Original article

Industrial Symbiosis and Circular Economy applied to the textile industry

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Abstract
The textile industry has significant environmental, economic, and societal impact, especially regarding the textile waste that is produced in the process of clothing production. A Circular Economy (CE) aims to eliminate waste produced altogether by finding a way for the waste to become a resource for another system or process. This is a promising solution for the textile industry, a system driven by cultures of "fast fashion" that produces exorbitant waste, with 85% of overall textile products ending up in landfills or incinerated after a single use. This paper examined some of the broader impacts of the textile industry on society, how the textile industry operates - with a special focus on the Korean context - and explored some potential technical solutions to more sustainably process textile waste. An analysis of the intersection between concepts such as CE, Industrial Symbiosis (IS), and the various biological and chemical approaches of processing textile waste was performed. The analysis was complemented by a site visit to a textile waste processing center in Seoul, South Korea to observe some of these processes firsthand. The paper calculated and compared the emissions related to the textile industry in Seoul from the one-time-use *versus* the those produced from the concept of the CE and IS. Results indicated that the CE-IS paradigm was net CO_2 negative by 26.9 kiloTons. However, challenges in deconstructing the existing product into acceptable quality recycled raw material, integrating the process into other downstream processes or downcycled products presents non-trivial, resource and man-power intensive and logistical challenges.

Keywords
Circular Economy, Industrial Symbiosis, Textile waste, Value-added products, Blockchain, Recycling, Downcycling, Carbon negative, Fast fashion, Incineration

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Introduction

Textile waste management is an increasingly challenging problem for today's consumer driven societies. Currently, the textile industry uses a linear economic model where raw materials are extracted, used to make products, which is then sold to consumers, and thrown away after use. This system is unsustainable because there is a finite amount of resources available to make textiles and a limiting capacity of how much pollution our ecosystem can handle before it collapses (1). The Circular Economy model (CE) is a possible solution to this problem because it "closes the loop" by using waste products to make new products with the goal of reducing waste and decreasing raw material use (2). CE can be applied through Industrial Symbiosis (IS), a concept that mimics the natural system of symbiosis in which two commercial systems mutually benefit each other by using the waste of one system as a resource for another (3). CE outlines this circular system in which there is minimal waste, whereas IS puts it into practical applications by replicating the symbiotic system so that different industries can collaborate to utilize byproducts or wasteproducts as resources.

One segment of society that could benefit from implementing a circular economy for textile waste management is Seoul, South Korea. As a rapidly developing city with over 841 different textile companies (4) and ~ 2,364,000 residents between the age of 15-40 (5) (the most likely age range to engage in "fast fashion" (6), between 54,677 to 64,075 tonnes of textile waste is generated from the Seoul district annually and only 5% is recycled, which shows the significance of the impact of "fast fashion" on the environment of Korea (7). Consequently, the implementation of IS and CE is critical to repurpose textile waste and reduce the extraction or import of raw textiles to maintain a sustainable environment.

Methods

Intellectual work done in this research paper is grounded in a survey of the research literature and an ethnographic site visit to a Seoul textile waste recycling center. For the literature review, several search engines and sources were used for the paper, including Science Direct, Google Scholar, and the Journal of Business Economics and Management. 11 out of 24 sources were obtained from Science Direct, 1 from the Journal of Business Economics and Management, and the remaining 2 from the Google Scholar search sources.

Keywords used in the literature review were derived from 5 themes. These categories were aimed to organize the different sub categories of research needed to answer the main inquiries of this research paper, which was to explore the socioeconomic and environmental dimensions of the textile industry while exploring technical and scientific solutions to the textile waste management systems, which reflected upon the concepts of the Circular Economy and Industrial Symbiosis.

Table 1. Search strategy implemented for literature review. Different keywords were used for each event type, shown by the "search string."

Event Type	Search String
News/Article	"textile industry" OR "textile not ethical" AND "environmental problems"
Research Paper	"Biochemical solutions" AND "Cotton-PET" OR "circular economy" AND "industrial symbiosis"
Organization	"Environmental" OR "Upcycling Center" AND "In Korea"

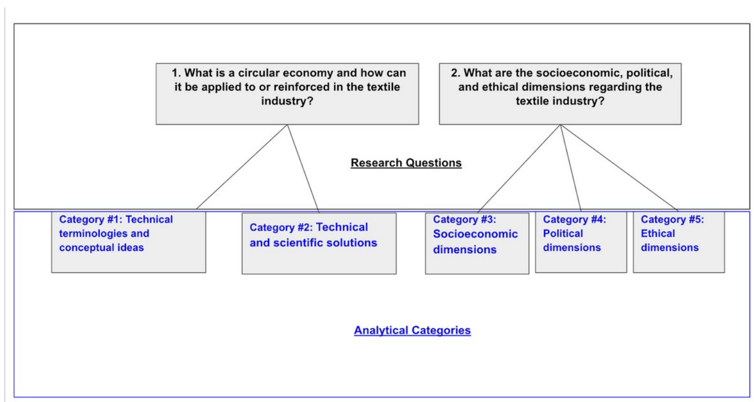

Figure 1. Connection between research questions and the five analytic categories that were used to guide and organize information generated from the literature review.

An evaluation of carbon emissions for the process was calculated according to the IPCC (Intergovernmental Panel For Climate Change) guidelines of using region-specific emission factors in regards to the energy, electricity, transport, and industrial process sectors. The IEA (International Energy Agency) reported on Korea-specific emission factors for 2023 (8). Formulae for each sector is presented in Table 2.

Table 2. Outlining the carbon emissions of each sector using the guidelines for carbon emission calculation.

Sector	**Formulae** (8)	**Factor #(Korea Average)** (5, 18, 28)
Energy (Fuel Combustion)	Fuel Consumption(m^3/L/kg) x **Emission Factor**	1. Natural Gases: 2.75kg CO_2/m^3 2. Diesel: 2.68kg CO_2/L 3. Coal: 2.51kg CO_2/kg
Electricity	Electricity Consumption(kWh) x **Grid Emission Factor**	1. General: 0.459 kg CO_2/kWh 2. CHP: 0.374 kg CO_2/kWh
Industrial Processes	Production Quantity(kg) x **Process Emission Factor**	1. Acetic Acid: 0.7 kg CO_2/kg 2. Yeast: 1.5 kg CO_2/kg 3. Agar: 0.2 kg CO_2/kg 4. Tris Buffer (fermentation tank): 0.5 kg CO_2/kg 5. Sodium Lauryl Sulfate(surfactant): 1.6kg CO_2/kg 6. Sodium Hydroxide: (mercerization /electrolysis) 1.0 kg CO_2/kg 7. Landfill Decomposition: 0.7 kg CO_2/kg 8. Incineration: 2.525 kg CO_2/kg
Transportation	Distance Traveled(km) x Fuel Efficiency(L/km) x **Emission Factor**	1. Gasoline: 2.31kg CO_2/L 2. Diesel: 2.68 kg CO_2/L

During the ethnographic site visit, careful observations of the figures that were presented in the "factory" portion of the center as well as the roles that each staff member contributed to the center were recorded. During and at the end of the tour of its exhibitions and displays, conversations were had with some of the faculty members leading the tour and answers were recorded in short-hand field notes.

Coding architecture was produced by the author, utilizing Python libraries, referencing the PapersWithCode dataset (9). The CNN model was trained in a conda environment through VS Code. The dataset was sourced through the search strategy.

Results

The nexus of the Circular Economy & Industrial Symbiosis with the textile industry

The Ellen MacArthur Foundation has termed the circular economy as "an industrial economy that is restorative or regenerative by intention and design" (10). It is also defined as "design and business model strategies [that are] slowing, closing, and narrowing resource loops," (10) which allows for the minimal usage of resources and therefore has minimal impact on the environment while providing the economy with a self-sufficient business model. The circular economy aims for sustainable development of the human race without sacrificing either one of the "triple bottom line" factors by closely examining the production and consumption cycle and how raw materials are used and processed. The stages of Circular Economy involve make, use, repurpose, reuse, and dispose. In the CE paradigm, the Use, repurpose, and reuse stages are repeated multiple times before the "dispose" section, when a material reaches its "end of life" stage (10).

The textile industry has significant potential to be transformed into a Circular Economy. Currently, up to 95% of the textile waste (11) that ends up in landfills can be recycled or reused before it technically reachs its "end of life" stage. For example, the company MUD shreds the end-of-life denim and blends it with virgin fibers to create new denim fabric. This process allows for 98% less usage of water when making denim (11). This conserves a significant amount of water, because denim production is usually deemed to be a water-intensive process. Similarly, Nike has introduced NikeGrind materials, which originate from shredded footwear, and are now present in 71% of Nike's footwear (11).

Industrial Symbiosis is a holistic approach to implement the Circular Economy in real world applications. Using collaboration between different sectors and industries, these industries are engaged in a symbiotic "circle" of resourcing so that no byproduct of a single industry goes to waste. In theory, this entails a complete "closed loop" within the economy and the environment and minimal waste with minimal resource consumption. This is a theoretically perfect system to create a sustainable future, to ensure the harmonization of human society with natural boundaries.

Site visit: Seoul upcycling center

To complement the literature review and case study analysis, the Seoul upcycling center was visited to learn more about the processes of upcycling and what technology the center was equipped with to address the challenge of textile waste management in Korea. This research was performed to observe the development of recycling and upcycling of textile waste in Korea over the years. The center was created in 2017 (12), and does not appear to have made significant progress based on no expansion of processing facilities. The most recent post from the facility, on July 17th, 2023, shows an identical structure that was in the plaza in 2017 (12). To analyze why this may be the case and identify any efforts that are currently being made to improve the system, a series of questions were posed, and answers recorded. 1] What technologies are used to process textile waste? What systems are in place? Textile waste is often repurposed directly into other clothes, shoes, bags, wallets, and other products. The products are repurposed rather than processed back into raw material for the manufacture of another textile product. This is because secondary reprocessing and chemical processes are complicated, expensive, and sometimes not very profitable (12). Furthermore, the back-processed raw material is often inferior in quality and does not meet the garment industry's raw material specifications. 2] Is the processed waste sold after it has been made into other products? On the website, http://seoulup.or.kr/eng/introduce.do?type=Organization , the products that are repurposed are sold. There is also a material bank where people can donate their waste or even buy resources. Those that buy resources are often businesses (12). 3] How much funding is received from the government? The center actually only receives funding for the renting of the building. The actual operation is supported by personal businesses and companies (12).

Figure 2. Above are photos of utilizations of the fabrics and the material bank. Some fabrics have been made into mesh boots, others cushions, jump rope, wallets, or even exhibition artwork (hanbok). (13)

Socioeconomic dimensions of the textile industry

"Fast fashion" is a term that designates those companies that sell cheap textiles in pursuit of continuous economic profit by utilizing planned obsolescence (14). This results in over 85% of clothes produced ending up in landfills (15).The factories of textile companies are often located in Asia and Africa, where labor cost is low, so that the textiles can be produced cheaper. These companies outsource the production to low-cost locations such as Asia or Africa so that the production can be sped up, hence, the "fast fashion" model (14).

93% of fashion companies do not provide their workers with a basic living wage (1). For example, in Bangladesh, the average living wage is 326.74 pounds, but workers are paid only an average of 62.33 pounds on average (1). For a $3.35 T-Shirt, only $0.05 are used to pay the sewing workers (1). However, the demand of cheap clothing is increasing; between 2000 and 2014, clothing consumption increased by more than 60% (16). Lower income countries such as Bangladesh, China, and Vietnam are being used for labor in the clothing industry, and their workers are often treated unfairly. A recent report from Oxfam shows that 0% of the Vietnamese workers earn a living wage (16). The workers are susceptible to sexual abuse and punishment due to misconduct. 1 in 4 Bangladeshi workers have been abused in their working environment (16).

Environmental dimensions of the textile industry

A recent investigation by the Swedish newspaper Aftonbladet found that fast fashion brands are dumping textile waste in the African continent where they are dumped in landfills or burned. As much as 70% of the textile waste created globally is sent to the African continent (1) . The used clothing often also ends up in freshwater bodies such as rivers and lakes, which interfere with the delicate ecological balance of these environments. In addition, the fashion industry uses over 1.5 trillion liters of water on average and produces 20% of the global water waste (15).

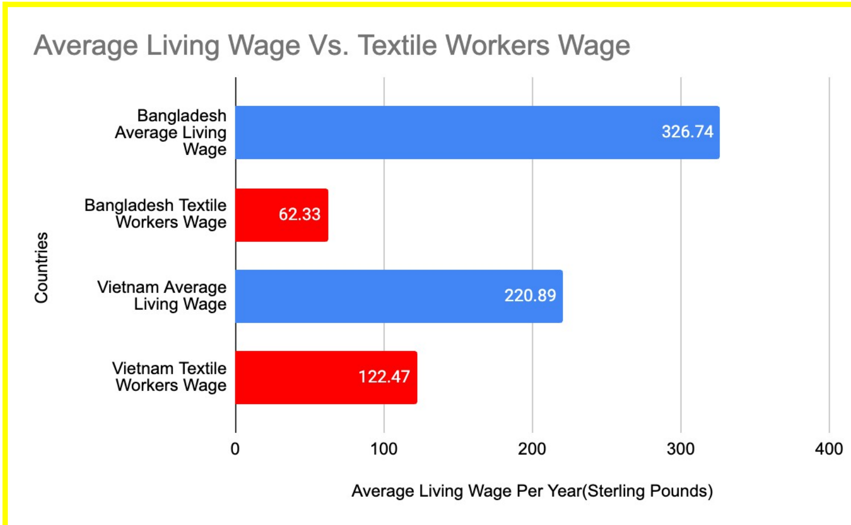

Figure 3. Discrepancy of basic living wage and textile workers' wage is shown, with a maximum of 264.41 pounds discrepancy.

Due to the rise of fast fashion, the energy consumption of the textile industry has risen by 29% whereas the GHG emissions have risen by 23% (14). Fast fashion companies focus on the economic value of the clothing, prioritizing quantity over quality to decrease price (17). Consequently, the amount of fibers used per person annually rose from 7.6 kg/person in 1995 to 13.2 kg/person in 2018, which is an ~ 82% increase (14).

Currently, the end-of-life cycle for textiles includes two methods: incineration and landfilling. 66% of clothing is transported to landfills while 30% is incinerated on a global average. (6) Landfilling processes include transportation to the landfills and decomposition in the landfills, while incineration includes transportation to the incineration site and the incineration process.

Table 3. Current methods of textile waste processing and their emissions.

Total			
13.2 kg textiles/person/year (14) x15,558,298 people (South Korean Population between 15-39 (6)) = **205,369,534 kg textiles/year**			
Method/Process	Transport[1](8)	Industrial Process (Energy, Fuel Emissions, Electricity)[2] (8, 5, 18)	Total
Landfilling (19)	4958 kg CO_2	94,880,724 kg CO_2	94,885,682 kg CO_2
Incineration (20)	2345 kg CO_2	155,567,422 kg CO_2	155,569,767 kg CO_2
Total: 94,885,682 kg + 155,569,767 kg = 250,455,449 kg CO_2			

[1]Transport: The fuel efficiency for heavy-duty transport trucks is on average 5L diesel/km (21).

1. Transport: There are 10 major landfills in Korea(Sudokwon, Nanjido, Yangsan, Wanju, Gwanju, Daejeon, Busan, Cheonju, Jeju, Daegu) (19).
a] Sudokwon: serves 50 km radius x 5L/km x 2.68 kg CO_2/L (derived from emission factor of diesel-powered transport, in table 2) [11]. b] Nanjido: serves 20 km radius x 5L/km x 2.68 kg CO_2/L c] Yangsan: serves 30 km radius x 5L/km x 2.68 kg CO_2/L d] Wanju: serves 30 km radius x 5L/km x 2.68 kg CO_2/L e] Gwangju: serves 40 km radius x 5L/km x 2.68 kg CO_2/L f] Daejeon: serves 40 km radius x 5L/km x 2.68 kg CO_2/L g] Busan: serves 40 km radius x 5L/km x 2.68 kg CO_2/L h] Cheongju: serves 30 km radius x 5L/km x 2.68 kg CO_2/L i] Jeju: serves 50 km radius x 5L/km x 2.68 kg CO_2/L j] Daegu: serves 40 km radius x 5L/km x 2.68 kg CO_2/L

There are 7 major incineration sites in Korea (Seoul, Incheon, Busan, Daegu, Gwanju, Daejon, Ulsan) (19).
a] Seoul: serves 20 km radius × 5 L/km × 2.68 kg CO_2/L[**11**] (8)= 268 kg CO_2 b] Incheon: serves 30 km radius × 5 L/km × 2.68 kg CO_2/L = 402 kg CO_2 c] Busan: serves 30 km radius × 5 L/km × 2.68 kg CO_2/L = 402 kg CO_2 d] Daegu: serves 25 km radius × 5 L/km × 2.68 kg CO_2/L = 335 kg CO_2 e] Gwangju: serves 25 km radius × 5 L/km × 2.68 kg CO_2/L = 335 kg CO_2 f] Daejeon: serves 25 km radius × 5 L/km × 2.68 kg CO_2/L = 335 kg CO_2 g] Ulsan: serves 20 km radius × 5 L/km × 2.68 kg CO_2/L = 268 kg CO_2

2. Industrial Process: Since 66% of the total textiles is landfilled, 66% of 205,369,534 kg total textiles = 135,543,892 kg textiles. The decomposition emission rate for textiles is 0.7kg CO_2/kg (8), so 135,543,892 x 0.7 = 94,880,724 kg CO_2 Since 30% is incinerated, 30% of 205,369,534 kg total textiles = 61,610,860 kg textiles. The incineration emission rate for textiles is 2.525 kg CO_2/kg (8), so 61,610,860 x 2.525 = 155,567,422 kg CO_2

Industrial Symbiosis and the Circular Economy

A chemical approach to the circular textile economy was proposed in a study by Eunjin Cho in 2023, titled,:"Converting textile waste into value-added chemicals: An integrated bio-refinery process," (2) focusing on one of the waste byproducts of the textile industry, namely lignocellulosic biomass (5–50% cellulose, 20–35% hemicellulose, and 10–25% lignin). If the cellulose is filtered out of this biomass, it can be converted to glucose; an important raw material for many industries.

Table 4. Different solutions for different types of fabrics to recover cellulose.

Treatment	Fabric Type	Produced Byproducts
HPAC-NaOH	*Colored Cotton Fibers*	Sorbitol, Lactic Acid, Ethanol
NaOH	*Non-colored Cotton Fibers*	Sorbitol, Lactic Acid, Ethanol
NaOH-ethanol	*Cotton-PET Fibers*	TPA, EG

The alkali pretreatment, also known as mercerization, was used for all fabric blends to maximize the yield of the cellulose fibers for extraction. The cellulose fibers swelled up to 97% during mercerization, recovering the initial textile materials (2). This procedure increased the yield of products after the enzymatic hydrolysis. This was because the cellulose structure changed as the Na^+ ions from NaOH widened the smallest pores of the cellulose fibres by penetrating them and forming a new sodium-cellulose-I lattice.

Dyed materials, however, yielded less glucose using the NaOH mercerization process, the yield decreasing from ~ 20 mg/mL to between ~ 13 to 19 mg/mL (2). This was because of the inhibitory effect of the dye molecules. Combining (Hydrogen peroxide-Acetic acid) HPAC with the NaOH increased the yield of glucose from the dyed textiles > 1.3 times then when compared to NaOH alone. This was attributed to chemical degradation of the dye by the HPAC. After the mercerization pretreatment, cellulase, an enzyme that hydrolyzes polysaccharides into glucose was used to hydrolyze the extracted cellulose to glucose. Glucose could then be fermented to ethanol, sorbitol, or lactic acid.

A biological process was reported by Navone in 2019 in a study titled: "Closing the textile loop: Enzymatic fiber separation and recycling of wool/polyester fabric blends (22)." This process was mainly used for wool and polyester blend fabrics. Several types of fabric including 100% wool, 70% wool-30% polyester, 45% wool-55% polyester, and 100% polyester could be used as raw material for this process. Ronozyme® ProAct was used as the protease in the experiments (22). Fabric samples of 5 mm x 5 mm were treated with between 2-10 KU/mL of Ronozyme® ProAct with between 1-3% of sodium thioglycolate for ranging durations of 6-16 h at ~ 37 ºC (11). SEM (scanning electron microscopy), infra-red spectroscopy, and nano-indentation was used to analyze the efficiency of removal of the wool fibers.

Sodium thioglycolate was used as a reducing agent to reduce the disulfide bonds. This fractured the keratin fibers, leading them to be dissolved into a peptide solution. The end products included keratin hydrolysate and polyester fibers. The keratin hydrolysate could be used for chemical substances for hair recovery or hair fiber strengthening (22).

Technical integration and optimization

In the manufacturing industry, especially in the context of reprocessing, repurposing, downcycling and reusing, it is important to keep a record of the supply chain to prevent greenwashing, guarantee consistent raw material, product intermediate or product waste quality and faciliate optimization of logistics including transportation, manpower utilization and automation. The blockchain – a distributed ledger of records linked securely with cryptographic protocols - can be used to keep track of the product components thereby enabling various industries to connect with each other to source materials needed or offer waste materials as resources, thus integrating the principles of Industrial Symbiosis.

Optimization complements the scientific solutions for industrial scalability. One such method to identify the correct type of textile and classify each category, such that optimized processes can be assigned to each, produces a time-efficient process for all types of textiles (Figure 4). A CNN architecture was developed utilizing Tensorflow, (23) an open-source machine learning platform.

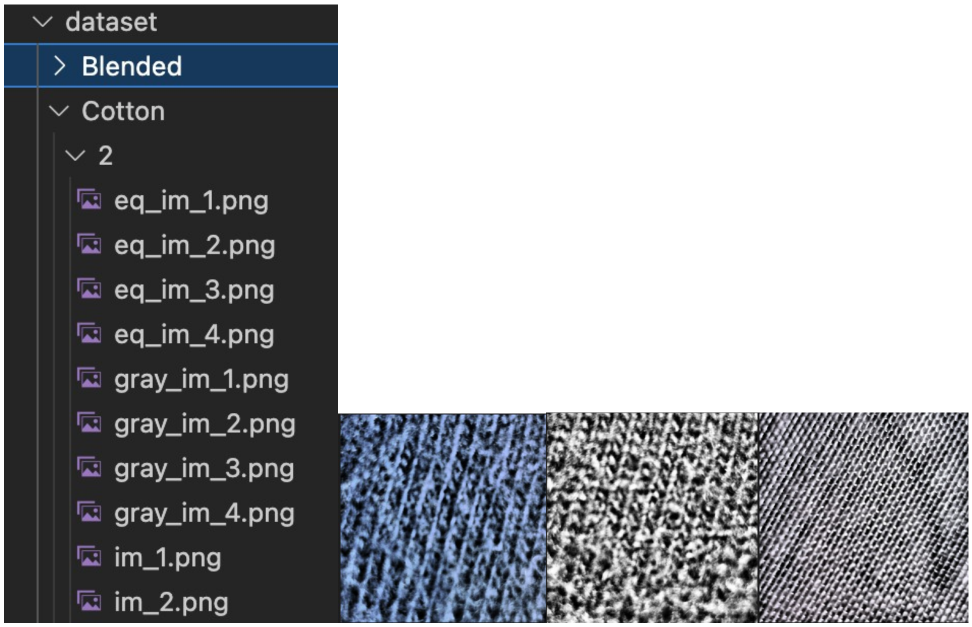

Figure 4. The hierarchy structure of the obtained dataset. Contains .png file format of 400 x 400 image files detailing textile texture. Examples of images included in the dataset.

There are 4 steps (appendix A) included in the model development process. First, the data was preprocessed through the ImageDataGenerator from the Keras library (Figure 1, Appendix A) (24). Second, the neural network, which consists of convolutional and max pooling layers are included, which extract important features from each image (Figure 2, Appendix A). Next, the feed forward and back propagation processes were formed, which allows the model to correct predictions based on the data generators, optimizing the loss function (Figure 3, Appendix A). The optimizer used was “Adam.” Lastly, the model was trained for 25 epochs (cycles of forward and backward propagation) (Figure 4, Appendix A).

Comparison of carbon footprint of the CE-IS compared to the current processes

In order for the proposed solution to satisfy a fully circular model, emissions must be net zero or net negative, i.e. the emissions generated when repurposing, reprocessing, downcycling, reusing or generally converting waste to value-added products must be less than the emissions generated by incinerating or landfilling the one-time use product. The latter also includes the emissions generated when shipping and transporting the waste textiles to countries predominantly in Asia and Africa.

Table 5. Assessment of Carbon Footprint Of The Proposed Process.

Total			
13.2 kg textiles/person/year (14) x15,558,298 people (South Korean Population between 15-39 (6)) = **205,369,534 kg textiles/year**			
Method/Process	Transport[1] (8)	Industrial Process(Energy, Fuel Consumption, Electricity) [2] (8)	Total
Chemical	2773.8 kg CO_2	70,852,489 kg CO_2	70,855,262 kg CO_2
Biological	2773.8 kg CO_2	51,342,383 kg CO_2	51,345,156 kg CO_2
Total: 70,855,262 kg + 51,345,156 kg = 122,200,418 kg CO_2			

3: All carbon emission factors below were calculated using reference 28.

1. Transport: The fuel efficiency for medium-duty transport trucks is on average 3L/km diesel (21). Since there are green boxes called "의류수거함" translated to clothes collection site that are collected from by government-operated systems, the exact transport distance can be approximated utilizing the "District Office Worn Clothes Collection Schedule" section (19). Specifically, by taking the average distance from each collection point to the recycling center (where sanitation and chemical processes are initiated), the transport distance can be approximated. The average distance from the collection point to the recycling center can vary between 5km and 15km, depending on the region of collection. There are approximately 93 collection points per "동," which is a district code for city. (19) These bins usually have an even distribution, with a roughly 3 square-kilometer area per average city, averaging around 300 m between collection points. Each servicing truck can visit up to 35 collection points, meaning that 3 trucks (3 x 35 = 105) would be in service in a day for each city (19). Averaging 10 km for each point to the region-specific recycling center, it can be assumed that each truck would travel 35(collection points) x 300 m (distance between collection points) + 10 km (distance to recycling center) = 105 km + 10 km = 115 km. Since diesel trucks have a fuel emission rate of 2.68 kg, 2.68 kg CO_2 /L x 3L/km x 115 km = 924.6 kg CO2 is emitted per truck. Therefore, each city collection duty, which is performed twice a week, would emit 924.6 x 3 = 2773.8 kg CO_2 .

2] The chemical process includes the following steps:

a] Sorting Using CNN Algorithm emits 0.05 kWh x operating 24 hours x 0.459 kg CO_2/1 kWh = 0.55 kg CO_2 b] Mercerization Using NaOH emits 1.0 kg CO_2/kg x 0.5 kg NaOH (per 1 kg of textiles) = 0.5 kg CO_2 c] Enzymatic Hydrolysis Using Acetic Acid emits 0.75 kg CO_2/kg x 0.24 kg Acetic Acid (per 1 kg of textiles) = 0.18 kg CO_2 d] Fermentation Tank Operation emits i) Yeast: 1.5 kg CO_2/kg x 0.1 kg Yeast = 0.15 kg CO_2 ii) Agar: 0.2 kg CO_2/kg x 0.05 kg Agar = 0.01 kg CO_2 iii) Tris Buffer (fermentation tank): 0.5 kg CO_2/kg x 0.2 kg Tris Buffer = 0.1 kg CO_2

iv) Sodium Lauryl Sulfate(surfactant): 1.6 kg CO_2/kg x 0.1 kg Sodium Lauryl Sulfate = 0.16 kg CO_2 e] Polymerization Heating Process For TPA emits 0.5 kWh x 4 hours x 0.374 kg CO_2/kW = 0.748 kg CO_2 f] Filtration Using Compressed Air emits 5 kWh x 8 hours x 0.459 kg CO_2/kW = 18.36 kg CO_2 g] Blockchain System Integration emits (1 kWh per transaction + 3.25 kWh basic operation) (25) x operating 24 hours x 0.459 kg CO_2/1 kWh = 48.77 kg CO_2

Hence, the total emissions are calculated as 0.55 + 0.5 + 0.18 + 0.15 + 0.01 + 0.1 + 0.16 + 0.748 + 18.36 + 48.77 = 69.53 kg/per process/100 kg textiles processed per process. The total emission factor is 69.53 kg CO_2/process, and since 100 kg textiles is transported per process at capacity (19), the total emission factor per kg is 0.69 kg CO_2. Assuming that 50% of the total of 205,369,534 kg textiles is used for chemical processes, 0.69 x 0.5 x 205,369,534 = 70,852,489 kg CO_2

The biological process includes the following steps:

a] Sorting Using CNN Algorithm emits 0.05 kWh x operating 24 hours x 0.459 kg CO_2/1 kWh = 0.55 kg CO_2 b] Ronozyme ProAct Conditioning (Fermentation) emits i) Yeast: 1.5 kg CO_2/kg x 0.1 kg Yeast = 0.15 kg CO_2 ii) Agar: 0.2 kg CO_2/kg x 0.05 kg Agar = 0.01 kg CO_2 iii) Tris Buffer (fermentation tank): 0.5kg CO_2/kg x 0.2kg Tris Buffer = 0.1kg CO_2 iv) Sodium Lauryl Sulfate(surfactant): 1.6 kg CO_2/kg x 0.1 kg Sodium Lauryl Sulfate = 0.16 kg CO_2 c] Sodium Thioglycate As Reducing Agent emits 1.0 kg CO_2/kg x 0.5 kg Sodium Thioglycolate = 0.5 kg CO_2 d] Blockchain System Integration emits (1 kWh per transaction + 3.25 kWh basic operation) (25) x operating 24 hours x 0.459 kg CO_2/1 kWh = 48.77 kg CO_2

The total emission factor is 50.24 kg CO_2/process, and since 100 kg textiles is transported per process at capacity (19), the total emission factor per kg is 0.50 kg CO_2.Assuming that 50% of the total of 205,369,534 kg textiles is used for biological processes, 0.50 x 0.5 x 205,369,534 = 51,342,383 kg CO_2

Compared to the original process of production, landfilling, and incineration, which emitted a total of 250,455,449 kg CO_2, this process emits 122,200,418 kg CO_2, which results in net less emissions of CO_2 compared to the original process.

Since a kilogram of average garment require 16.43 kg CO_2 (26) to produce, 205,369,534 kg textiles x 16.43 kg CO_2/kg = 3,374,221,443 kg CO_2, which shows that this process is certainly a net loss of carbon emissions compared to producing new textiles.

Table 6. Comparison of all emissions.

Original reproduction	Landfilling/Incineration **(Held Standard)**	Proposed Solution
3,374,221,443 kg CO_2	250,455,449 kg CO_2	122,200,418 kg CO_2
+3,123,765,994	**+0**	**-128,255,031kg CO_2**

Discussion

Assessment of textile industry waste management In Seoul, South Korea

Fast fashion culture is difficult to eradicate in Korea, especially since the culture is nearly embedded in the daily lives of the Korean population. It is known that each year, each Korean spends more than 136.15 thousand Korean won to buy clothing and footwear (27). A lot of fast fashion chains such as ZARA, H&M, and UNIQLO are located in Seoul (28), and most people frequently buy clothing to follow the "trend." The ethnographic site visit revealed that the Seoul Upcycling Center focuses on repurposing the materials received from private companies to "give the waste a second life", but there is no "true" application of the circular economy since waste is only repurposed once. More funding is required for more advanced procedures to chemically process the fabric so it can be continuously repurposed and be coupled with other industrial processes for the conservation of raw materials. More improvement and funding is needed to qualify the center as a "solution" to textile waste management, thereby emphasizing the lack of a clear solution in the regional context of Seoul.

Implementation of Solution In Seoul, South Korea

This cycle is able to reflect the 5 essential steps of a circular model, which is: make, use, repurpose, reuse, and dispose. Step 1 is making the product, such as a t-shirt, as shown in the example column. This product will be recorded as a "block" in the blockchain network of that company. In step 2, this product will be shipped to the store, where it is sold. After using the product, the customers will dispose of the textile in the container in their apartment, which is already implemented in Seoul. The textile waste must then be sent to a theoretical "processing center," where the CNN model discussed in the results would classify the textiles (Step 3). Then, in step 4, each clothing will be processed differently(cotton, wool, cotton-PET…) The collected byproducts will then be listed on the market by creating a "block" in the blockchain network of "textile industry byproducts". In the final step 5, companies from other industries will be able to view this blockchain network and trade with the brand so that they can use it for their own products.

Appraisal of solution

The proposed system reduces raw material extraction to create products, not just in the textile industry, but other industries, since Industrial Symbiosis ensures that less material is extracted but rather circulated. Since more technology will be incorporated in this system, including the blockchain server and clothing processing center, more jobs can be created to counteract the job loss created by the reduction in clothing factories and cotton extraction factories. With a net decrease of 26.9 kiloTons CO_2 from the original solution, this can be seen as an appropriately net negative solution in terms of carbon emissions. Therefore, this solution provides a more ethical and environmentally beneficial replacement for the current system.

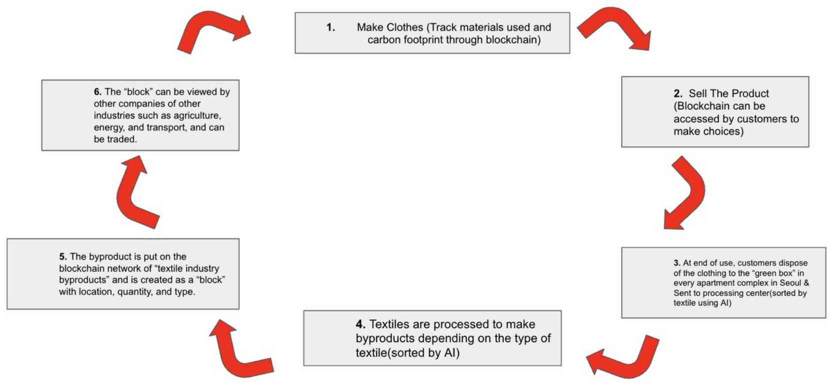

Figure 5. A conceptual model of how the proposed solution operates.

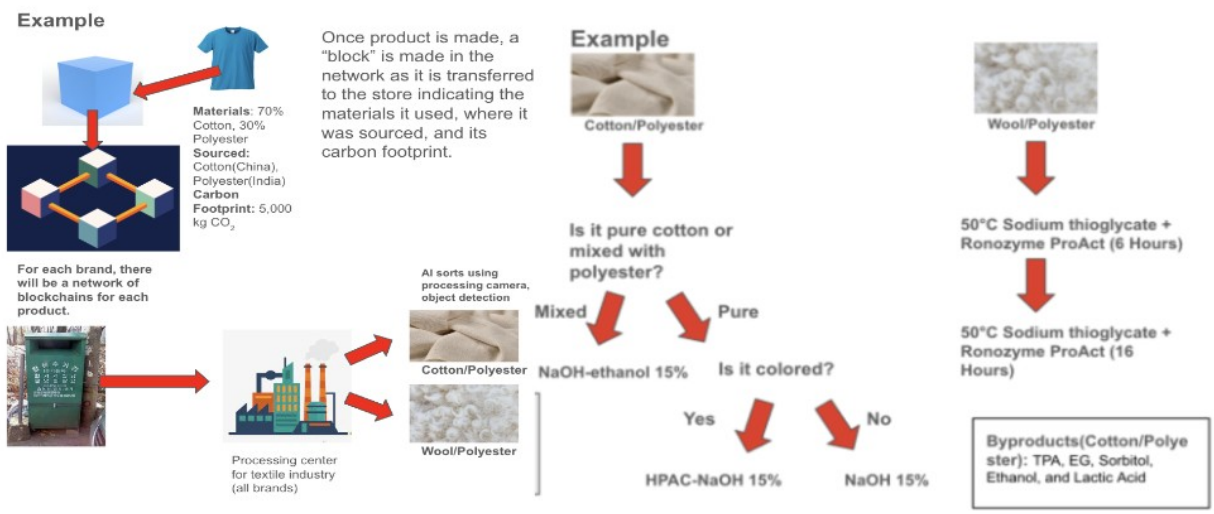

Figure 6. Further supporting the implementation through examples. As demonstrated in Figure 9, the clothes are sold, used, and processed, all trackable in the blockchain system, making our supply chain into a completely digital system.

Limitations

However, it is necessary to state that this system is not a perfect implementation of the circular model. The circular model, although optimal in theory, has limitations, especially in the realistic sense (29). Although the overall rate of CO_2 emissions is reduced, it only prolongs the life cycle of the waste product and ends up accumulating eventually (29). Nonetheless, the circulatory system allows a prolongation of the usage of the waste stream before it reaches the end-of-cycle and has an overall positive environmental effect, in terms of reducing the rate of increase of CO_2 emissions; not necessarily causing a net decrease in the amount of emissions.

Additionally, it is crucial to emphasize that approximately 70% of the carbon emissions of the proposed process is derived from the blockchain system. This reemphasizes the sheer energy consumption of blockchain. The blockchain process is used in order to connect different suppliers together in order to enhance the concept of Industrial Symbiosis; however, if the security of the blockchain system can be replicated with other communication systems through mutual trust and collaboration between the corporations, the blockchain system is not necessary, which would decrease the carbon footprint of the process even further. Moreover, if the blockchain system is to be used, it is critical to derive the power source from renewable energy such as wind energy, solar energy, geothermal energy, or tidal energy.

Lastly, the fact that even though recycling of textiles is net CO_2 emissions negative, emitting approximately 30% less emissions compared to incineration or landfilling, it is not widely used primarily because of logistical constraints, manufacturability, automation unsuitability and supply chain continuity. Recycling facilities need a steady stream of used garments to enable reliable and consistent supply of the recycled raw material or intermediate to other industries in the CE loop.

In the absence of a dedicated collection infrastructure, which is the case for most countries other than a few, including South Korea, the process is not easily expandable. The process is not amenable to automation and is labor intensive because many extraneous and non-recyclable components that are not compatible with the recycling process need to be manipulated or removed such as zippers, buttons, laces, decorative epaulettes and paraphernalia. The recycling process involves deconstruction of garments using procedures such as alkali treatment, bleaching and exposure to heat, that degrade the original quality of the polymeric materials to the point where conventional processes can no longer use this as acceptable raw material for manufacturing garments. Consequently, the re-processed raw material must be downcycled to produce other products. This necessitates incorporating the technology, logistics, automation into the recycling plant to enable manufacture of the downcycled product. If this is not possible, it then necessitates re-shipping and reselling the re-processed raw material to other off-site industries; thereby creating its own logistical challenges. Hence even though the recycling process -considered in isolation - is net CO_2 negative, challenges in deconstructing the existing product into recycled raw material, integrating the process into other downstream processes or downcycled products presents non-trivial, resource and man-power intensive and logistical challenges.

Conclusion

The textile industry presents an opportunity for the application of industrial symbiosis and circular economy, which is exemplified by the proposed model. By decreasing 26,921,544 kg CO_2 from the original process, the model clearly shows a drastic improvement in the net loss of CO_2. This proposed model, although it holds numerous benefits, has to be adjusted considering the criteria of feasibility so that the model can be applied in real life. For example, 48 kg out of the 69.5 kg of produced kg of CO_2 per 100 kg of textiles is consumed by the blockchain system; a 70% CO_2 footprint decrease is probable if the blockchain system can be vetoed in the process altogether, which emphasizes the high energy demand of technology integration, a important point of consideration for any solution to climate change that integrate technical components. Lastly, the fact that the recycling and separation of clothing into cotton and cotton-PET types is a limiting case especially since recycling is a manually tolling process which is highly impractical for many parts of the world. Even with a CNN model that can separate the fabrics, the accuracy is still pending at 87%. Further adjustments will allow this model to apply the circular model to the textile industry globally.

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References

1. Geissdoerfer M, Savaget P, Bocken NMP, Hultink EJ, The Circular Economy – A new sustainability paradigm? Journal of Cleaner Production, 143, 757-768, 2017. https://doi.org/10.1016/j.jclepro.2016.12.048

2. Cho EJ, Lee YG, Song Y, Kim HY, Nguyen DT, Bae HJ. Converting textile waste into value-added chemicals: An integrated bio-refinery process. Environmental Science and Ecotechnology, 15, 100238, 2023. https://doi.org/10.1016/j.ese.2023.100238

3. Ware M.The big circular economy myth – it's not round ,it's a straight line, Green Giraffe, 2022. https://green-giraffe.com/publication/blog-post/the-big-circular-economy-myth-its-not-round-its-a-straight-line/

4. English-Dart. FSS English Data Analysis and Reporting Tool, https://englishdart.fss.or.kr/dsbb002/main.do

5. "Population of Seoul by Age, Statista, 2024. https://www.statista.com/statistics/1290102/south-korea-population-of-seoul-by-age/

6. Fast Fashion Facts. Earth.org, https://earth.org/fast-fashion-facts/

7. Seoul Metropolitan Government.Seoul Reuse Plaza :At the Core of Reuse Culture .서울정책 아카이브 , 2015. https://seoulsolution.kr/en/content/3417

8. International Energy Agency. "Emissions Factors 2023." IEA, 2023, https://www.iea.org/data-and-statistics/data-product/emissions-factors-2023#emissions-factors

9. Papers with Code - Fabrics Dataset. https://paperswithcode.com/dataset/fabrics-dataset

10. Ellen MacArthur Foundation. What is a circular economy? Ellen MacArthur Foundation. 2024. https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview

11. Moorhouse D, Moorhouse D. Sustainable Design: Circular Economy in Fashion and Textiles. The Design Journal, 20 (Sup1), S1948-S1959, 2017. http://dx.doi.org/10.1080/14606925.2017.1352713

12. https://english.seoul.go.kr/seoul-upcycling-plaza/

13. Kim, Kyla. Photograph of Displays in the Seoul Upcycling Center. 13 Aug. 2023. Author's personal collection.

14. Rashid AA, Koc M. Additive manufacturing for sustainability and circular economy :needs, challenges, and opportunities for 3D printing of recycled polymeric waste, Materials Today Sustainability, 24, 100529, 2023. https://doi.org/10.1016/j.mtsust.2023.100529

15. Godina R, Bruel A, Neves A, Matias JCO. The Potential of Blockchain Applications in Urban Industrial Symbiosis, IFAC-PapersOnLine, 55(10), 3310-3315, 2022. https://doi.org/10.1016/j.ifacol.2022.10.122

16. McCosker J. The Impact of Fast Fashion on Garment Workers. https://goodonyou.eco/impact-fast-fashion-garment-workers/.

17. Fast Fashion. Investopedia, https://www.investopedia.com/terms/f/fast-fashion.asp.

18. Kumar PS, Suganya S. 8- Systems and models for circular economy, Circular Economy In Textiles And Apparel, processing manufacturing and design, 169-181, 2019. Ed. Muthu SS, Woodhead publishing, Cambridge, UK. https://doi.org/10.1016/C2017-0-03221-4

19. "Gwanak District Overview." Gwanak-gu, https://www.gwanak.go.kr/site/gwanak/08/10803010800002021012201.jsp.

20. Intergovernmental Panel on Climate Change. "Waste Incineration." IPCC. https://www.ipcc-nggip.iges.or.jp/public/gp/bgp/5_3_Waste_Incineration.pdf#:~:text=URL%3A%20https%3A%2F%2Fwww.ipcc.

21. Vehicle Energy Consumption. Department of Energy, https://dcoenergy.com/

22. Navone L, Moffitt K, Hansen KA, Blinco J, Payne A, Speight R. Closing the textile loop: Enzymatic fibre separation and recycling of wool/polyester fabric blends, Waste Management, 102, 149-160, 2020. https://doi.org/10.1016/j.wasman.2019.10.026

23. TensorFlow.Convolutional Neural Network (CNN) | TensorFlow Core [Internet].TensorFlow, 2019. https://www.tensorflow.org/tutorials/images/cnn

24. Team K.Keras documentation :KerasCV [Internet].Keras.io, 2022. https://keras.io/keras_cv/

25. Bajra UQ, Rogova E, Avdiaj S. Cryptocurrency blockchain and its carbon footprint: Anticipating future challenges, Technology in Society, 77, 102571, 2024. https://doi.org/10.1016/j.techsoc.2024.102571

26. Stelios Andreadakis S, Owusu-Wiredu P. Fashion Footprint: How Clothes Are Destroying Our Planet and the Growing Impacts of Fast Fashion, in Global Warming – A Concerning Component of Climate Change, Ed. Kumar V, Intech Open, London, UK, 2023. https://www.intechopen.com/chapters/1144940

27. Statista. 2023. https://www.statista.com/statistics/1048941/south-korea-monthly-household-expenditure-on-clothing-and-footwear/

28. South Korea Business Directory.Textile South Korea - List of South Korea Textile companies.South Korea Business Directory, 2024. https://www.southkoreayp.com/category/Textile#google_vignette

29. Korhonen J, Honkasalo A, Seppala J. Circular Economy: The Concept and its Limitations, Ecological Economics,143, 37-46. https://doi.org/10.1016/j.ecolecon.2017.06.041

Appendix A

```
#Step 1
datagen = ImageDataGenerator(
  rescale=1./255,  # Rescale pixel values
  rotation_range = 20,  # Randomly rotate images
  width_shift_range=0.1,  # Randomly shift images horizontally by up to 20% of the width
  height_shift_range=0.2,  # Randomly shift images vertically by up to 20% of the height
  shear_range=0.2,  # Apply shear transformations, kind of like stretching
  zoom_range=0.3,  # Randomly zoom in or out on images
  horizontal_flip=True,  # Randomly flip images horizontally
  vertical_flip = True,
  fill_mode='nearest',  # Fill in new pixels with the nearest pixel values
  validation_split=0.2  # Use 20% of the data for validation)
```

```
train_generator = datagen.flow_from_directory(
  '../dataset',
  target_size = (400,400),
  batch_size = 32,
  class_mode = 'categorical', # make sure that it labels with one hot, mutually exclusive
  subset = 'training')
validation_generator = datagen.flow_from_directory(
  '../dataset',
  target_size = (400,400),
  batch_size = 32,
  class_mode = 'categorical',
  subset = 'validation')
```

Figure 1. Datagen performs random transformations for data augmentation, with a 80/20 training/validation split.

```
#Step 2
model = Sequential()
model.add(Conv2D(32, (3, 3), activation='relu', input_shape=(400,400,3))) #is input layer (kernel size, (strides-how many times it skips over))
model.add(MaxPooling2D((2, 2))) #largest pixel value from each sector
model.add(Conv2D(64, (3, 3), activation='relu'))
model.add(MaxPooling2D((2, 2)))
model.add(Conv2D(128, (3, 3), activation='relu'))
model.add(MaxPooling2D((2, 2)))
```

Figure 2. Neural network is built. Input layer has dimensions 400 x 400 x3. Max pooling layer is 2x2, traversing over kernel size of 32. Activation functions decide which inputs to feed forward, in this case, "ReLU."

```
#Step 3
model.add(Flatten())
model.add(Dense(512, activation='relu'))
model.add(Dropout(0.5))
model.add(Dense(len(train_generator.class_indices), activation='softmax')) #last output layer, getting input from the train generator
#Step 4: Back Propagation
model.compile(optimizer = 'adam', loss = 'categorical_crossentropy', metrics = ['accuracy'])
model.summary()
```

Figure 3. Dense layers form fully connected layers, with dropout layers preventing overfitting. Cross Entropy Loss was the loss function used.

```
#Step 4
history = model.fit(
   train_generator,
   epochs = 25,
   validation_data = validation_generator)
model.save('textile_classifier.h5')
model = tf.keras.models.load_model('textile_classifier.h5')
```

Figure 4. The model is trained, with the true value set as the validation_data.