Life Cycle Assessment of Fiberglass Building Materials in Kuwait

Rawan Al-Sammar* **and Esra Aleisa****

*Kuwait Institute for Scientific Research (KISR), P.B. No. 24885, Safat 13109, Kuwait. Email: rsammar@kisr.edu.kw

**Industrial and Management Systems Engineering Department, Kuwait University, 5969 Safat 13060 Kuwait, Kuwait. Email: e.aleisa@ku.edu.kw; ORCID: https://orcid.org/0000-0002-5301-468X

ABSTRACT

Air conditioning (AC) is responsible for more than 70% of the electricity consumption in the summer. This study conducts an environmental assessment on fiberglass (FG) rooms focusing on the AC requirements and energy consumption. The boundary of the study includes building materials, construction of the room structure, which consists of the foundation, wall, floor and roof, and the use phase for energy consumption on AC. The environmental analysis using Life Cycle Assessment (LCA) approach involved evaluating the following categories: climate change human health (CCHH), ozone depletion (OD), fossil fuel depletion (FD), and metal depletion (MD), during the construction of an FG room versus an autoclaved aerated concrete (AAC) room to identify opportunities for reducing energy consumption. The operation phase energy consumption of the FG and AAC scenarios was found to be 8174.7- and 5274-kilowatt hour (kWh) per year, respectively. With reference to the single-score evaluation, the CCHH had the highest impact in both scenarios mainly caused by electricity used to operate the AC.

Keywords: Construction, Life Cycle Assessment (LCA), Fiberglass, Autoclaved Aerated Concrete (AAC)

1 INTRODUCTION

The development of sustainable ecosystems, reduction of greenhouse gas emissions, and energy control measures are all at the forefront of global efforts. Globally, the building and industrial sector is responsible for up to 40% of energy consumption, 30% of raw materials utilization, and 33% of greenhouse gas emissions (Tulevech et al., 2018). The global energy consumption and CO_2 emissions of the residential sector are 25% and 17%, respectively (Maria del P. Pablo-Romero, 2017). In the countries making up the Gulf Cooperation Council (GCC), total energy consumption and total electricity consumption in the residential sector were 18% and 43% in 2015 (Ridah Sabouni, January 2018). Research shows that energy consumption in the building sector is continuing to grow and that this is related to inefficient heating systems and thermal insulation (Ardente et al., 2008; Fan Hu and Xuejing Zheng, 2015; Casas-Ledon et al., 2020). More than 40% of energy produced worldwide is consumed by the building sector (Wrålsen et al., 2018; UNEP-SBCI, 2016).

Fiberglass is now being studied as a potential building material to reduce environmental pressure from Buildings (Bjånesøy et al., 2022). Fiberglass is a composite material that offers comparable stability and strength to steel, is resistant to corrosion, weighs less than steel, and is inexpensive. These materials are gaining popularity since they may be used in a wide range of construction projects. Its application is gaining popularity and has many uses worldwide (Wibawa and Birmingham, 2018). The global fiberglass market is currently at \$16.72 billion and is expected to grow within the upcoming decade (Fortune Business Insights, 2022) due to the focus on improving sustainable building materials (UNESCO, 2021). However, for warmer climates like Kuwait, beside studying the sustainability of building materials, the environmental impact of the operation phase needs to be addressed.

The building sector is responsible for 70% of Kuwait's energy consumption due to air conditioning (AC) (Krarti, 2015; Alotaibi, 2011). Therefore, this study sheds the light on the life cycle, including operational phase with specific focus on arid climates in Kuwait. The results of this study can have a wider repercussion, particularly in the Arabian Peninsula with mega construction projects taking place, that use fiberglass buildings during operation. Due to their durability and relatively low cost, however, their impact during their service life needs to be considered, which is the focus of this study. To make the results comparable to the modus operandi, construction building, the functional unit was constructed in a similar manner to have results comparable. Despite the importance of the new emerging technology of employing fiberglass composite materials, the AC assessment has not been completed which is critical in arid and hot climates as in Kuwait.

2 BACKGROUND

The building sector is responsible for 70% of Kuwait's energy consumption, and is continuing to grow at a rate of 8% per year (Krarti, 2015; Alotaibi, 2011; KISR, 2019). In 2011, there were 391,661 residential buildings registered in Kuwait, making up 86.6% of the total number of buildings. Residential buildings account for 57% of the electrical power peak load distribution. Population growth and subsidized power rates are two factors that have contributed to a rise in household electricity usage. Kuwaiti households pay 5% of the actual cost of their energy. It costs around 40 fils to produce one kWh, while the residential electricity tariff is only 2 fils per kWh (Hussain Ali, 2018). The government energy generation fuel bill in 2011–2012 amounted to 2.5 billion KD (AlMulla, 2015).

Kuwait has one of the world's largest per capita energy usages (KISR, 2019). Between 2000 and 2015, electricity generation in Kuwait grew annually by 5.1% (Hussain Ali, 2018). According to world data records for 2014, Kuwait was using 15590.6 kWh per capita (World Bank, 2018). Moreover, Kuwait's CO_2 emissions per capita amounted to 21.62 metric tons in 2018. This reflects the country's reliance on fossil fuels for energy production (Krarti, 2015). Almost half of the oil produced in Kuwait is used for electricity generation and water desalination, which significantly contributes to air pollution and global warming (Al-Shayji and Aleisa, 2018).

Kuwait has a hyper-arid desert climate, occupies a land area of 17,818 km^2, and a population of 4.2 million as of 2022 (CSB, 2022). Temperatures in Kuwait have risen in recent years because of climate change. On 30 July 2020, Kuwait recorded its highest maximum temperature ever, reaching 52.1 °C in the shade (MET, 2021) and highest peak load recorded which was 14,960 MW (MEW, 2020). As AC and illumination account for 85% of annual peak load and 65% of annual electricity usage (AlMulla, 2015). As the demand for cooling increases, so will energy consumption and the electrical load, which will eventually lead to a warmer climate through climate change (IEA, 2018).

LCA has been effective in assessing building materials for their environmental impact. Studies on LCA building materials have repeatedly focused on building energy consumption and associated costs (Najjar et al., 2019; Azari et al., 2016; Ben-Alon et al., 2019; Cornaro et al., 2020; Kovacic et al., 2018). The studies conducted by Hafliger et al. (2017) and Guardigli et al. (2011) compared the environmental impact of two structures: wood and reinforced concrete. Pujadas-Gispert et al. (2020) compared two types of concrete deep foundations: bored piles that are placed directly into the excavated ground, and precast driven piles that are assembled in a factory. Ansah et al. (2020) analyzed four material composites: concrete blocks and mortar, stabilized earth blocks, galvanized steel insulated composite panels, and shotcrete insulated compound façades. Ardente et al. (2008) and Kylili and Fokaides (2016) tested using kenaf fibers and phase change materials, respectively, as insulation materials. LCA has also been applied to calculate the environmental impact of using natural materials such as eucalyptus bark panels, cob, and straw made of cereal plants (Ben-Alon et al., 2019; Casas-Ledon et al., 2020; Cornaro et al., 2020).

The goal of this study is to investigate the impact of constructing the substructure phase of fiberglass (FG) buildings focusing on AC energy consumption and compare them to conventional autoclaved aerated concrete buildings (AAC). The two scenarios for a single room are analyzed over 25 years, the lifetime expectancy for conventional buildings. The methodology is constructed using the LCA approach based on ISO 14040 and 14044 standards. The system parameters are demonstrated in the materials, energy, and AC operation required to construct the rooms up to the substructure phase. Findings of this study will aid in understanding the impact of construction and operation of fiberglass buildings, AC costs, and environmental impact in Kuwait. The results could be used to promote solutions to sustainable energy challenges through economically feasible methods and support decision makers to act in energy policy and planning and enforce laws in the building sector.

3 MATERIALS & METHODS

This study compares two different scenarios, FG and AAC, for a single room of residential building using local materials environmentally as shown in Figure 1. The environmental evaluation is accomplished using the LCA, which will assess the scenarios environmental inputs and outputs through each stage of the life cycle according to the ISO 14040 and 14044 standards.

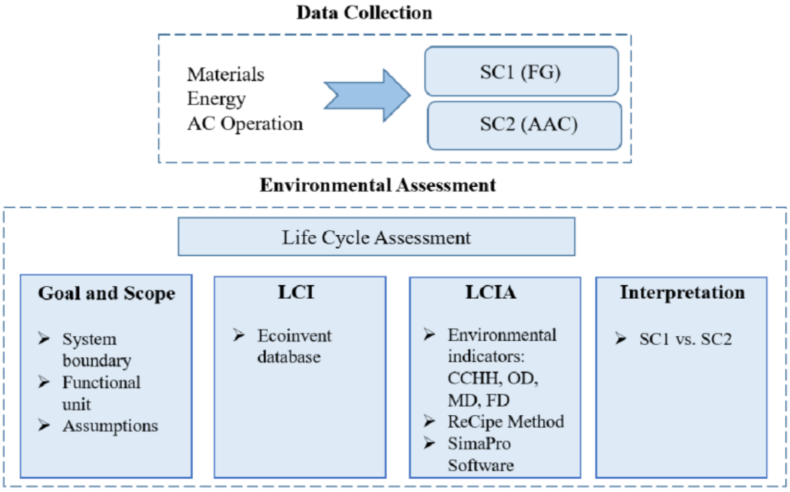


Figure 1: Research methodology for comparing the two scenarios based on FU, AC, AE, and PW.

3.1 Goal and Scope of LCA

The goal of LCA is to evaluate the environmental impact of constructing the substructure phase of FG room in warm environments focusing on AC requirements and energy consumption. The FG room will be compared to an AAC room which is a traditional concrete substructure.

The scope of this study is cradle-to-gate. It includes building materials, construction of the room substructure, which consists of the foundation, wall, floor and roof, and the use phase for energy consumption on AC. This was determined based on previous literature that shows that the use phase, due to AC is significant compared to construction for warm climates. The study boundary is first order, it considers the manufacturing of the materials and excludes the production and disposal of capital goods. The material extraction and production were included as background data, while data on material and energy consumption were collected as foreground data of the study.

The functional unit (FU) used is 18 m^2, the total room floor area, which is consistent with the work of Thiel et al. (2013), Tulevech et al. (2018), Wrålsen et al. (2018), and Lamnatou et al. (2014) averaged over the total floor space area of the buildings in their studies. The room dimensions are 3.0 m x 6.0 m with an overall floor area of 18 m^2. The room has three windows and one door with an initial elevation of 2.5 m. The reference flow of the system is the required energy, materials, and AC operation to provide the function of human habitation for 25 years.

3.2 Life Cycle Impact Inventory (LCI)

The data regarding quantities of materials per product stage were collected with the assistance of local contractors. Data collected for the building processes will form the basis for the environmental assessment. Background processes were conducted using Ecoinvent database V.3. Production data can be obtained from Al-Sammar (2022).

3.3 Life Cycle Impact Assessment (LCIA)

The ReCiPe method V1.10 was applied to conduct LCIA using SimaPro software. The impact assessment categories investigated were based on reviewed literature review. These include climate change and human health (CCHH), ozone depletion (OD), fossil fuel depletion (FD), and metal depletion (MD) as they are most adversely impacted (Aljuwaisseri et al., 2022; Aldei et al., 2022; Aleisa and Heijungs, 2020; Aleisa and Al-Shayji, 2018).

3.4 Life Cycle Interpretation

In this phase of the evaluation process, the results are analyzed to identify the causes of impact on the impact categories. This is accomplished by examining the process contribution throughout the life cycle of a product, process contribution connects the effect of each particular process to a specific impact category (ISO, 2006). Interpreting the results makes it possible to compare products and processes, and consider how to reduce the impact on different categories (G Rebitzer, 2004).

4 DATA COLLECTION AND INVENTORIES

4.1 The Fiberglass Building Scenario

For SC$_1$, the building room is constructed from FG of reinforced plastic flattened into sheets or rolls. The raw materials required to form chopped fiber mats are mainly silica sand, soda ash and limestone (Madehow, 2000). The materials included in the construction of the room include resin, fiber, wood, and steel. The roof is made from a single FG sheet made of fiber and resin. The wall and roof are assembled onto the steel structure with steel clips that help to seal the fiber parts together. Finally, the floor is covered with wood that is insulated with fiber on the top and bottom sides. The infrastructure of the AC split system and electrical pipes are included in the design, together with plumbing pipes for future expansion to include an in-suite bathroom. When the structure is complete, electrical, plumbing PVC pipes are installed. Fiber molds produced from the wooden mold can be used up to 40 times before being disposed of. Attempting to maintain the molds for longer than this is costly and may result in the production of poorly finished products (Alharbash, 2020).

4.2 The Autoclaved Aerated Concrete Building Scenario

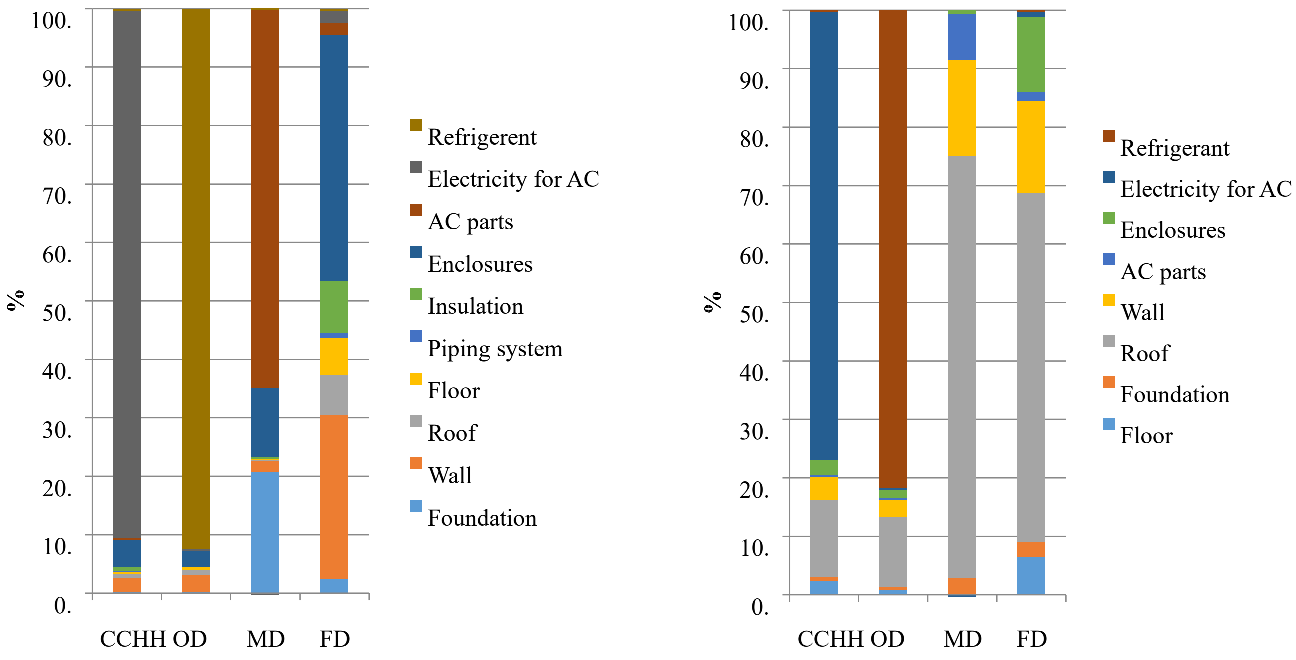
For SC_2, the AAC room is constructed from a lightweight foam concrete material used to produce concrete masonry blocks. The AAC blocks' volume is composed of 80% air bubbles and 20% building materials. The solid materials are 68% fly ash, 14% cement, 14% lime, 3.5% gypsum, and 0.5% other materials (Brikolite, 2016). The walls include concrete column, metal lath, steel column, AAC blocks, mortar, and electrical polyvinyl chloride (PVC) pipes. The roof consists of concrete, steel beams, medium-density fiberboard (MDF) wood, and steel. The floor requires screed and plumbing PVC pipes. The infrastructure of the AC split system and electrical pipes is included in the design, together with plumbing pipes for future expansion to include an -in-suite bathroom. The quantities for the materials used in each product stage for constructing the FG room with 2.0 cm insulation thickness (baseline) and the AAC room can be obtained from Al-Sammar (2022)

4.3 LCI Processes

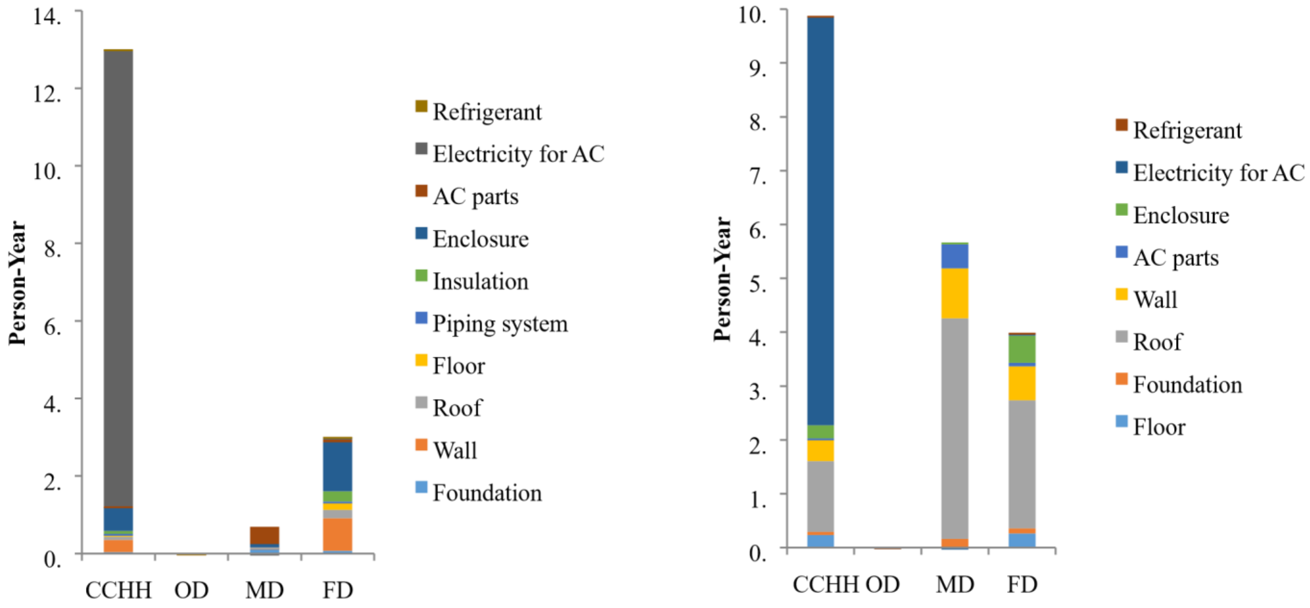
The LCI unit processes were built using Eco-invent 3.0 database. The LCI processes were entered according to their product stages. The quantities of each component can be obtained from Al-Sammar (2022). The energy usage for the FG room has been altered based on the R-value factor difference. The R-value of AAC is about 1.25 for each inch of material. Since the AAC blocks used in the construction of the room have a thickness of 20 cm, the R-value is around 9.8 (Rodriguez, Dec. 17, 2018). The FG walls consist of 6.0 mm of chopped strand fiber and 2 cm of polyurethane material. FG batts and rolls offer an R-value of 4.3 per inch (Protection, Nov. 21, 2017). On the other hand, the R-value of polyurethane insulation is 6.25 per inch (InspectAPedia, 2019). Consequently, the power consumption of the AAC room is multiplied by the R-value factor difference (1.55) to calculate the electricity required for the FG room.

5 RESULTS

The FG room results indicate that steel and copper were responsible for the majority of the environmental burden in the AC parts, the reinforcing steel in the foundation structure, and the wood and aluminum used in the enclosures. On the other hand, in the AAC room, the reinforcing steel is responsible for most of the environmental impact caused by the wall and roof. In both scenarios, steel accounts for the highest environmental impact. Figure 2 illustrates the characterization and normalization results of the midpoint analysis on the construction of SC_1 (FG) and SC_2 (AAC). In SC_1, 92% and 90% of the environmental burden on the OD and CCHH category was due to the refrigerant and electricity consumed by the AC respectively. The AC parts had the biggest impact on MD (64%). The largest contributor to FD is the system enclosure and walls, which contribute to 42% and 28% respectively. On the other hand, the product stage that contributed the most to both FD and MD in SC_2 is the construction materials of the roof (60% and 72%, respectively). The electricity used by the AC had the biggest impact on CCHH (77%). The refrigerant was responsible for 82% of the damage on the OD category. The normalization results in both scenarios indicate that the electricity used by the AC had the greatest negative impact on the CCHH category. The findings in SC_1 also indicate that the damage in the FD category is mostly from the enclosure, followed by the construction of the walls. In SC_2, the electricity used by the AC and the materials used in the roof had high environmental impacts on the CCHH, MD, and FD categories compared to the average reference values.



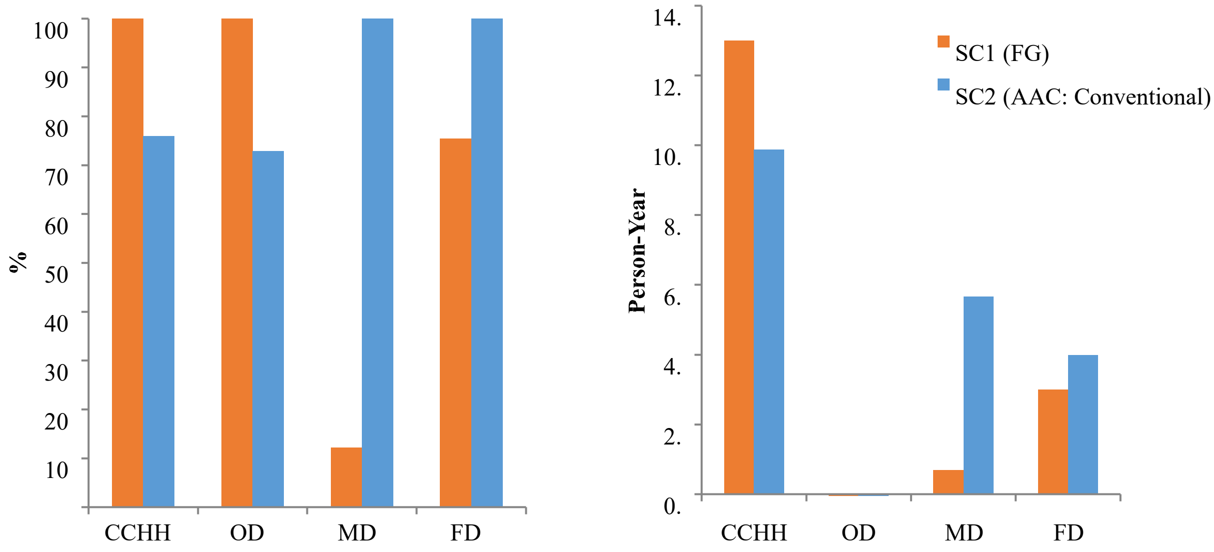
(A) Characterization results for SC_1 (FG) **(B) Characterization results for SC_2 (AAC: Conventional)**



(C) Normalization results for SC_1 (FG) **(D) Normalization results for SC_2 (AAC: Conventional)**

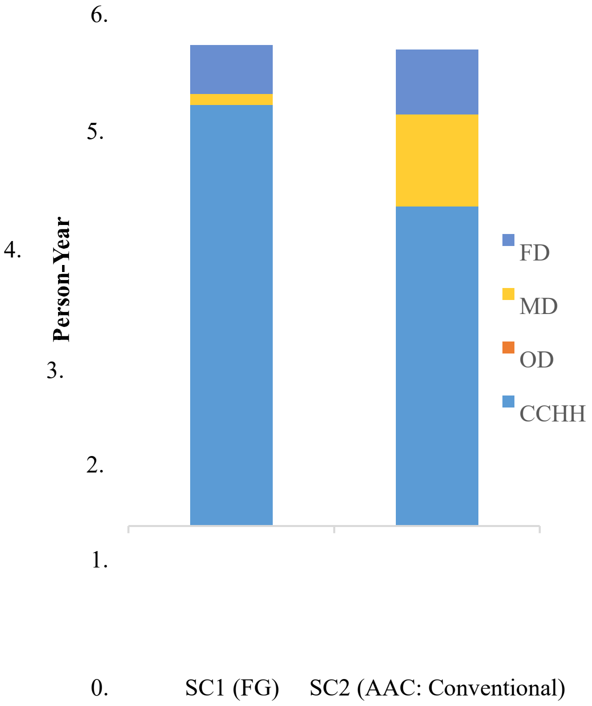
Figure 2: LCIA results for SC_1 (FG) and SC_2 (AAC) substructures using ReCiPe (H) V1.10

The characterized comparison for both scenarios shown in Figure 3 (A), SC_2 had the highest score in the MD, and FD categories. However, SC_1 had a higher score in the CCHH and OD category. Additionally, the effect of SC_1 on the MD category was minimal compared to SC_2. The same results are displayed in the normalized comparison results for both scenarios Figure 3 (B), however, OD scores are negligible compared to other impact categories. According to the single score results shown in Figure 3 (C), the CCHH indicator had the highest score in SC_1 and SC_2. In SC_1, the second-highest category was FD, followed by MD. By contrast, in SC_2, the second-highest environmental indicator was MD, followed by FD. In both scenarios, the OD impact category had the lowest score (equivalent to zero).



(A) Characterization Results

(B) Normalization Results

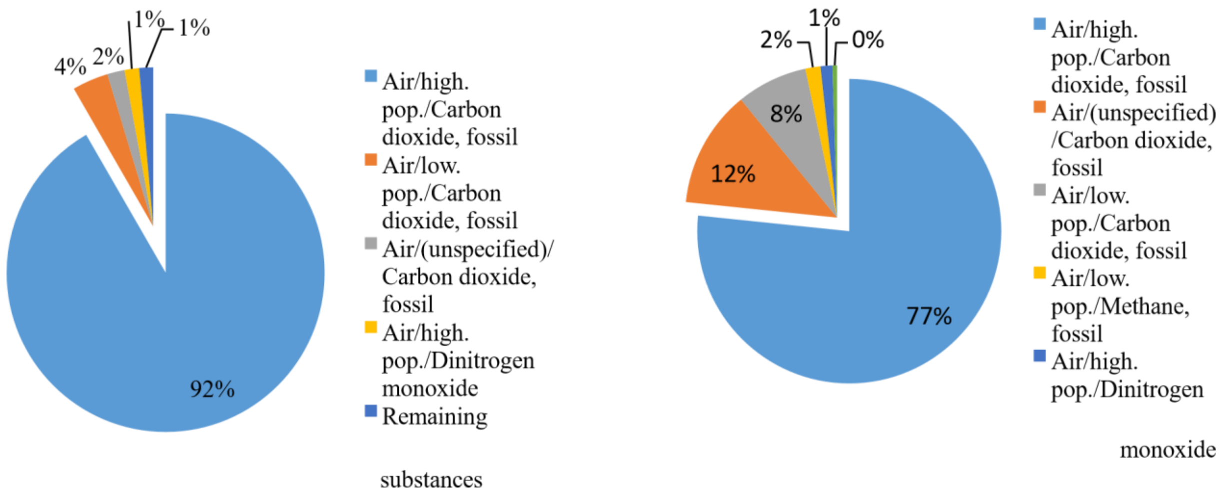


(C) Single Score Results

Figure 3: LCIA results for SC_1 (FG) vs. SC_2 (AAC) substructures using ReCiPe (H) V1.10

5.1 Interpretation

It is important to identify processes contributing most to the CCHH impact category since it was presented with the highest score in both scenarios. Figure 4 (A) and (B) display the element contribution in terms of the elementary flow leaving the techno-sphere for the ecosystem, using a cutoff of 0.1%. The pie charts show that carbon dioxide was the highest element contributor in the CCHH category, accounting for 92% and 77% of the score in SC_1 and SC_2, respectively. It was found that the process having the greatest impact in both scenarios was the electricity required to operate the AC with a contribution of 91% and 77% respectively.



(A) SC1 (FG)

(B) SC2 (AAC)

Figure 4: Element contribution for SC1 (FG) and SC2 (AAC) CCHH category.

6 CONCLUSIONS

In this study, an LCA was conducted to investigate the environmental impact of FG building in arid environments focusing on AC requirements and energy consumption. The FG room was compared to the conventional AAC. The first scenario involved building an FG room and compared it to the conventional AAC building method. The two scenarios were evaluated against CCHH, OD, FD, and MD environmental impact categories. Our findings show that electricity consumption for AC had the greatest impact on the CCHH category. The generation of electricity released most of the carbon dioxide which alone accounted for 90% and 77% of the CCHH impact for the FG and AAC rooms, respectively.

The limitation of the study was a lack of available data related to standard materials used to construct residential buildings in Kuwait. Similarly, there are few studies on FG buildings. FG rooms can be built and customized in many ways. This may affect the quantities of materials utilized in the construction of such rooms, which may in turn be expensive and cause significant environmental damage. Outcomes of this research could encourage decision makers to update the residential building codes and standards to include necessary amendments related to fiberglass buildings', to save energy and ensure the safety of the inhabitants, stored materials, and equipment.

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