights for improving IS implementation.

The 2023 research in Syria gathered extensive field data through interviews with development and planning directors in each plant. Due to challenging circumstances and bureaucratic barriers, data collection was difficult. Therefore, the study relied on interviews and questionnaires with operational and energy directors, providing valuable insights. The focal elements of the case study were identified as production plants. The list of plants selected for the case study was obtained from the General Administration of the Industrial cluster in Hassia, Syria. Through the interviews and questionnaires undertaken, the annual production capacity of each factory within the case study was estimated.

Once the foundational plants were identified, an in-depth examination of the material and energy flows for each plant commenced. Subsequently, an input and output diagram was crafted for each factory, capturing the dynamics of these flows. The primary focus was on three key flows: materials, energy, and water, in line with the findings of Kastner and others [16]. Drawing upon the insights of Kuznetsova and others, the energy flows were classified into distinct categories [31]. Specifically, electricity (EL), fossil fuels (FF), and waste heat (WH) were identified as energy flows, while all other flows were considered as matter flows. This categorization served as a framework for comprehensively understanding the energy dynamics within the studied plants. The classification of waste heat was informed by studies conducted by Brückner and others [32] and Oluleye and others [33]. Waste heat was categorized based on temperature thresholds, distinguishing between low heat (below 100 degrees Celsius), medium heat (between 100 and 400 degrees Celsius), and high heat (above 400 degrees Celsius). In this study, the focus was primarily on waste heat transmitted through liquids and gases, as recovering energy from solid waste posing significant practical challenges.

3.1 Data Collection

This project faced significant challenges in obtaining data for investigating industrial symbiosis (IS). Three main obstacles were identified: bureaucracy, reluctance from factory owners and managers to share sensitive information, and insufficient documentation of material and energy flows. Bureaucratic complexities were the primary impediment due to the lack of obtaining the necessary data. This lack of cooperation required alternative data collection methods. Factory owners and managers were hesitant to share certain production data, considering it sensitive. Consequently, complete transparency regarding material and energy flows data was hard to find.

Another challenge was the lack of documentation of material and energy flows, which plant managers often overlooked. This posed a significant obstacle to obtaining accurate data. To overcome this, a multi-faceted approach was used: interviews and questionnaires with plant owners and managers, reviewing official reports and relevant data from similar plants, and making estimates when necessary. The final dataset was thoroughly compared with multiple sources to ensure consistency and accuracy.

A collection of accurate data on plant operations involved several approaches: 1) Interviews: Conducted with key stakeholders i.e. industrial cluster managers, plant managers, and domain experts for insights into plant operations. 2)

Official Documents and Diagrams: Accessed to gather accurate flow data on material and energy within the plants. 3) Plant Design Data: Used to understand technical specifications and configurations for accurate analysis. 4) Operating Data from Similar Plants: Referenced to supplement information and identify trends. 5) Academic Research and Studies: Provided additional insights and data on industry practices. 6) Data Calculation and Estimation: Made when complete data was not available from at least two sources. 7) Data Verification and Resolution: Comparing collected data to identify and resolve discrepancies. 8) Acceptance of Consistent Data: Verified data was accepted for further analysis and interpretation.

3.2 Calculation

At this stage, annual rates of material, energy, and water flows were computed using collected data. Thermodynamic properties were considered when necessary, referencing Green and Perry (2008). Limited data was supplemented with literature and international factory insights. Table 2, Table 3 and Table 4 show material, energy, and water flows, with power flows in megawatts. Waste stream temperatures were also gathered. Energy inputs from fossil fuels and electricity were estimated based on each factory's annual needs. The cluster's energy output was waste heat. Ratios between primary materials and the main product and by-products if available, were calculated. When direct data was lacking, academic publications provided these ratios. Annual material flows were estimated by multiplying ratios with annual production quantities, reported in tons.

3.3 Waste Recovery

One crucial aspect of waste recovery processes lies in the existence of viable and effective utilization methods, as highlighted by Bailey and Gadd [27]. In this project, "sinks" refer to consumers or recipients of waste materials. Extensive academic studies identified suitable sinks for each waste source, unlocking waste recovery potential. The literature offers many energy recovery techniques, as shown by Huang and others [34], Jouhara and others [35], Oluleye and others [36], Oluleye and others [33] and Reddy and others [37]. Each technique has a distinct efficiency, measuring the ratio of useful output to waste heat and work produced. This efficiency depends on the temperatures of the heat source and sink, affecting the overall effectiveness of the energy recovery process [32]. In a comprehensive study by Oluleye and others [38], the efficiency of six different waste heat recovery technologies was thoroughly evaluated. This evaluation aimed to identify the most suitable technologies for waste heat recovery from heat sources with temperatures below 265 °C. A study by Oluleye and others [38] guided the selection of effective waste heat recovery technologies. Building on their approach, this study applied their methodology to choose optimal technologies for specific heat source temperatures. A review of previous studies identified ways to utilize by-products, aiming to integrate them into industrial processes and promoted a circular economy for better resource efficiency.

4. RESULTS AND DISCUSSION

Energy procurement and management in the cluster were coordinated with Syrian authorities and cluster management, ensuring a regulated approach. Material exchange within the cluster was minimal, focusing on selling by-products to external parties for small-scale production. Resource circulation was limited, emphasizing the commercial value of by-products. Unfortunately, the cluster did not incorporate energy recovery from gas and water flows. Future investigations may enhance energy efficiency and sustainability. Fig. 1 shows the flow patterns of materials, energy, and water for each factory, with water as both an input and output.

4.1 Technical Structure

Fig. 2 shows the total material flows within the cluster. Analysis revealed that 45% of input materials became main products, 35% became gaseous products and 21% became solid by-products. Inputs included iron pellets, natural gas, alumina, and various alloys. Outputs were iron, reinforcing bars, aluminum alloys, and industrial aluminum profiles. The cluster produced 840 thousand tons of solid by-products, with 50% being slag. Energy came from natural gas, electricity, and coke. Fig. 1 details energy inputs and outputs for each factory. The cluster's total energy input was 799 megawatts, with 169 megawatts (21%) lost as flue gases. The rest met production needs. Water, used mainly for washing and cooling, totaled 3.8 million cubic meters. There was no water recycling, so the cluster relied on Al-Qalamoun Basin for its water supply.

Table 2. Materials flows

Plant	Material-inputs	Annual rate t/y	Field data t/t product	Material-output	Annual rate t/y	Field data t/t product
EMC	Natural Gas	268716	0.30	Billet	900000	
	Iron pellet	1637908	1.82	Dust	76040	0.08
	Scrap	16531	0.02	Sludge	101480	0.11
	Lime	63368	0.07	Gaseous products	652777	0.73
	Ferroalloys	22500	0.03	Slag	229592	0.26
				CCM Losses	18000	0.02
				Other SMP losses	31133	0.03
IIR	Natural Gas	186609	0.25	Billet	750000	
	Iron pellet	1364923	1.82	Dust	63367	0.08
	Scrap	13776	0.02	Sludge	84566	0.11
	Lime	52806	0.07	Gaseous products	506659	0.68
	Ferroalloys	18750	0.03	Slag	191326	0.26
				CCM Losses	15000	0.02
				Other SMP losses	25944	0.03
TAI	Calcined Coke	34200	0.36	Aluminium ingot	95000	0.13
	Pitch	8550	0.09	SPL (Spent Pot Lines)	1900	0.003
	Alumina	186200	1.96	Gaseous products	138700	0.18
	Cryolite	2850	0.03			
	Aluminium fluoride	3800	0.04			
SHZ	Calcined Coke	27360	0.36	Aluminium ingot	30400	
	Pitch	6840	0.09	Aluminum profiles	45600	
	Alumina	148960	1.96	SPL (Spent Pot Lines)	1520	0.002
	Cryolite	2280	0.03	Gaseous products	110960	0.15
	Aluminium fluoride	3040	0.04			

Table 3. Energy flows

Plant	Energy-inputs MW	Annual rate t/y	Field data kW/t product	Energy-output MW	Annual rate t/y	Field data kW/t product
EMC	Natural Gas	90.1	0.10	Exhaus Gas	45.6	0.05
	Electricity	113.3	0.13			
	Coke	14.1	0.02			
IIR	Natural Gas	64.0	0.09	Exhaus Gas	38.9	0.05
	Electricity	83.8	0.11			
	Coke	12.1	0.02			
TAI	Natural Gas	5.4	0.06	Exhaus Gas	42.9	0.45
	Electricity	209.6	2.21			
SHZ	Natural Gas	7.3	0.10	Exhaus Gas	41.2	0.54
	Electricity	199.1	2.62			

Table 4. Water flows

Plant	Water-inputs m3/y	Annual rate	Water-outputs m3/y	Annual rate
EMC	Makeup water	2,060,444	Drain Water	892,596
IIR	Makeup water	1,757,717	Drain Water	761,453
TAI	Makeup water	222,149	Drain Water	95438
SHZ	Makeup water	178,110	Drain Water	77,037

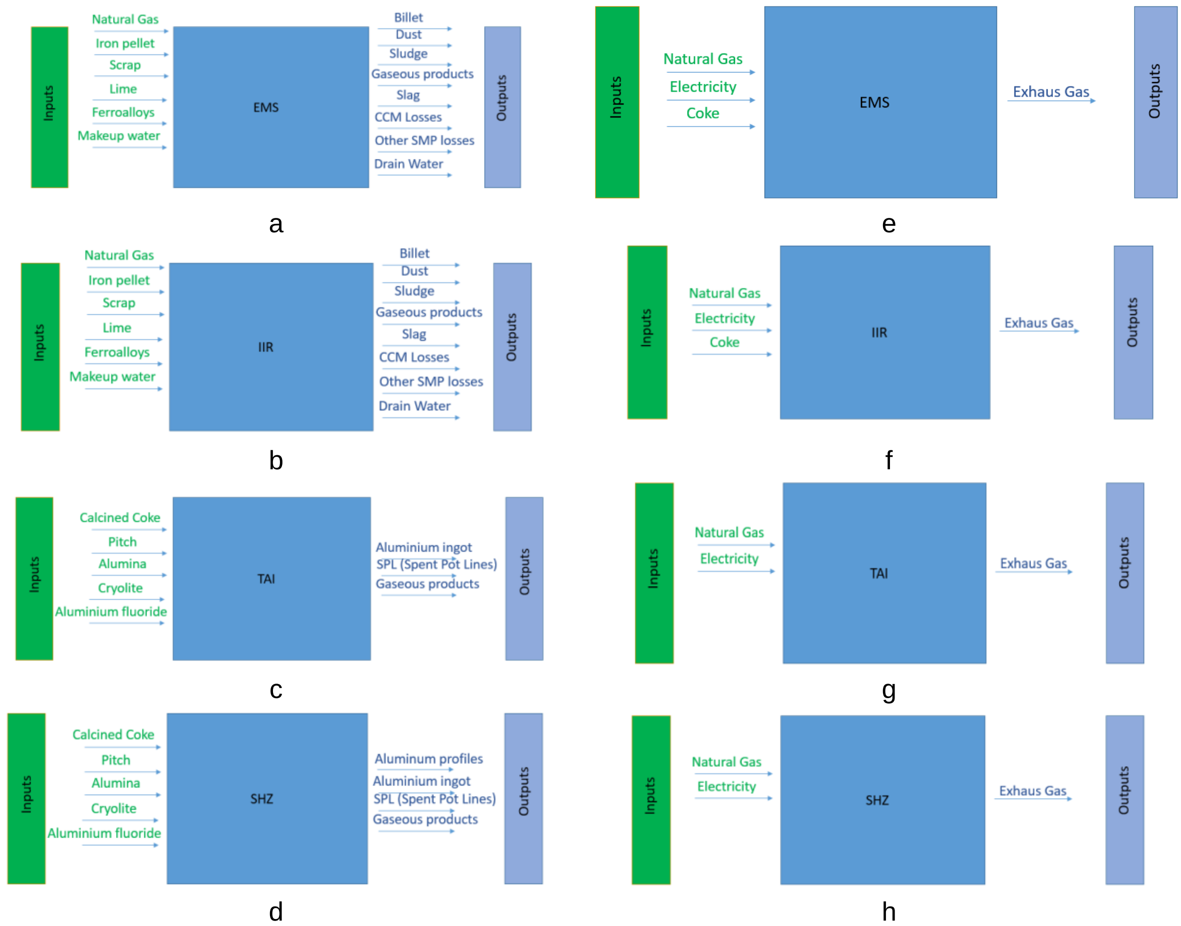

Fig. 1. (a) EMS material input-output, (b) IIR material input-output, (c) TAI material input-output, (d) SHZ material input-output, (e) EMS energy input-output, (f) IIR energy input-output, (g) TAI energy input-output, (h) SHZ energy input-output

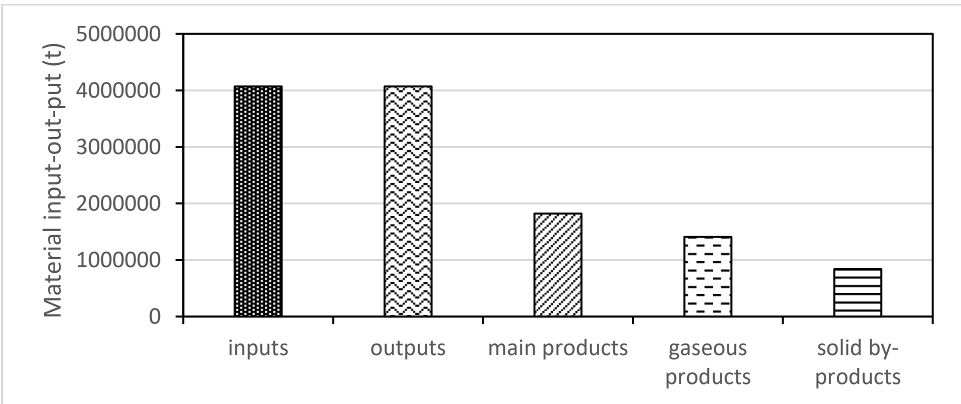

Fig. 2. Material input-output of the cluster

4.2 IS Potential

4.2.1 Energy exchange

According to the investigation conducted by Oluleye and others [33], the potential for recovering wasted energy is contingent upon two crucial factors: the specific energy requirements of the intended consumer and the efficiency of the selected waste heat recovery (WHR) technology. In the context of this study, the aim was to recover the dissipated energy in the form of electricity. Consequently, a noteworthy achievement was made as a total of 44 megawatts of previously wasted energy flows were successfully harnessed and recovered within the cluster's operations. To accomplish this feat, the utilization of the organic Rankine cycle has emerged as one of the viable options for electricity recovery, particularly suitable for heat sources operating within the temperature range of up to 340 degrees Celsius. It is worthily noting that the efficiency of this technology is known to exhibit a range between (10 – 27) %, with the actual value dependent on the specific temperature conditions encountered [33].

Further corroborating evidence from various scholarly sources attests to the availability of multiple heat exchanger technologies that hold promise in effectively recuperating waste heat above the threshold temperature of 180 degrees Celsius [37,34,35]. According to Reddy and others [37], the average efficiency of these heat exchangers was estimated to be approximately 80%. However, it is important to emphasize a key observation highlighted in the study conducted by Oluleye and others [38], which suggested that cooling, as an energy recovery mechanism, was not a feasible option for waste heat streams exceeding the temperature of 180 degrees Celsius, primarily due to inherent constraints within the workflow structure. Upon careful data analysis and the successful completion of the calculation phase, it had become evident that the group under careful observation has achieved a remarkable feat in the recovery of waste heat flows. Specifically, 26 megawatts (MW) of cooling capacity and 73 MW of heating capacity have been recovered. These findings showed a significant breakthrough in harnessing and utilizing waste heat as a valuable resource within the examined group. The noteworthy magnitudes of the recovered cooling and heating capacities further emphasize the potential and effectiveness of waste heat recovery methods employed in this study.

4.2.2 Material exchange

In order to address the challenge of solid by-product recovery within each plant, potential solutions were proposed based on an extensive review of relevant literature. However, it is acknowledged that the current capabilities within the cluster are insufficient, necessitating the construction of dedicated facilities to effectively repurpose these materials. For instance, in the case of iron oxide sludge, one viable option is the establishment of a pelletizing plant that utilizes the sludge as a raw material, as proposed by Noori and others [39]. On the other hand, slag, which comprises various metal oxides, has been extensively studied as a supplementary cementitious material. Consequently, it can be utilized in ready-mix concrete production plants or cement manufacturing facilities, offering an ideal solution due to its ability to enhance the properties of both fresh and hardened concrete. Furthermore, slag can also find applications in asphalt mixtures, as discussed by Skaf and others [40]. EAF (Electric Arc Furnace) dust, especially when it contains a high proportion of zinc, is considered a hazardous substance, as noted by De Araújo and others [41]. Therefore, prior to reuse, appropriate treatment measures must be implemented [42]. Several researchers have proposed various methods for the treatment of EAF dust, as demonstrated in the studies conducted by [43] and [44]. Low-zinc dust resulting from the treatment process can be effectively utilized in several applications, such as red ceramics [45], glass ceramics [46], and cement mixtures [47]. The formation of Continuous Casting Mold (CCM) deposits occurs due to the oxidation of the steel surface during the casting process. To mitigate this issue, various methods have been proposed based on previous studies. For instance, carbon-based approaches, as outlined by [48], or hydrogen-based methods, as discussed by Azad and others [49], have been suggested as effective means of reducing CCM deposits. Spent Pot Lining (SPL) is generated during the replacement of cathodes in aluminum melting cells, as highlighted by [50]. It is considered a hazardous material, as noted by Breault and others [51]. However, SPL can be reused and recycled as an additive in steelmaking plants to improve slag composition as proposed by Meirelles and Santos [52] and Parhi [53]. Additionally, SPL can be reused in cement plants, as recommended by Personnet [54].

The proposed solutions put forth by researchers have the potential to greatly enhance and improve the implementation of industrial symbiosis in cases characterized by industrial diversity and complicated input and output flows. The presence of a diverse range of industries not only offers growing opportunities but also presents various viable options for conducting exchange operations encompassing matter, energy and water. This noteworthy observation has been highlighted and emphasized by various researchers in the field, including Van Berkel [15], who has shed a light on the significance of embracing industrial symbiosis as a means of optimizing resource utilization and minimizing waste generation. In order to shed light on the practical implications and real-world applicability of these proposed solutions, a comprehensive and realistic case study was conducted within the industrial cluster of Hassia, situated in Syria. The findings of this study have undoubtedly emphasized the critical importance of awareness among all stakeholders involved in the industrial sector, including raising company owners, factory managers, and official government agencies, regarding the immense value and potential benefits of industrial symbiosis. However, it is worth noting that this study accomplished a significant challenge when it came to obtaining the necessary data from factory owners and managers, who expressed concern in disclosing information they considered private and sensitive, fearing a potential loss of competitive advantage in the market. Consequently, their cooperation was limited to providing only superficial insights into their respective industries, hindering the ability to conduct a comprehensive analysis. Likewise, dealing with official government agencies proved to be a difficult task, primarily due to the bureaucratic nature of the processes involved. Lengthy and intricate procedures had to be followed in order to obtain the crucial statistical data related to the industrial activities taking place within the Hassia cluster. The time-consuming nature of these procedures further complicated the study efforts, impeding the ability to gather comprehensive and up-to-date information regarding the industrial landscape.

The lack of awareness about industrial symbiosis has led to poorly documented input and output flows. Solid by-products are often disposed of or sold without considering reuse or recycling. Energy outputs are also disregarded, resulting in significant waste. Therefore, raising awareness and promoting efficient energy management in the industrial sector is essential.

This study has yielded several significant findings, including the notable absence of prior studies focusing on industrial symbiosis within the context of Syria. Consequently, this study represents a pioneering endeavor in exploring this subject. The identification of this study gap highlights the critical need for further investigations and the expansion of industrial symbiosis research in Syria to encompass additional industries. This attempt tried to partially fill a gap and aims to achieve a more comprehensive understanding and realization of industrial symbiosis.

Recognizing the importance of industrial symbiosis and accurate material flow assessment, fostering cooperation among all industrial stakeholders is crucial. Using engineering and economic methods, optimal solutions for industrial symbiosis can be determined. This study provides a foundation for future efforts to implement industrial symbiosis in other Syrian clusters, potentially leading to significant positive changes and sustainable industrial practices.

5. CONCLUSIONS

This study was an attempt to evaluate industrial symbiosis in Emerging Industrial Clusters (EICs) in Syria taking Hassia industrial cluster in Homs as an example. It also opens the road for more serious contributions regarding the industrial symbiosis in Syria.

The paper highlighted the need for industrial diversification within the cluster to achieve optimal industrial solidarity. Current industries i.e. iron, steel, and aluminum do not fully exploit solid by-products due to similar input and output flows. The paper proposed adding complementary industries within the EIC to fully utilize solid by-products, avoiding the economic drawbacks of transporting them over long distances.

Implementing waste recovery solutions resulted in significant energy gains: 26 megawatts of cooling and 73 megawatts of heating were recovered. By-products could also be used in cement, concrete, and ceramics production. These results suggested that incorporating new industries to maximize waste flows and exchanges can enhance industrial solidarity, promoting a sustainable and efficient industrial ecosystem.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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