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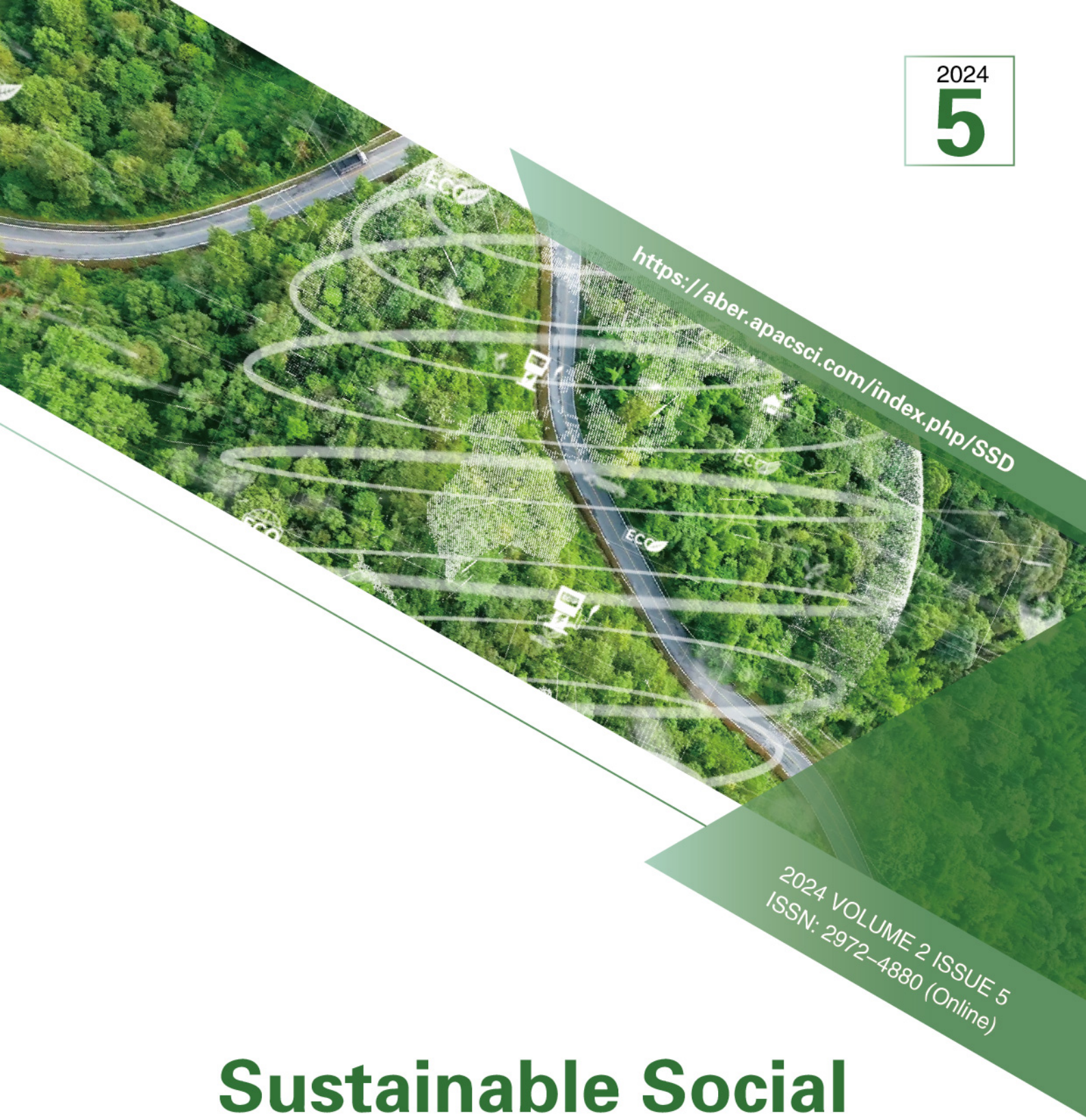

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Article

A comparative study of the potentials of Oman and UAE in condensate water recovery

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Abstract: Freshwater is essential for everyday activities including drinking, irrigation, farming and many industrial processes. However, freshwater is less than 1% of the total water resources in the planet and, therefore, it is considered a very valuable commodity. Limited resources and growing needs for freshwater triggered global exploration for alternatives to produce enough freshwater for human needs. Today's most widely used methods to produce freshwater is desalination. However, critical appraisal of the desalination procedures raised the alarm about sustainability of desalination and indicated that significant research is needed to develop alternative green resources of freshwater. Countries in the Gulf area such as Oman and UAE experience hot and humid climates and use air-conditioning units to achieve acceptable comfort levels and create a healthier indoor environment. The cooling process release a large amount of condensate water through cooling coils. This amount of water is usually considered as a problem rather than opportunity and, thus, is wasted into municipal sewerage systems via a system of drainage pipes. This alternative source can be utilized in various drainage, irrigation, and cooling applications to reduce the use of considerable amount of municipal potable water. This source not only takes part in controlling the water scarcity, but also in saving energy and to reducing the carbon footprint. This paper focus on highlighting the opportunities for Oman and UAE to utilize the condensate water from air-conditioning process, as a viable alternative source of green fresh water. It provides a comparison of the potentials of both countries to collect condensate water, based on meteorological data, location and climate. It was concluded that both countries have great potentials and opportunities to utilize this wasted resource.

Keywords: freshwater; condensate water; metrological data; air temperature; relative humidity; solar radiation; sunshine hours; Oman; UAE

1. Introduction

Water is considered one of the most important plentiful resources on earth but freshwater, which is needed for human everyday needs, is considered a rare commodity. Salty water covers three fourths of the globe's surface and, accounts for a massive 97% of all water resources on earth. Unfortunately, this salty water cannot be used in most activities such as drinking, irrigation, farming livestock and many industrial processes. Freshwater, on the other hand, is essential for human needs, but its amount is very limited, as it accounts for 3% of the total water on earth. Furthermore, the available freshwater is actually less than 1% of the total water resources in the planet, as about 70% of the existing freshwater is not readily available [1–4].

The World Health Organization (WHO) reported that only 2.1 billion people gained access to safely managed drinking water between 2000 and 2022 [5]. Accordingly, only one out of four people have access to safe drinking water, but three quarters of the world population do not.

In 2018, the Population Division of The United Nations reported that the world population is increasing and could approach ten billion by 2050, as can be seen in **Figure 1**. About half of the current world population lives in highly dense cities, particularly in developing countries with high demand of water. It is projected that the population of these countries will be more than two-thirds the world population in the next two decades, leading to further increase in the demand for fresh water [6].

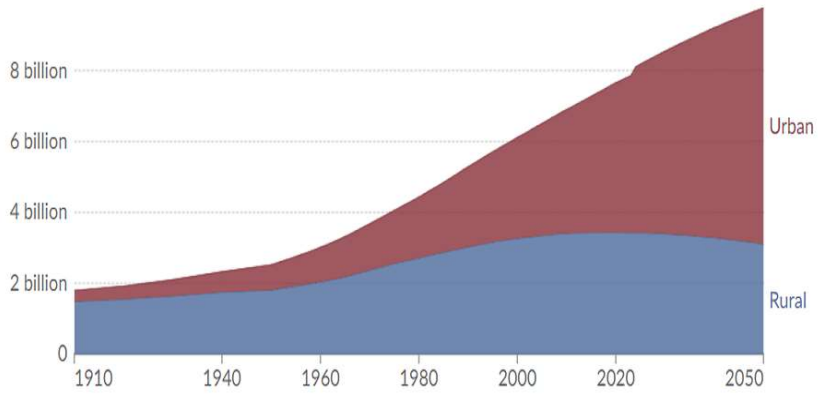

Figure 1. Projection of urban and rural population, to 2050 (UN Population Division).

As the global demand for freshwater is increasing, many countries are facing severe shortage of freshwater supply or even encountering water stress [7]. The concept of water stress is widely used to present the case when demand for water excessively exceeds available amount of water or when water usage is restricted due to poor water quality. Many countries in the Middle East, Gulf region and North Africa are facing water stress [8,9]. These countries confront numerous issues including water shortages, unsustainable water consumption and over exploitation of already limited groundwater [10]. This situation is not expected to get any better because many of these countries are projected to become even drier, as one of the consequences of global warming.

Several countries in the Gulf area, including Oman and UAE (The United Arab Emirates) are among the countries with limited water resources and facing severe shortage of fresh [11–13]. Therefore, managing their water resources and exploring new methods and alternatives to produce enough freshwater are crucial for these two countries to achieve water security. In another word, to cover the gap between supply and demand of freshwater.

Today's most widely used methods to produce freshwater is desalination. However, Badr [14] scrutinized desalination processes and provided critical appraisal of its sustainability from input to output. The author raised the alarm and recommended that significant research is needed to develop alternative green resources of freshwater.

Capturing condensate water from air is an interesting alternative method that is gaining more attention from researchers around the globe. There are several techniques to capture condensate water, either as the main product such as in direct air capture of moisture processes (DAC) or as by-product as in condensate water from air-conditioning systems. The DAC processes include variety of different methods.

Broadly there is two main types including fog water collection and dew water collection [15–18]. Further details of each DAC process is given elsewhere [18]. This research focus on condensate water produced as by-product from air-conditioning systems, as a viable alternative source of green fresh water. The aim is to investigate the opportunities for Oman and UAE environmentally and economically. A case study of a typical residential house is used to highlight the potential,

2. Geography and climate

Geographically, Oman and UAE are located on the southeastern coast of the Arabian Peninsula in Western Asia. Oman lies between latitudes 26°12′ and 17°1′ North, and longitudes 52° and 60° East. UAE share 450 km southeast border with Oman. It is located between latitudes 25°47′ and 24°12′ North, and longitudes between 51° and 56°25′ East [19]. Summary of the location and climate zone of Oman and UAE is given in **Table 1**.

Oman and UAE are in the arid tropical zone, as can be seen **Figure 2**, which shows that the climate of Oman and UAE can be classified as BWh climate [20]. It is described as subtropical dry, hot desert climate with low annual rainfall, very high temperatures in summer and can be as high as 48 ℃.

Table 1. Location and climate zone of Oman and UAE [19].

	Oman	**United Arab Emirates**
Climate zone	Subtropics to tropics	Subtropics to tropics
Latitudes	26°12′ N to 17°1′ N	25°47′ N to 24°12′ N
Longitude	52° to 60° East	51° to 56°25′
Distance to equator	1900–2900 km	2700–2900 km

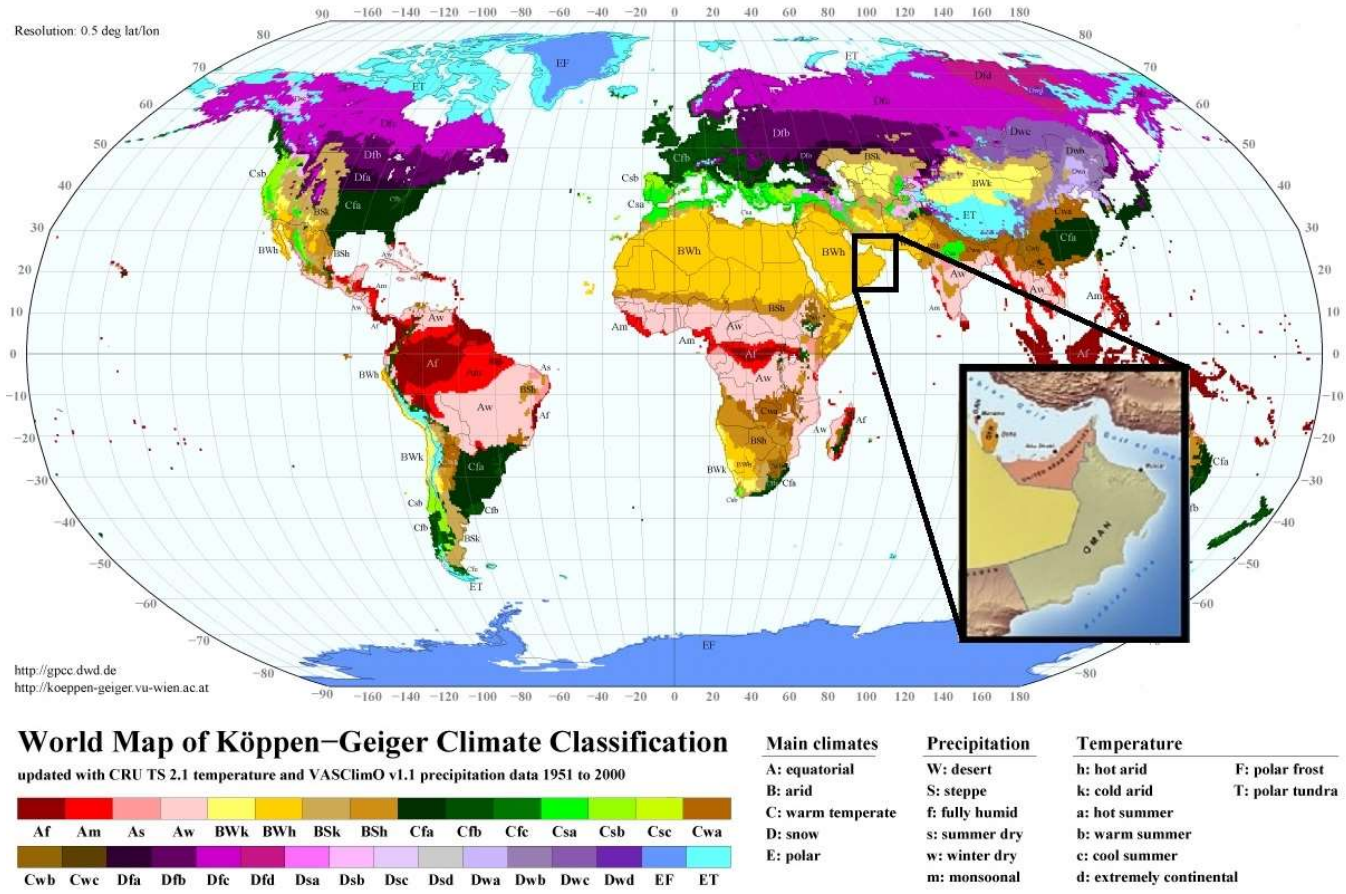

Figure 2. Location of Oman and Koppen-Geiger climate classification map, adapted from [20].

3. Water resources in Oman and UAE

The main water resources in Oman include 1400 MCM (Million Cubic Metres) of underground and surface, 440 MCM from desalination of seawater and 100 MCM from wastewater treatment. Representing 70%, 23% and 5% of annual freshwater production per year, respectively. In addition, there is a small amount of fog harvesting water [21].

According to the UAE state of environment report 2020, UAE produces annually 2.52 BCM (Billion Cubic Metres) of underground water, 2.02 BCM of desalinated seawater and, 0.53 BCM of treated wastewater used. Thus, the main water resources in UAE includes groundwater (50%), desalinated water (40%) and treated wastewater (10%).

In their effort to reduce the demand of energy environmental impact of desalinations, both countries are increasingly using solar energy to power Distillation plants. This subject is out of scope of the current paper and is addressed by many researchers elsewhere [22–23]. It has been mentioned earlier that the author, Badr [14], critically appraised the sustainability of desalination and highlighted the pressing need for alternative green resources of freshwater.

4. Analysis of meteorological data

The geographical location determines the climate of a country, city, district, or a property. Tropical and humid regions have a high potential for condensate recovery. The amount of condensate water captured from the moisture in the atmosphere during the operation of an air-cooling unit is directly proportional to the value of humidity. The potential decreases as the humidity decrease and, thus, places with low humidity levels have low potentials and might not be suitable for condensate collection if humidity drops under certain limit. Therefore, meteorological data should be considered and analysed to decide on the feasibility of using this technique as an alternative method of collecting condensate water in a specific location, city or country.

The air temperature and its humidity are interrelated. The hotter the air, the more water it can accommodate, as hot air expands and offer more space for the moisture. For example, when the air temperature is 30, a cubic meter of air could have 26 grams of moisture. Five more degrees will facilitate about 3 more grams of moisture, that represents an increase of more than 10%. In fact, the term absolute humidity is rarely used. Rather, the term relative humidity (RH%) is commonly used, which gives the air humidity as a percentage value relative to the temperature-dependent maximum value. Therefore, information about the air temperature is vital in predicting the potential of collecting condensate water.

The amount of the by-product condensate water collected during a full cycle of one day depends also on two more factors. The first is the difference between the hot atmospheric temperature outside the property and the required cool temperature inside the closed place. The second is the number of operating hours of the cooling unit [24]. the longer the exposure to sunshine the longer the cooling unit are required to work to maintain the same level of comfort inside a specific property. The number of sunshine hours per day is more in summer than winter and varies according to the location and geography of a place. Therefore, the potential of harvesting the by-product condensate water from cooling systems is greater for locations exposed to longer hours of sunshine.

Oman and UAE have long coastlines with high relative humidity due to their geographical location. They are also exposed to a very high solar radiation and long hours of sunshine during the day, particularly in summer months. The meteorological data for these two countries is analysed in the following section around the year (annual values) and within the cycle of one day (daily) to appreciate the potential of harvesting condensate water from cooling units, in each country.

Table 2 shows a summary of average annual values of the most significant meteorological parameters for Oman and UAE, including daytime maximum temperature, daily low temperature, humidity, precipitation, rain days and hours of sunshine (World Meteorological Organisation).

Table 2. Average annual values of meteorological data, in Oman and UAE.

Average annual values	Oman	United Arab Emirates
Daytime maximum temperature	34.10 ℃	34.40 ℃
Daily low temperature	23.10 ℃	23.10 ℃
Humidity	65 %	61 %

Table 2. (*Continued*).

Average annual values	Oman	United Arab Emirates
Precipitation	117 mm	77 mm
Rain days	10.8 days	12.0 days
Hours of sunshine	2263 h	3066 h

4.1. Air temperature

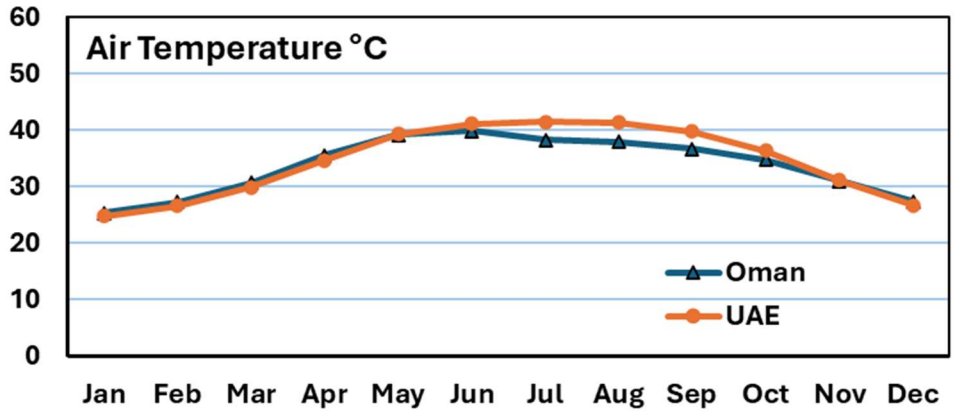

Figure 3. Daily maximum temperatures in a full year, in Oman and UAE.

It has been shown earlier that Oman and UAE shares borders, location and are in the same climate zone. They are both classified as BWh climate, which is described as subtropical dry, hot desert climate with low annual rainfall. It is, therefore, not surprisingly that the curves of the daily maximum temperatures are almost the same for a full year, as can be seen from **Figure 3**. The highest daytime temperature in Oman is about 41 ℃ and it is recorded in June, which is the hottest month in Oman. Although the maximum temperature in the UAE is the same as that of Oman (41 ℃) it occurs on several months from June to August, inclusive.

The coldest month in both countries is January. The recorded coldest temperature in both counties is almost the same of about 25 ℃.

The comfortable temperature for most people is between 24 ℃ and 26 ℃, therefore, the common operating temperature for air-conditioning units is 24 ℃. For a viable collection of condensate water there should be a significant difference between the temperature of the outside air and the operating temperature of air-conditioning units. Studying **Figure 3** reveals that the method would be effective for more than 6 months of the year from April to September. The potential decreases either side of these months in March and October; and might be ceased from November to January, inclusive.

Judging by the results of the analysis of the daily maximum temperatures in a full year, it could be suggested that both Oman and UAE have the same potential for collecting condensate water as by-product from air-conditioning units, provided that all other variables are similar.

4.2. Air humidity

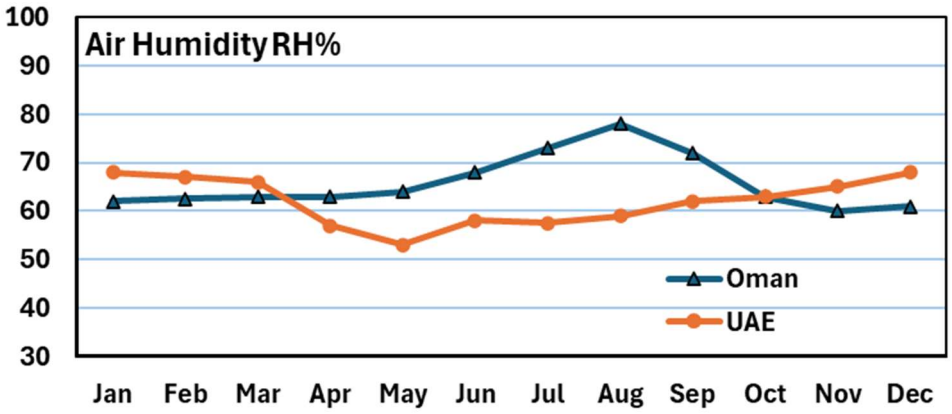

Figure 4. Daily maximum RH% in a full year, in Oman and UAE.

The relative humidity (RH%) is a commonly used expression that gives air humidity as a percentage value relative to the temperature-dependent maximum value. **Figure 4** presents the annual average relative humidity RH% in both countries. The RH% in both countries is very high and almost flat around the year with a band of less than 20%. However, the RH% in the UAE is about 10% less than that of Oman. The latter has an average RH% of about 66% compared to 62% for the UAE. Oman has a minimum value of 60% and a maximum of 78%. The corresponding values in the UAE are 53% and 68%. The higher RH% in Oman indicates that the potential for collecting the by-product condensate water is slightly better in Oman than in the UAE.

4.3. Daily sunshine hours

Combining the outcome of the results of the analysis of the daily maximum temperatures and RH% in a full year for Oman and UAE, both countries have great potentials for collecting condensate water as by-product from air-conditioning units. This is attributed to the fact that Oman and UAE have experience high temperatures and high RH% around the year due to their geographical location and climate.

In addition to the high air temperature and RH%, Oman and UAE are also exposed to very high solar radiation and long hours of sunshine during the day, particularly in summer months. As a result, the air-conditioners will be operating longer periods during summer days. The number of sunshine hours per day in Oman and UAE is plotted in **Figure 5**.

The actual amount of condensate water that could be collected during a full cycle of one day depends on the operating hours of the cooling unit [24].

Once again, with more than 3,000 hours of sunshine per year, the UAE comes on top for potential air-conditioning operating hours. Most days in the UAE has more than 8 hours of sunshine with a maximum of 9.9 hours recorded in June. Although the average hours of sunshine in Oman looks inferior to those in the UAE, they are still high with an average of 6.6 hours and a maximum of 8.5 hours. The annual value is a decent total of more than 2200 hours of sunshine per year.

The daily and total hours of sunshine in Oman and UAE indicate great potential for both countries to get huge quantities of collected condensate water due to the long

operating hours of air-conditioners. However, once again, the longer operation hours indicates that the potential in the UAE is higher.

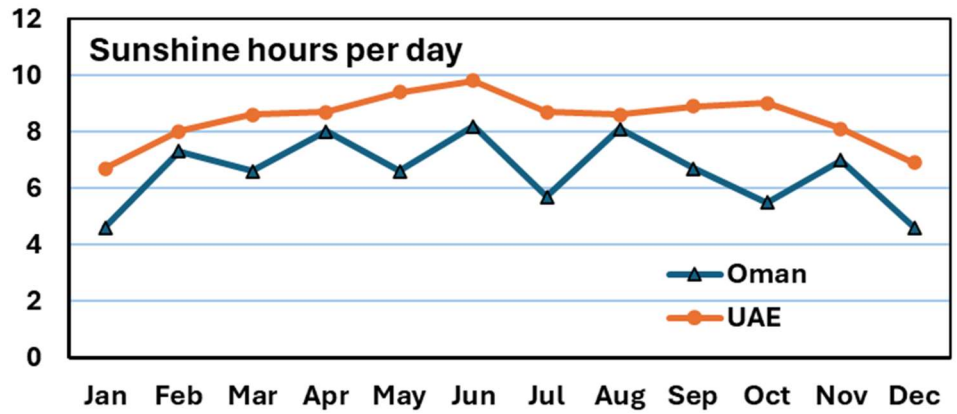

Figure 5. Sunshine hours per day, in Oman and UAE.

5. Condensate production

Most air-conditioning units are designed to not only cool the air but also to dehumidify it as well. In fact, some air-conditioners are primarily designed as dehumidifiers or make the dehumidification mode the default mode of operation of air-conditioners. Furthermore, some air-conditioners are designed with extra features that allow users to adjust the levels of dehumidification and cooling, separately.

During the cooling process, the hot air passes over the cooling coils of an air-conditioner, the temperature of the air is lowered below its dew point, causing moisture in the air to condensate on the coils. Lowering the humidity level in the air by removing excessive moisture improves the comfort level and creates a healthier indoor environment by preventing bug growth. However, condensate water is naturally produced as a by-product of the of an air-conditioning process.

Various types of air-conditioning units (AC) are used for cooling and conditioning domestic and commercial buildings. These are Window AC, Split AC, Chiller based Air Handling Units (AHUs), Fan Coil Units (FCUs). These machines generate considerable amounts of condensate water during cooling and dehumidification process at the cooling coil [10]. However, Split AC is the most common type used in Oman and UAE for residential buildings and small commercial enterprises.

Regardless of the type of the air-conditioner, the by-product condensate water has the potential to be a valuable alternative source of freshwater. It can be utilized in various drainage, irrigation, and cooling applications to reduce the use of similar amounts of municipal potable water. This source not only takes part in controlling the water scarcity, but also in saving energy and to reducing the carbon footprint.

6. Condensate production rates

The quantity and quality of recovered condensate from outdoor air are influenced by parameters such as climate zone and associated climate parameters, the type of building, how it is used, and the volume of the supply air. In general, these factors could be grouped in four main categories including but not limited to:

- Installed air-conditioner: Type, capacity, and efficiency.
- Outside air parameters: Air temperature, humidity, and sunshine hours per day.
- Building parameters: Building type, design, area, personnel density, and usage.
- Indoor conditions: Fresh air volume, indoor temperature, and humidity.

Considering the factors affecting the recovery of AC condensate water, it is very difficult to predict the condensate rate of the collection prediction, due to the variability of each factor. However, the effect of each factor could be predicted assuming that the other variables are constant for a specific case or at one point of time. For example, for air-conditioners with similar power and efficiency, the main factor controlling the collection potential depends on the difference between the outside humidity and the desired one inside. Vice versa, the AC power and efficiency will be the main factors if the meteorological factors are constant.

Therefore, the potential of condensate recovery should be assessed on a case-by-case basis, including cases for whole countries, cases for specific regions, cases for particular property or facility.

In many of the cases reported in the literature, the amount of recovered condensate is sufficient to cover all or part of the water demand for plant watering, or toilet flushing [25]. There are cases in which the recovered amount of condensate water exceeded the water demand of the building [26]. In a full-scale experiment conducted by the University of Birmingham, in Alabama USA, the amount of condensate water was 55.27 million L recovered in 17 months. The collection rate was not constant over time, with the largest output of condensate water was collected in June and represented about 6.5% of the total water demand. The results provided encouraging indication of the great water-saving potential [27].

However, in all cases when air-conditioning is needed to mitigate hot temperature and humidity, the condensate water collected is a naturally by-product produced during the air-conditioning process, with no additional cost.

7. Quality of condensate water

Theoretically, the quality of the condensate water should be as pure as droplets of water condensate on leaves in the early mornings (**Figure 6**). However, due to the existence of metal, plastic and fabric parts and particles within any AC unit, there could be some contamination or pollution during the condensation process, collection, and transportation of the condensate water.

Several researchers conducted chemical analysis, physical tests, and bacterial tests on released drain-water collected from different types of cooling air-conditioner in experiments conducted around the world. Recently, Moosa et al. [11] reported that freshwater collected directly from air-cooling units as a byproduct was almost distilled water with very low electrical conductivity and a pH of about 7. They, therefore, concluded that the collected by-product condensate water is almost pure.

As would be expected, there could be a possibility of contamination with some types of bacteria because there are some types of bacteria that exist naturally in the moisture of the atmosphere. However, such contaminated water could be easily disinfected using solar disinfection by raising the water temperature above 60 ℃. Moosa et al. [11] recommend that the temperature of the contaminated water must

reach a range of 60 ℃ to 65 ℃ to guarantee completion of the disinfection by solar energy.

Figure 6. Droplets of water condensate on leaves in the early mornings.

Uddin et al. [28] collected condensate water samples from different locations. After conducting a full analysis of the collected samples, they found that the collected condensate water was good for drinking according to WHO standard. Since using the condensate water has no potential risk for drinking it is will be safe and suitable for washing and other household purposes, irrigation, and fisheries purposes.

8. Applications of condensate water

Condensate water could be used directly in many applications without any treatment, including toilet flushing, landscaping, gardening, green roofs, water features, and roof ponds. It could also be utilized in several other applications with some sort of treatment. Furthermore, with proper treatment and disinfection it could even be used for drinking. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [29] conducted a study to investigate reusing condensate water for non-potable purposes and concluded that a typical office building could offer significant savings by using it in applications such as landscaping and irrigation.

The best choice of applications should be decided on the actual needs of the location where it is collected. However, any amount of condensate water used instead of using municipal potable water will have an equal value to the municipal water, in addition to the extra benefit of reducing the sewerage flow by the same amount of water.

Examples of applications for AC condensate water that could contribute to water security in Oman and UAE and minimize the dependence on municipal water include:

8.1. Applications without pre-treatment

8.1.1. Toilet flushing

Condensate water can be effectively utilized without any treatment in toilet flushing. However, it is suggested that condensate water could be mixed with suitable

dye to distinguish it from potable water supplied to sinks, kitchens, and bath hubs in the same building [24,26].

8.1.2. Landscaping and gardening

Landscape and gardening irrigation is an ideal application to use condensate water effectively without any treatment. Gardens could be provided with self-watering systems including piping network connected to a storage tank that is supplied with condensate water. The quantity of condensate water produced in a specific building will probably be more than enough to provide the water required for gardening and the surrounding landscape in the same property.

8.1.3. Water features

Fountains and similar water features are similar applications to landscaping and gardening but would require less amount of condensate water, as the system works by circulating the same amount of water for a relatively longer time before the need to change or top-up. Therefore, these could be ideal for smaller buildings with low number of occupants and fewer air-conditioning units.

8.1.4. Green roofs

Green roofing is a nice landscaping and a habitat for birds. It also offers a cheap passive cooling system for the top floor of any facility. The quantity of condensate water produced in a specific building could be enough to provide the water required for its green roof. The main components of a green roof include root barrier layer, a growing medium, vegetation, a drainage layer and an irrigation system [30]. Similar to the application of gardening it could be provided with self-watering systems including piping network connected to a storage tank that is supplied with condensate water.

8.1.5. Roof ponds

Condensate water could be utilized in roof ponds to provide passive cooling system in the most effective way by using water as an ideal thermal mass. This application is particularly beneficial in places characterised with rare rainwater or hot dry environment. At night, the insulation is removed to expose the wate in the roof bond, so it loses significant amounts of heat by radiation to atmosphere [24].

8.2. Applications with little pre-treatment

8.2.1. Agriculture Irrigation

This application is similar to gardening irrigation but needs huge quantities of condensate water that could be collected from a city, district or several residential quarters. For edible crops, it may be a good idea to periodically analyse samples and pre-treat the condensate water before using in fruit and vegetable farms. For flowers and decoration plants, the condensate water could be used without pre-treatment.

8.2.2. Livestock farming

With little pre-treatment, condensate water could be used for livestock farming, including raising animals and birds. Animals could be raised for their meat, such cattle, sheep, goats, horses, buffalo, and camels. Similarly, it could be used for raising birds

commercially or for domestic use for their meat or eggs, chickens, turkeys, ducks and geese.

8.3. Applications with pre-treatment

Drinking

Moosa et al. [11] reported that freshwater collected directly from air-cooling units as a byproduct has very low electrical conductivity and a pH of about 7 and, therefore, concluded that the collected by-product condensate water is almost pure. However, the collected water could be contaminated with some types of bacteria because that exist in the atmosphere. It is, thus, recommended to use solar disinfection by raising the water temperature to 65 ℃ to guarantee completion of the disinfection.

9. Conclusions

This study conducted a comparison between the potentials of Oman and UAE to utilize the condensate water from air-conditioners as a viable alternative source of green freshwater. Meteorological data, location and climate of both countries were used to investigate the potential of each country. The following conclusions could be made:

- Oman and UAE, have great potentials for collecting condensate water as a by-product from air-conditioning units, as both countries experience high temperatures and high RH% around the year due to their geographical location and climate.
- The relative humidity (RH%) in the UAE is about 6% less than that of Oman. The latter has an average RH% of about 66%, whereas the corresponding value in the UAE is 62%, indicating that the potential for collecting the by-product condensate water could be slightly higher in Oman than in the UAE.
- In addition to the high air temperature and RH%, Oman and UAE are also exposed to long hours of sunshine during the day, particularly in the UAE. As a result, the actual amount of condensate water that could be collected in the UAE could be more than that in Oman, due to longer operating hours of the cooling units.
- Considering all the analysed meteorological data, it could be suggested that both countries have similar great potentials for collecting condensate water from air-conditioners.
- Collecting condensate water in Oman and UAE will be effective for more than 6 months of the year from April to September. The potential decreases either side of these months in March and October; and might be ceased from November to January, inclusive.
- Any amount of condensate water produced in both countries and used instead of using municipal potable water will have an equal economical value to the municipal water, in addition to the extra environmental benefit of reducing the sewerage flow by the same amount of water in Oman and UAE.

10. Recommendations

For countries with great potential for collecting and using condensate water from air-conditioners and cooling systems, such as Oman and UAE, it is recommended to:

- Encourage private sector to investment in condensate water recovery and reuse systems, both at national and local facilities. The increases in water demand and high cost of wastewater treatment indicate that such investment could be very cost-effective.
- Propose, approve, and implement polices that require all new residential and commercial buildings that install certain number of air-conditioners or cooling systems to include a properly designed separate drainage systems to collect condensate water and reuse it within the facility until a national system is constructed.
- Invest in designing and construction of national system to collect reusable water resources, including rainwater and condensate waters among others.

Conflict of interest: The author declares no conflict of interest.

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Article

Analysis of gender and institutional level of arrangement in REDD$^+$ pilot sites, Cross River State, Nigeria

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Abstract: This study assessed genders' institutional level of arrangement in REDD$^+$ pilot sites, Cross River State, Nigeria. Data were collected through literature and policy document review and Focus Group Discussion (FGD). The total number of 270 documents with three, **Level 1:** Non-substantive inclusion, **Level 2:** Superficial inclusion and **Level 3:** Integrated inclusion. The gender were classified as Men and Women for the search engine. The results showed that only 95 of the 270 REDD$^+$ related documents mentioned gender (representing 51% of the total documents). Nearly half of the texts that include the crucial phrases were categorized at Level 1, which means that gender concerns were not material. Regardless of how it is seen, the meager inclusion of gender mainstreaming discussion can only be found in Level 3. This 7% translated to only 12 out of the 270 documents which truly and fully understood the gender mainstreaming ideas. The study concluded that communities' policy interventions such as REDD$^+$ still exhibit non-compliance of gender mainstreaming and institutional level of arrangement, therefore, this study recommend that "*sincerity*" of gender mainstreaming from the government and other stakeholders is a panacea for the success of any climate change adaptation programme such as REDD$^+$.

Keywords: climate change; vulnerability; men; women; adaptation; mainstreaming

1. Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) classified the Reducing Emissions from Deforestation and Forest Degradation (REDD$^+$) as a global initiative seeks to lower greenhouse gas emissions by reducing deforestation and forest degradation, enhancing and conserving forest carbon stocks, and promoting sustainable forest management. While maintaining and increasing forest carbon reserves is REDD$^+$'s core objective, community welfare is also a crucial component of the framework, as noted by [1]. The countries that participate in REDD$^+$ are required by the UNFCCC's Cancun safeguards and Warsaw Framework, respectively, to address and respect social issues and to report on how all safeguard-related issues are being addressed and respected during REDD$^+$ implementation.

The emphasis on a gender-responsive climate policy, as shown in the 2016 resolution on gender and climate, and the Paris Agreement has acknowledged women's engagement in climate policy in recent years. Additionally, some multi and bilateral donors as well as third-party certifiers, like the Climate Community and Biodiversity Alliance and the World Bank Forest Carbon Partnership Fund, have additional requirements for demonstrating high social and environmental performance [2]. In addition, since its creation in 2008, UN-REDD has actively promoted gender integration by forging connections and linkages with other REDD thematic areas, including governance, REDD$^+$ national strategies/action plans, policies and measures (PAMs), safeguards, multiple benefits, and stakeholder engagement [3]. On the other hand, in order to completely ensure gender equality in global development by 2030, the United Nations has also set out to accomplish Goal 5 of the Sustainable Development Goals (SDGs), which is Gender Equity and Women Empowerment. All of these serve as a reminder to include gender as a fundamental component of any global program, such as REDD$^+$ [1].

Nigeria's forestry sector seems fully committed to respect and address gender related issues at least in the policy arena. Among the appropriate action plan are: National Adaptation Strategy and Plan of Action for Climate Change in Nigeria (NASPA-CCN 2011); (ii) Nigeria Climate Change Policy Response and Strategy (2012); (iii) National Agricultural Resilience Framework (2014); (iv) Agriculture Promotion Policy (2016); and (v) National Gender Policy 2006 (revised 2015). Other related policy instruments include (vi) Nationally Determined Contributions (NDCs) and its Sectoral Plans. In addition, Nigeria's National REDD$^+$ Strategy [4] demonstrates a strong commitment to establishing and bolstering gender-related grievance resolution procedures as well as incorporating and guaranteeing social and environmental protections in REDD programs and activities. However, these documents have warned us to address the possibility of social exclusion of Indigenous people, dalits, and other marginalized communities, as well as gender discrimination against women, in the forestry-cum REDD$^+$ program. They have also recommended that women be encouraged and included at all levels, from policy making to program formulation, implementation, monitoring and reporting, and evaluation. Poverty and vulnerability are made worse by climate change's effects on biodiversity, agriculture, energy, health, food security, and physical infrastructure. All countries will be impacted by climate change, but the effects will vary depending on the region. For developing nations in Africa, Asia, and Latin America, for instance, climate change exacerbates already complex development challenges (such as high rates of poverty and inequality, rapid population growth, underdeveloped financial markets, and weak governance systems).

According to Basiru et al. [5] there is a correlation between an individual's age, gender, economic group, and occupation and the effects of climate change. Because men and women experience social, economic, and environmental realities differently, there is a gender difference in the effects of climate change on both genders [5]. The contributions made by men and women will differ and be just as significant [5]. Solutions to mitigate and adapt to climate change, such as REDD$^+$, must take these gender-specific demands and contributions into account. Therefore, it is imperative that Nigeria promote a gender-sensitive REDD$^+$ process. "Gender mainstreaming is

the process of assessing the implications for women and men of any planned action, including legislation, policies and programmes in all areas and at all levels" [6]. It is a tactic for incorporating the issues and experiences of both men and women into the planning, implementing, overseeing, and assessing of policies and programs in all social, economic, and environmental domains in order to achieve equality for both genders by changing the status quo. Gender mainstreaming include affirmative action and gender-specific actions when one or both of the sexes are in a particularly unfavorable situation. To allow women to participate in and benefit equally from development activities, gender-specific interventions might focus only on women, on men and women combined, or simply on men [7]. These are essential short-term steps intended to counteract the direct and collateral damage caused by prior prejudice.

Despite these policy requirements, women were noticeably underrepresented in the drafting of policy documents, and their concerns were disregarded when developing policies and implementing programs [8]. Specifically, there aren't enough critical evaluations of how Nepal REDD$^+$ initiatives address gender issues according to [9]. Women would be deprived of benefits and put in a position of social, economic, and political disadvantage if the gender issues raised by the REDD$^+$ program were not acknowledged and addressed [10]. Thus, in order to make the REDD$^+$ program or project generally accepted, it is imperative that gender-related concerns be evaluated, acknowledged, and promptly addressed as the case related REDD$^+$ in Cross River State, Nigeria.

2. Materials and methods

Geographically, Cross River State (CRS) is situated in the South-Southern part of Nigeria, and bound by Latitudes 4°27′to 5°32′ N and Longitudes 7°50′ to 9°28′ E with an approximate landmass area of 20,156 square km respectively [11]. A early evaluation of REDD$^+$ initiative was reported by the Cross River State Government in 2010 after many scoping missions in Cross River State by officials from UNREDD and the World Bank's Forest Carbon Partnership Facility, consequently, three primary clusters for the REDD$^+$ pilot project were discovered through this evaluation process. Contiguous tropical high forests under community management, adjacent forest reserves, and national parks make up these clusters (The Ekuri, Afi/Mbe and mangrove clusters).

As a result, these regions are combined into a single cluster since it is the only way the project can be made feasible and qualify for international carbon funding under the REDD$^+$ initiative. The majority of these communities' forests are under oversight of Old and New Ekuri villages, which together make up one of the largest surviving tropical forests in West Africa under community-based management. In several of these areas, gender has played distinct and useful roles in community-based conservation initiatives that are now underway in cooperation with international organizations. These consist of the UK-based CERCOPAN and the NGO Ekuri Initiative.

Another cluster for the REDD$^+$ investigation includes the Afi River and Mbe Mountain Wildlife Sanctuary, as well as the neighboring community forests and reserves. This cluster, which is in the Boki Local Government Area of the State, is

made up of over 50,000 hectares of forest area and is governed by 18 villages. According to the same deforestation baseline scenario, the PIN also estimated that this cluster had the capacity to release around 12.3 million tons of CO_2 over a two decades. The main forest in this cluster is under the ownership of the villages of Kanyang I and II and Buanchor. The Conservation Association of Mbe Mountain (CAMM) is responsible for the conservation efforts of the nine villages that surround the Mbe Mountains [12]. The preliminary assessment study from 2010 also highlighted the Mangrove Cluster, stating that the state's mangrove reserves are extremely rich in forest biodiversity and span an area of about 5% of the overall land area. Currently participating in the REDD$^+$ process in Cross River State are more than thirty villages that reside on mangrove swamps. This area, which has been maintained by Cross River National Park, forest reserves, and indigenous forest communities with high species richness and diversity, including both vascular and nonvascular plants that reflect the local microclimatic conditions, is thought to be unique because it contains the last remaining pristine rainforest vegetation in all of Nigeria.

These regions together make up over 900,000 hectares of forest land. The population is culturally varied, speaking over 39 distinct regional languages and dialects that are dispersed unevenly throughout all eighteen local government areas (LGAs). According to Akindele et al. [13] the languages spoken in the state of Cross River are classified into three groups: native, English, and Nigerian pidgin. Both the majority and minority populations speak Efik, the most widely used of the indigenous languages. The Efik language has been used for trade, religious instruction, and other business-related activities for many generations. The educated elite speaks English frequently, and it continues to be the official language of communication and administration.

Most of the communities have a diverse range of traditional religious belief systems. Some tribes continue to preserve locations of worship that are symbolic of their ancient gods and customs, such as prohibited woods, sacred ponds, evil streams, and bad forests. This suggests that the majority of African communities have benefited from decades of resource conservation thanks in part to these traditional methods. Fishing, Non Timber Forest Products (NTFP) harvesting, logging, ecotourism, and agricultural potentials are all strong points of the research site economy. Due to the strong gendered nature of family systems in Cross River State communities, men and women perform separate culturally assigned tasks. For instance, Juma et al. [14] argued that married women in Cross River State towns around protected areas are expected to stay at home and take care of the family while males attend meetings on forest management. The authors contended that despite their extensive backgrounds in forest management, women still find it extremely challenging to participate in these meetings because they are typically held at night. They said that even if some ladies are eager to take part, they are not well-educated or linguistically proficient enough to converse in English. A significant amount of the tropical high forests in Cross River State are maintained as Community Forest Estates, Forest Reserves, and National Parks.

2.1. Gender, REDD$^+$, Institutional level of arrangement and implementation in Cross River State, Nigeria

In Cross River State, the Forestry Commission oversaw the whole REDD+ implementation process. The Forestry Commission has the manpower and resources required to fulfill its legislative purpose. The REDD+ Technical Committee offers technical advice on all REDD+ related issues, and the REDD+ Unit is in charge of implementation. The Cross River State Climate Change Council, chaired by the State Executive Governor, is the top coordinating body for all climate change matters in CRS. The national Safeguards Information System (SIS) was managed by the Forestry Commission, which was also responsible for forest inventory, GHG emissions reporting, remote sensing and GIS, and information management. Relevant Ministries were in charge of ground implementation, as were departments and agencies, non-governmental organizations (NGOs), local communities, CBOs, traditional authorities (TAs), local government authorities (LGAs), university and research institutions, the business sector, and the media [4]. For the purpose of defining equitable opportunities for women and other vulnerable groups in REDD+ planning, decision-making, and implementation, stakeholders have recognized gender and equality as a critical aim. Addressing the gender gaps that come from sociocultural norms, low literacy rates, and deeply held patriarchal beliefs is crucial since these factors all impede the adoption of new concepts, ideas, and attitudes. It was necessary to take gender issues into account while interacting with both men and women as well as marginalized and vulnerable groups in order to exchange information, build capacity, promote, and push for the utilization of forest resources [4].

2.2. Instrument of data collection

Using Google, a search for documentation of REDD+ initiatives in Nigeria was carried out in May 2021. We accessed and inspected every page that came up when we typed in the search keywords "REDD Nigeria," "REDD+ Nigeria," "REDD projects Nigeria," or "REDD+ projects Nigeria" to make sure it was indeed about REDD+ in Nigeria. There were no new websites or REDD+ initiatives found despite searching till saturation. The following crucial phrases were looked for in every document: "gender," "man or woman," "men or women," or "male or female." There were no mentions of a female animal. The document was designated as "includes gender" and included in the study if the crucial phrases appeared in it at least once. By using this search technique, 270 documents that correspond to 95 were identified and analysed. Each every one of the 270 papers were composed in English. Additionally, questions were asked about (a) how gender and the REDD+ initiative were perceived; (b) policy discourses on institutional level of arrangement; (c) opinions and perceptions on bottlenecks; and (d) how gender were perceived and evaluated using actors and institutions standard in forest resource governance. The interview groups included Village Head, Principal Officers of the Cross River State Forestry Commission, and REDD+ staff.

2.3. Document analysis of gender mainstreaming and institutional arrangement of REDD+ in Nigeria

Three "levels" were used to code each document. The ideas listed for this study are closely connected to levels two and three. Documents that draw a link between the

social/gendered and ecological systems are included in level two. These materials explain why gender matters for REDD$^+$ efforts, but they don't go into detail about how to best include gender and women's issues into them. Level three documents are those that examine the obstacles to include women in these programs and policies or provide detailed instructions on how to improve their involvement and capabilities. Though level one papers have some mention of gender but do not match the requirements for any of the other two levels, this is based on the understanding that any consideration of gender in these REDD$^+$ related documents is a positive start in the right direction. **Table 1** presented each level's concept and examples in a clear and concise manner.

2.4. Focus group discussion

The following member breakdowns were achieved through focus group discussions (FGDs) in the selected communities across the pilot sites: adult men and women aged 36–59, male and female youth aged 18–35, and elderly men and women aged 60 and above. The purpose of the group discussions was to gain an understanding of the perceptions, participation, decision making, and institutional level of arrangement of REDD$^+$ in Cross River state. The emphasis on gender disaggregation allowed for full participation of gender representative sections of the community members.

The discussions were guided and focused on pertinent topics related to the major research questions using a check-list or FGD guide of questions. Each participant was given an equal opportunity to voice their views without any person suppressing the opinions of others.

2.5. Statistical analysis

After literature review, data were entered into MS Excel, and then analyzed with SPSS (version 25) using descriptive and inferential statistics and the results were presented in form of tables.

3. Results and discussion

Gender and Institutional level of arrangement in REDD$^+$ pilot site, Cross River State

Approximately two hundered and seventy (270) linked documents on the REDD$^+$ projects were analyzed using criteria in **Table 1**, of which 95 includes gender at some level and 175 do not at all. Each occurrence of the key phrases in the papers was categorized into one of the three levels after they had been located (**Table 1**). The document was coded at that level if all occurrences of the keywords were coded at the same level. The whole document was coded at the highest level present in the document when a single document included many levels, which was common.

Table 1. Gender inclusion and mainstreaming level by in REDD$^+$ initiative.

Levels	Types of gender references included at each level
Level 1: Non-substantive inclusion	Demographies/statistics alone without any explanation
	Men/Male and Women/Female basic appearance

	Lists of potential partners, organizations, policies etc.
	Gender acknowledgement and consideration without any further explanation on why both acknowledgement and consideration is priority
Level 2: Superficial inclusion	Explanation of best practices or definitions of concepts without specific details or plans of how they were integrated into the policy/project
	Statements that male/men and women/female were included, but without details of their level of participation or inclusion
	Acknowledgement of *why* gender should be considered and/or the importance of gender inclusion, but without details of how it has been or were integrated into policy or projects.
Level 3: Integrated inclusion	Discussions of the potential barriers to men and women's participation, and how barriers were been addressed
	Explanation of *how* gender considerations has been or were been included in the policy project

Based on the results of this analysis's fundamental level, it is clear that gender is neither mainstreamed nor given significant consideration in Nigeria's REDD$^+$ programs, especially at the institutional level of arrangement when putting resilience measures into practice. Only 95 of the 270 REDD$^+$ related documents in the nation, mentioned gender or men/women at all. (translated to 51% of the total). Nearly half of the texts that include the crucial phrases were categorized at level 1, which means that gender concerns were not material. Gender were discussed in 7% of the total number of papers in a way that was substantial, integrated, and mainstreamed. Regardless of how it is seen, the significant inclusion of gender issues, which appears in 7% of the 270 publications relating to REDD$^+$, does not reflect mainstreaming. A breakdown of the number and percentage of documents categorized at each level is shown in **Table 2**. A closer look at how gender is constructed at every level makes it more evident that gender mainstreaming remains mostly theoretical rather than useful in day-to-day affairs. At this level, documents would often include organizations, a women's or gender organization being one of many, but they would seldom explain or consider why their involvement was important for REDD$^+$ efforts or policy. Alternatively, by reporting on the number of men and women living in a certain village of interest, these publications may have appeared to provide gender-disaggregated statistics, but without offering a thorough context through which such data may potentially not be evaluated. The majority of the time, this data was provided as extremely basic demographic data without any connection to potentially interesting outcome factors. The following excerpt from a design paper for the REDD$^+$ documents in Cross River State provides another example of how the keywords are typically used at this level. This text does not truly consider women as stakeholders, even though it is clear that they are involved in the forest activities and are active participants. Rather, it simply enumerates the involvement of women without delving deeper into how men and women have influenced the forest's changes in comparable or different ways, or how these changes have affected individuals whose lives and livelihoods depend on the forest in different ways according to their gender. The document goes on to analyze and discuss important changes that have occurred in the communities that have been assessed, including concerns about land ownership, economic activity, providing for basic needs, and opinions about the future of the forest. However, it fails to consider

how these important aspects of community life may differ depending on a person's gender or affect men and women differently.

Table 2. Gender inclusion in REDD$^+$ documents by level and language in Nigeria.

Total number of documents analyzed: 270							
Any level		**Level 1**		**Level 2**		**Level 3**	
Language	Number	% of total	% of gender	% of total	% of gender	% of total	% of gender
English	95 (100%)	(51%)	(40%)	(26%)	(19%)	(14%)	(7%)

Source: Field survey.
*Figures in parenthesis are percentages of total and gender inclusion levels in REDD$^+$ overall analysed documents.

The second most prevalent inclusion at level 2 is (26%) of which gender consideration accounted for (19%). Gender concerns in these papers are more extensive than in level one, although they are still *superficial*. The great majority of these publications mention gender mainstreaming explicitly as a recommended practice, suggesting that these guidelines were followed or ought to be followed, but they don't go into any depth about how that inclusion was achieved. They have a broad understanding of the significance of gender issues, frequently establishing a connection between gendered and ecological social systems, but they lack specifics about how these factors should be included. Without these facts, it is unclear whether the authors of the documents actually comprehend the value of gender mainstreaming and support its use, or if they are merely repeating the required axioms in order to meet gender mainstreaming standards.

This kind of rhetorical gender inclusiveness was recorded in level 3, which prioritizes involvement to appearance. Only 12 out of 270 documents showed that they truly and fully understood the gender mainstreaming ideas. Gender had to be incorporated throughout the text for it to be coded at this level, and specifics on how gender was or will be taken into account had to be included. These articles consciously attempt to investigate the obstacles to gender mainstreaming and/or the methods of effectively incorporating women and their experiences, concerns, and ideas into programs and policies, clearly surpassing a cursory and procedural inclusion of gender. Rather of being just or even predominately defined as "vulnerable," women are respected and entire members of society who take part in REDD$^+$ and forest management initiatives. The terms, for instance, may be found almost everywhere in the 2011 annual national REDD$^+$ program report (2012). Additionally, it offers specific instances of the gender mainstreaming initiatives implemented so far in the national REDD$^+$ program, such as a national communications plan to inform the public about the connection between gender issues, climate change, and REDD$^+$. Additionally, it offers recommendations, suggestions and objectives for further development. This outcome demonstrates the formation of a team to address issues related to gender equality, roles, and land rights, knowledge access, and economic activity. In order to make sure their goals are achieved, the team may also collaborate with external non-profits, which are listed. It is interesting to note that this national semi-annual report, which is submitted to UN-REDD for review, was coded as level three, despite the National REDD$^+$ Strategy, which directs the national level REDD+

program, being categorized at level two. The method clearly took gender issues into account, but it did not go beyond stating that gender should be taken into account and why.

The goal of applying the principles, criteria, and indicators within the social safeguards framework is to offer a strong basis for both the general governance process and the full restoration of the public's right. Therefore, it is essential that the social safeguards framework be specifically created to benefit marginalized groups, such as women who are disproportionately affected by changes in family income, indigenous peoples, local communities that live near forests, and other societal groups whose status in society makes it difficult for them to exercise their human rights.

The National REDD$^+$ Strategy's inclusion of gender issues is best exemplified by this quotation. It emphasizes that women should be involved in the process for a number of reasons, including their potential vulnerability, but it makes no recommendations for how to do so. It also serves to illustrate the variations discovered between the organizations in charge of document writing and publication, as seen in **Table 3**.

Table 3. Level of inclusion by responsible agencies.

	Any level	**Level 1**	**Level 2**	**Level 3**
	Total documents at any level			
Intergovernmental	27	14 (52%)	15 (56%)	5 (19%)
National/Sub-national	15	10 (67%)	11 (73%)	2 (13%)
International NGO	28	18 (64%)	9 (32%)	5 (18%)
Business	6	6 (100%)	0 (0%)	0 (0%)
Total	**95**	**48**	**35**	**12**

Source: Field survey.
*Figures in parenthesis are percentages of total and gender inclusion levels in REDD$^+$ analysed documents by agencies.

Reference to assessment of institutional level of arrangement in related to gender and REDD$^+$, level three of the assessed document does have the lowest percentage mainly from international organizations such as UN-REDD, Cross River State Government which demonstrated the most consistency. On the other hand, national and subnational level texts are least expected to contain gender issues at level three and most expected to do so at category two. Otherwise, despite the fact that international NGOs like the UN-REDD, World Bank's FCPF, Ministry of Environment, Cross River State Forestry Commission, Community-Based REDD$^+$, etc., and the World Wildlife Fund (WWF) produce the most documents related to REDD$^+$ in Nigeria and play a crucial role in project implementation, the majority of their documents only briefly mention gender considerations. This implies that agencies display less compliance with the gender mainstreaming rule in their documents which refers to the farther they are to the actual execution of REDD$^+$ programs using the gender lens. As evidenced by their uniformity across all levels and relatively high quantity of papers categorized at level three, intergovernmental agencies naturally appear to have understandood gender mainstreaming best with adequate implementation procedures. The majority of level two documents created by Nigerian

agencies provide best practices, which shows the gap between policy requirements and actually carried out practice rather than showing that gender mainstreaming is actually understood or how to be included. On the other side, NGOs are perhaps the most closely associated with project execution. They have contacts to, and occasionally representation inside, the communities themselves, and assist in the Free, Prior, and Informed Consent (FPIC) procedure. They work on the ground to bring REDD$^+$ initiatives ranging from policy formulation to implementation stage, however the great majority of their publications show a lack of awareness of gender mainstreaming or the reasons why gender considerations can be crucial for the success of these programs.

One of the two issues that consistently appear in many of the papers included in this study is highlighted in the passage from the National REDD$^+$ plan that was previously mentioned. Even while it takes into account gender concerns, it also makes the case that women should be involved in REDD$^+$ only because of their vulnerability, rather than because they are important stakeholders such as: forestry policy, management, sustainable development, and community involvement respectively. In fact, regardless of degree, the notion of women as vulnerable predominated all the publications. There are various issues with this one-dimensional portrayal of women. First and foremost, gender mainstreaming at its finest considers "observations, practices, acquaintance and interests of women [and] men" in the formulation and execution of projects and policies [15]. The experience of women as a group subject to shifting political, economic, and ecological contexts should not be used as a sole justification for limiting their involvement. Women play a significant role in managing natural resources, forests users, and participating in communities [5]. They contribute to these processes and are both sensitive to a changing environment and degraded and deforested trees. Women have also developed strategies for adjusting to and minimizing these changes. The whole scope of Nigerian women's encounters with and in the woods is not captured by policy or programs that do not take into account women's views, experiences, worries, and thoughts beyond their status as a vulnerable group. Similar to how women are regularly identified as a vulnerable group in these publications, men may also feel vulnerability in these forest communities. However, these materials seldom discuss how this vulnerability may affect men and women differently in the framework of REDD$^+$ initiative in Nigeria.

The way obstacles to women's participation were handled was a second issue that was noted in several of the records. Even papers coded at level three mainly failed to identify that, even when and when room is established for them, women may still be prevented from participating in policy creation and project execution due to cultural, social, economic, or political concerns. The majority of the few texts that mention this fail to address these obstacles, much less offer suggestions for how to do so: "Interviewing women informants was challenging given the cultural background and socio-political structure of the community in the research location". In order to successfully and comprehensively integrate gender mainstreaming principles into REDD$^+$ policies and programs, a detailed analysis of the institutions that impede women's participation in these processes must be conducted. This is closely related to Sen's theory of capabilities. Examining and debating the issues women face is essential in a country like Nigeria where women's relations with the state have historically been unclear. Although women are commonly recruited into sustainable

development initiatives and have influential positions within the government structure, the bulk of women in these jobs come from the political and social upper classes. Nonetheless, others may argue that gender has been mainstreamed and is no longer an issue in the country that needs to be solved simply because women do hold positions of leadership and influence [6].

The $REDD^+$ initiative's activities for women were deemed "exclusionary" in some communities to the point that Cross River State's implementation of $REDD^+$ and the conservation laws that go along with it was imposed rather than agreed upon [16]. The local chiefs who were approached were not fully informed on the advantages and effects of the project in their forests, and no prior information about $REDD^+$ was supplied. As a result, the $REDD^+$ process in Cross River State is comparable to that in Cameroun, where a formal (Free Prior Informed Consent) FPIC process, according to Tegegne et al. [17], was not carried out at the Mount Cameroun project site. The communities in Cameroun were not formally introduced to $REDD^+$, which has led to their marginalization. In contrast to the situation in Cameroun, the $REDD^+$ project's proponents in Nigeria formally announced it, and alternative livelihoods programs and incentive payments are being explored. However, there are disagreements over adequate livelihood alternatives that are acceptable to all local groups in Cross River State between the $REDD^+$ proponents and local people. This study supports the idea that the FPIC procedure is still something that will be planned for the future rather than something that must be done right away. The transformative change anticipated in $REDD^+$ does not address uneven power and institutional relationships between actors involves $REDD^+$ project in Cross River State, which may weaken collaboration and ultimately compromise policy implementation, especially from the perspective of gender.

Focus group discussions (FGD) were used to conduct gender analysis and community mapping at the local level in order to identify stakeholders and obstacles preventing women and other vulnerable groups from effectively participating in $REDD^+$ [18]. The results of the gender analysis and community mapping of focus group discussions (FGD) revealed the specific needs of women and other vulnerable groups in $REDD^+$, especially with regard to the institutional level of arrangement. If these needs were met, it would enhance equity and encourage the effective participation of women and other vulnerable groups in $REDD^+$.

This study comes to the conclusion that formal free prior and informed consent was not given in the pilot communities because proponents believe the state-selected representatives speak for them. Nuesiri [19] noted that as a result, local representation is lacking in Nigeria, even during UN-REDD policy board meetings and consultation processes during the project's early stages. He said that local government representatives from the state were not invited to meetings because the project's proponents claimed that there were insufficient fund to finance their travel arrangements. Nuesiri argued that the reason local representatives were excluded was because the majority of them lacked the environmental competence necessary to make significant contributions and were probably only interested in advancing their own interests. Asiyanbi [20] contends that because the government only wants to share authority with NGOs and not with the local groups in charge of managing the woods,

there is no decentralized forest governance under REDD$^+$ in Nigeria. These ideas are supported by this study's findings.

4. Conclusion

This study concluded that though there was an institution level of arrangement for the implementation of REDD$^+$ project in Nigeria created to include many stakeholders through invitation. The institutional arrangement set up follows bureaucratic and social norms with non-compliance of gender mainstreaming, and out of non-substantive, superficial and integrated inclusions this study used to assessed gender and institutional level of arrangement in REDD$^+$ pilot site Cross River State, only *integrated* that accommodate element of gender mainstreaming was low.

5. Area for further research

This study on social consideration analysis should be embarked on which will show the power relations between the REDD$^+$ actors. Gender indices and social analysis such as:

- Gender socialization and inclusion.
- Role constraint.
- Intra-household and community decision making.
- Intra-household and community participation.
- Gender and Institutional climate change management approach, and Climate change initiative burden and benefit sharing on gender which have remained relatively scanty thus far should be considered.

6. Limitation of the study

Owing to the unique characteristics and UN-REDD's consideration, the study was conducted at a REDD$^+$ pilot site that was authorized in Cross River State, Nigeria. Furthermore, researchers need to devote greater time to a number of other important topics. This research specifically does not look at places where women are customarily denied inheritance rights and other social privileges. One of the primary constraints of this study is the gendered dimension of Nigerian REDD$^+$.

Lastly, the implementation of the community-based REDD$^+$ program by UN-REDD as a parallel project with other readiness demonstration activities is not evaluated in this paper. The current Cross River State government's policy orientation and the escalating disputes between the state and local communities over the revocation of their customary forest rights are two aspects of Nigeria that will be of special relevance.

Author contributions: Conceptualization, AOB and AOO; methodology, AOB, AOO, ACA, OHA and OOA; software, LAA and DSM; validation, VOO and CF; formal analysis, AOB, OOA, AOO, LAA and ACA; investigation, AOB, AOO, ACA, OHA and CF; resources, AOB and AOO; data curation, AOB, AOO, ACA, OHA and DSM; writing—original draft preparation, AOB, AOO, ACA, OHA and VOO; writing—review and editing, AOO, AOO, ACA, OHA and VOO; visualization, OOA,

OOA and CF; project administration, AOB and OOA; funding acquisition, AOB and AOO. All authors have read and agreed to the published version of the manuscript.

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Article

Enabling gender responsive low-carbon transport in India using SDG5 framework

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Abstract: Gender and mobility are strongly related and address challenges of safety and accessibility for women. Studies worldwide highlight the need to create more gender-responsive transport systems that maximize women's mobility, civic participation, and safety. Gender inequality in urban transport is evident in Indian cities in terms of women's longer walking trip lengths, longer time spent in commute and hence time poverty, impoverished health, and compromised personal safety. Even the public transport systems, often perceived as more gender-equal, overlook women's needs and mobility concerns such as affordability and scheduling. This article presents transportation challenges faced by women (recorded through primary surveys and focus-group discussions) and further investigates how low-carbon urban transport, as perceived under the Paris Agreement and Sustainable Development Goals (SDGs), can be delivered with gender-equitable outcomes. For a more holistic perspective, the assessment is grounded in two Indian cities, Surat (4.5 million population), a fast-growing industrial metropolis, and Udaipur (0.5 million population), a small but important tourist destination in the nation.

Keywords: gendered mobility; low-carbon transport; gender-sensitive transport; Global South; public transport

1. Introduction

Amid the intersecting crises of COVID-19, the climate emergency, and rising economic and political insecurity, progress on gender equality has not only failed to move forward but has begun to reverse [1]. Around the world, a growing backlash against women's rights is threatening even well-established freedoms and protections [1]. At the current rate of progress, it will take another 286 years to reform legal frameworks to promote, enforce, and monitor gender equality in public life [1]. Violence against women and girls continues to rise in the wake of the intersecting crises; estimates indicate that 736 million women across the globe have experienced physical or sexual violence at least once in their lifetime [2]. In urban areas, stressors like lack of access to decent work, ill-planned infrastructure, and unreliable and inadequate urban systems (including transport systems) limit women's attainment of economic and social rights. In addition, safety in mobility is a particular concern for women; about 49 percent of women in urban areas feel less safe walking alone at night [3].

Transport is crucial to women's empowerment, enabling their access to economic opportunities and participation in civic and public life. Women's mobility, especially in low-income households, often increases their family's chances of escaping poverty (SDG5.2 and 5.5) [4]. Urban transport also has a direct, two-way relationship with

SDG5, as easy access to economic, social, and civic opportunities (via transport), in turn, increasing women's trip rates and hence additional travel demand (**Table 1**). In cities with affordable healthcare services, access to robust transport systems is also linked to improved health outcomes for women, young and old (SDG5.6). Yet transport systems in cities worldwide fail to cater to women and girls, curbing their mobility and restricting their economic and interpersonal growth [3,4].

Although transport is considered gender-neutral, studies over the last decade show that transport is deeply gendered. Gender-responsive planning is a differentiated planning culture that considers the gender-, age-, and group-specific interests [5]. The lack of gender-responsive transport systems is universal. Yet women in the global South often experience exacerbated impacts of inequity and discrimination owing to the highly unequal urbanization landscape and the prevalence of traditional gender roles. For example, studies indicate that women in developing countries are less likely to have access to personal vehicles or hold a driver's license than men [6], reducing their options to access work, healthcare, and other essential services. Lack of transport access along with the fear of sexual violence hinders women's workforce participation; in developing countries, these factors are believed to decrease Female Workforce Participation Rate by 16.5% [7]. Moreover, in about 20 countries of the global South, laws restrict women from working the same way as men. Studies indicate that road-based transport solutions in these cities deepen gender inequity, especially for poor women [6,8–11]. Hence, there is a dire need to redesign transport plans and policies to suit women's travel behaviour and solidify their "right to the city" claims by maximizing their mobility and safety.

This paper argues for locating urban transport solutions within the SDG frame. In other words, the transport solutions for the cities need to be contributing to achieving the SDG targets. The critical thrust of the SDGs is the social goals of poverty and inequality reduction, improvement in human development, human-centric economic growth, environmental sustainability, and partnerships. While the SDGs have a separate goal related to gender, all other goals too have a cross-cutting gender concern. This paper picks up the gender goal and assesses urban transport from a gender lens to achieve gender equity. The paper's objectives are to conceptualize the links of SDG5 targets in particular and embellish the conceptual understanding with the data obtained from the ground. This exercise also helps in understanding whether the transport options available in the cities of the global South would enable achieving the SDG5 targets and what options need to be included to be able to do so. We are therefore arguing two things in this paper: firstly, sustainable transport or low-carbon transport has to be gender inclusive, and second, the achievement of SDG5 requires addressing transport.

The following section briefly presents the methods used for the analysis. This is followed by a section that introduces the two cities in India within which the research is grounded to develop our arguments. The sections after that present conceptual linkage of transport and gender development based on literature as well as primary data for the achievement of three broad aspects included in the SGD5 targets: (i) women's safety and comfort while using transport, (ii) women's access to economic and civic opportunities, and (iii) women's access to healthcare in urban areas. The last section discusses the policy implications.

Table 1. Conceptual relationship between urban transport and gender equity through the SDG5 framework.

	SDG5 Targets	Relationship with Urban Transport	Relationship with Non-motorized Transport (NMT)	Relationship with Intermediate Public Transport (IPT)	Relationship with Public Transport (PT)
Women's Safety & Comfort	5.1. End all forms of discrimination against all women and girls everywhere	Transport systems, albeit public transport, possess the potential to eliminate discrimination against women and girls by providing access to economic and civic opportunities. Mediating Condition: Transport systems (especially public transport) must be affordable, reliable, and well-connected.	Women walk more often than men, longer distances than men, and women tend to walk with dependents. Adequate and safe pedestrian and cycling infrastructure ensures women's access to economic and civic opportunities.	IPT is the only motorized transport mode that efficiently responds to women's travel needs. Yet the higher IPT costs increase women's transport expenditure. For example, although the average trip lengths of women are 38% shorter than men's, their average travel costs are 35% higher than men's [11]. High transport costs deter women's willingness to travel as they often must justify it.	Women's travel demand in Latin America and South Asia shows that women take shorter and more frequent trips for multiple purposes at off-peak hours and with dependents [8]. Due to the lack of gender mainstreaming in public transport system routing and design, women are often forced to use IPT for convenient access at higher prices or walk to save money. Hence, public transport systems that cater to women's travel needs are crucial for mobility and participation.
	5.2. Eliminate all forms of violence against all women and girls in the public and private spheres	Transport systems possess the potential to eliminate violence against women and girls in the public sphere by ensuring safe access to basic services, education, employment, and public spaces. Mediating Condition: Routing and scheduling of public transport systems can create safe mobility options; footpaths can be designed to maximize women's personal and sexual safety.	Since women's dependence on non-motorized transport modes—especially walking—is far greater than men's, adequate and safe non-motorized infrastructure is vital in enabling their mobility. Yet, the poor state of NMT infrastructure in cities of the global South makes women more susceptible to violence against women.	Most South Asian cities lack integration of IPT in the City Development Plans and Mobility Plans. Hence, the IPT sector often needs more infrastructure provision, fair regulation, or other operating norms. Therefore, women who largely depend on IPT tend to face precarious boarding conditions, overcrowding, and inconsistency in fares. All this increases their susceptibility to exploitation and violence; hence, formalizing and regulating IPT is crucial for ensuring women's safety.	Women tend to chain trips and travel during off-peak hours; hence, the low frequency translating to longer waiting times and lower ridership make women more susceptible to harassment and violence while accessing PT. Routing of PT can ensure bus stops in service-level proximity to increase women's use of PT.

Table 1. (*Continued*).

	SDG5 Targets	Relationship with Urban Transport	Relationship with Non-motorized Transport (NMT)	Relationship with Intermediate Public Transport (IPT)	Relationship with Public Transport (PT)
	5.3 Recognize and value unpaid care and domestic work through the provision of public services, infrastructure, and social protection policies and the promotion of shared responsibility within the household and the family as nationally appropriate	Public transport systems form vital components of any city's public services. Their ability to provide access to basic services and employment makes them crucial elements of any city's social protection policies. Hence, transport systems are essential in reducing women's unpaid work. Mediating Condition: Public transport systems must be affordable, safe, and well-connected.		IPT enables women to travel from "home to home," reducing time spent in unpaid work. However, since this convenience comes with a steep travel cost, most low-income women resort to walking, increasing their time poverty. Or these are unsafe for women, which requires better governance of IPT. Mediating Condition: Better governed IPT.	Time spent walking to work due to lack of affordability for public transport forms a considerable share of women's unpaid work. Hence, women's time allocated to unpaid work increases due to the lack of affordable, convenient, and safe transport; this time can be substituted by paid work or personal care if affordable public transit is available.
Women's Access to Economic & Civic Opportunities	5.4 Ensure women's full and effective participation and equal opportunities for leadership at all levels of decision-making in political, economic, and public life	Along with enabling access to education and employment, transport systems possess the potential to ensure women and girls have equal opportunities by allowing them to participate in public life, politics, and social interaction. Mediating Condition: Transport systems (especially public transport) must be affordable, safe, and reliable.	Safe, adequate, and well-maintained footpaths are crucial for women's interactions with the public and civic realm, as most "non-work" trips in South Asian cities are generally within walking distance. And since most women walk to work, walking infrastructure becomes crucial for women's effective participation. Yet the poor state of walking and cycling infrastructure in these cities often curtails women's mobility and representation.	Similar to 5.1	While access to public transport is linked with improved socio-economic and health outcomes for women, the poor state of public transport systems (inadequate coverage, lack of last-mile access, poor frequency of buses, unsafe and ill-maintained bus-stops, overcrowding, etc.) in most cities of the global South deter women from actively choosing public transport and curtails their mobility. This affects their full and effective engagement in the city.
	5.5. Enhance the use of enabling technology, in particular information and communications technology, to promote the empowerment of women	Transport-sector platform economy avenues like Mobility-as-a-Service (MaaS), i.e., Ola, Uber, Lyft, etc., empower women (i) by enabling 'safer,' door-to-door mobility, and (ii) employing women within the transport sector (ex. Pink Auto in Jaipur, Sakha Cabs in Delhi). Mediating Condition: for increased employment in the transport sector via platform economy avenues, women would need access to vehicles (cars or auto-rickshaws)	GIS-enabled apps like SafetyPin[a]—using big data to improve infrastructure and services in cities for women- enhance women's perception of safety while walking.	Women-run autos via platform economy provide women employment in the transport sector and enhance safety for women passengers.	Display of route information and automated vehicle monitoring (AVM) system and smartphone applications for the city's PT system (like London's TfL GO or Mumbai's M-Indicator) allow women to predict waiting times and best routes, facilitating better decision-making while traveling.

Table 1. (*Continued*).

	SDG5 Targets	Relationship with Urban Transport	Relationship with Non-motorized Transport (NMT)	Relationship with Intermediate Public Transport (IPT)	Relationship with Public Transport (PT)
Women's Access to Healthcare	5.6 Ensure universal access to sexual and reproductive health and reproductive rights as agreed in accordance with the Programme of Action of the International Conference on Population and Development and the Beijing Platform for Action and the outcome documents of their review conferences	Although universal access to sexual and reproductive health for women and girls goes beyond physical accessibility to healthcare facilities, transport systems are crucial in ensuring access to healthcare. Similarly, access to healthcare for women goes beyond access to sexual and reproductive health, as women are primary caregivers (irrespective of their employment status) and are often responsible for healthcare trips of dependents (children, elderly, or differently-abled household members). Mediating Condition: Adequate and affordable healthcare and maternal care facilities are available	NMT infrastructure is vital to access primary healthcare (as it is ideally provided within a walking radius). NMT infrastructure also forms a core part of the last-mile access to PT—more appropriate for longer distances.		Affordable, reliable, and safe PT systems are crucial for women to access healthcare facilities. Yet, many cities lack transport, and land-use integration (especially healthcare) hinders women's healthcare access.

[a] SafetyPin is a personal safety app designed to enable women (and other vulnerable groups) take safer mobility decisions based on the safety scores of a neighborhood. These scores are based on safety audits that evaluate a neighborhoods physical and social infrastructure.

2. Methods

To identify relevant SDG5 goals for assessment, we undertook a rigorous scoping literature review of over 250 publications that focused on the global South context. To validate the findings from the literature and ground the interactions in cities, we chose two case study cities- Surat, an industrial metropolis, and Udaipur, a tourist town with rich cultural and built heritage. The cities were selected based on- (i) the diversity of their socio-demographic profile, (ii) the contrasting city size, urban fabric and built form, (iii) the diversity of their economic base, (iv) availability of well-developed transportation plans, (v) the presence of political and administrative will for a transition towards Low-Carbon Mobility, and (vi) easy access from the city of the authors. We then critically assessed the mobility and development plans in both cities to evaluate the service levels. Quality of service of transport is measured by the Level of Service (LOS) benchmarks (often referred to as service levels). These are based on numerous parameters like level of comfort, fleet, average waiting time, average speeds, street light, intersection delay, and encroachment, etc. As per MoHUA's Service Level Benchmark (SLB) Handbook, the Service Level is measured on a scale of 1 to 4, indicating the lowest to highest LOS, for each element of the transport system, i.e., the Non-Motorised Transport (NMT), the Public Transport (PT), and others. Service levels of each component of the transport system in case study cities were compared against the national transport SLBs [12]. They were marked compliant for those services that aligned with national benchmarks and non-compliant if otherwise. To further ground the assessment, the authors, in consultation with the urban local bodies in both case studies, conducted three focus group discussions with about 35 participants on the following three themes: (i) mobility challenges and scope in rapidly urbanizing cities, (ii) mobility challenges and scope in heritage towns, and (iii) mobility of socio-economically vulnerable groups. This was followed by analyses of 1,665 samples of detailed transport user surveys (containing about 75 questions), 350 household surveys, and 185 semi-structured stakeholder interviews in both cities- all via stratified random sampling. These surveys captured demand-side trends, including travel patterns, mobility challenges, safety, affordability, resilience by mode, socio-economic and health impacts of transport projects, their willingness to shift, and recommendations for enhanced access and mobility. The literature review forms the framework to assess urban transport and SDG5 interactions, and the critical analyses and fieldwork form the final assessment.

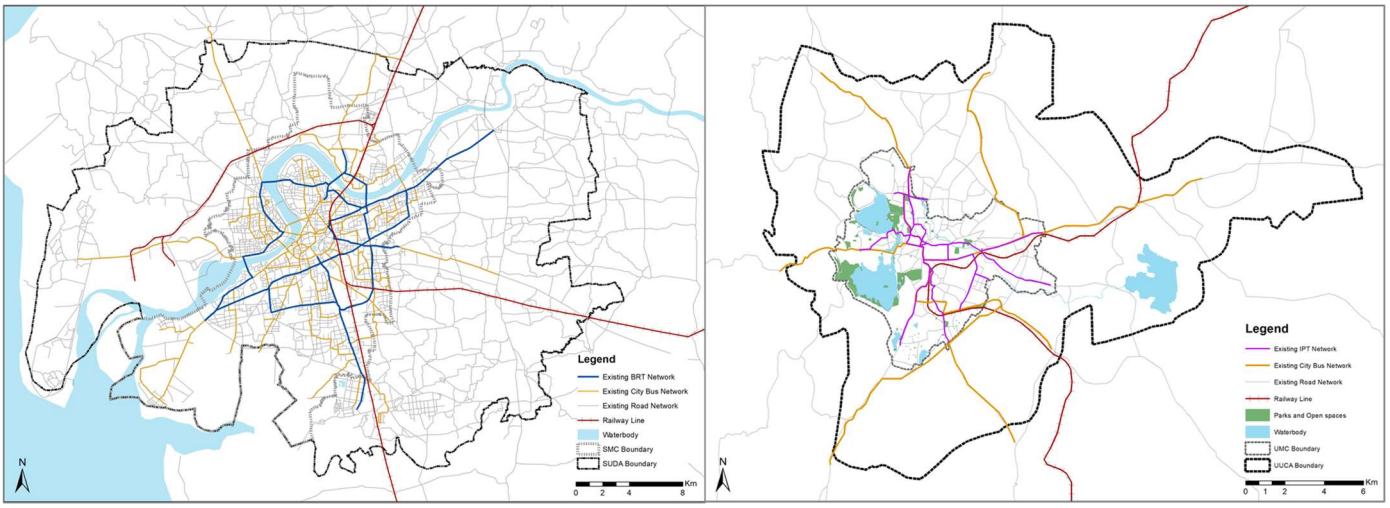
Transport landscape of Surat and & Udaipur[1]

Udaipur, the City of Lakes, is a small, compact, 12-minute city with rich cultural and built heritage and a natural ecosystem. Its population in 2011 was 0.63 million. It is among the world's fifteen most-visited tourist destinations and receives India's second-largest fleet of international tourists. Several state and national highways surround Udaipur; the city is rapidly urbanizing along the highways. Udaipur lacks a robust formal Public Transport (PT) system; a weak fleet of thirteen buses operates on five routes in the city (**Table 2**, Section 2). Hence, the city's Intermediate Public Transport (IPT) system, operating on 27 designated routes (shared rickshaws and auto-rickshaws), functions as its informal PT (Refer **Figure 1**). Rapid urbanization

unaccompanied with robust public transport networks results in rapid motorization (annual growth rate of 11.3%). Udaipur's lively historic core is rendered with narrow lanes, a concentration of economic activities, and multiple heterogeneous road users (refer to **Figure 1**). Udaipur represents several global North and South tourist towns, grappling with adequate and inclusive transport provision within its dense urban fabric and limited resources.

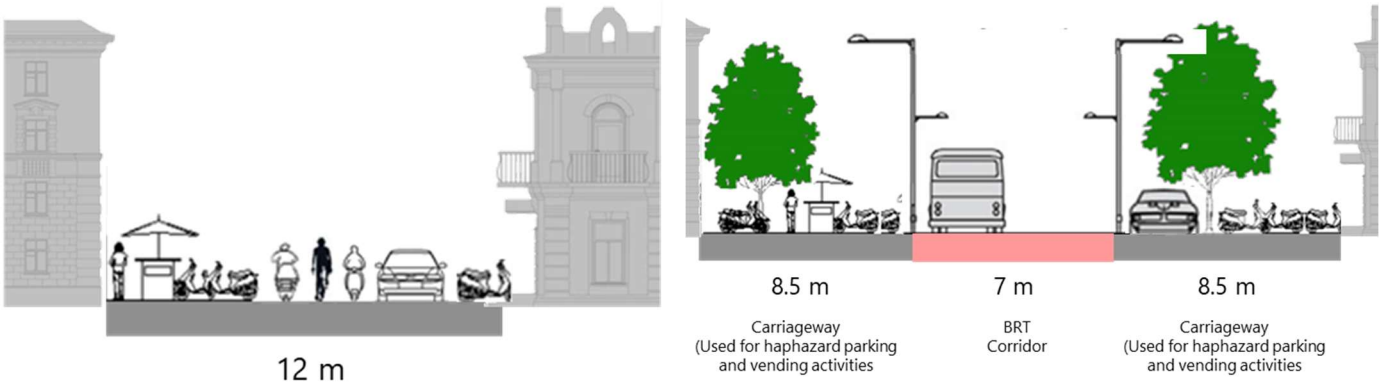
Table 2. Transport system characteristics in Surat Urban Development Area (SUDA) and Udaipur Urban Control Area (UUCA) for 2016 [13–15].

		Surat	**Udaipur**
Demography	Population (as per census 2011)	5,929,821	637,717
	Area (in sq km)	958	348
	Density (people per sq km)	6190	1833
Transport Characteristics	Registered Vehicles	4,195,348	580,271
	Annual Vehicular Growth	9%	11.3%
	Trip Rate	1.6	1.1
	Female Trip Rate	-	0.67
	Average Trip Length (in km)	6.04	5.09
	Annual Vehicle Kilometres Travelled	9,400,415,130	880,489,000
	Mode Share (as of 2016)		
	Pedestrian	40%	48%
	Cycle	2%	2%
	PT	1.4%	2%
	IPT	10.3%	11%
	2-W	35.6%	34%
	4-W	2%	3%
	Other	8%	NA
Transport Systems & Infrastructure	Road Network Length (in km)	5773	1585
	Bridges, Fly-overs & Underpasses	123	7
	Non-motorized Transport		
	Footpath Coverage	20%	4%
	Cycle-Track Coverage	8%	0%
	Pedestrian Crossing	38	0
	Public Transport		
	City Bus Fleet	811	13
	City Bus Network (in km)	274	89
	City Bus Routes	29	5
	BRT Bus Fleet	116	NA
	BRT Network (in km)	102	NA
	BRT Routes	35	NA
	Intermediate Public Transport		
	IPT Fleet	38,000	8950
	IPT Routes	52	29



(a) **(b)**

Figure 1. Public transport network maps of **(a)** Surat; and **(b)** Udaipur.



(a) **(b)**

Figure 2. A typical street section in case study cities. **(a)** Udaipur with mixed traffic, informal vending activities, and haphazard parking, making it unsafe; **(b)** Surat with inadequate NMT infrastructure and a spill-over of parking and vending activities on the carriageway creating conflicts.

Surat, with a population of 5.9 million in 2011, is among the world's fastest-growing cities and has a high concentration of migrant population (26% of the total population) owing to its labour-intensive textile and diamond industry. Surat is compact and polycentric, rapidly urbanizing along its radials. Surat's formal PT system consists of a Bus Rapid Transit (BRT) system (length of 102 km), a City Bus, and an upcoming Metrorail (proposed length of 274 km). Surat's IPT Fleet, mainly the autorickshaws (three-wheelers), primarily operates on 52 designated routes (**Table 2**). Even individual IPT trips that provide point-to-point connections are possible. Intensification of road-based transport solutions and disinvestment in public transportation over the past two decades has resulted in a 22% decline in non-motorized transport (NMT) (walking and cycling) trips' share and a 4.3% decline in PT) mode-share. Additionally, the rise in average household incomes increased dependency on personal motorized vehicles, leading to a tripling of traffic volume over the last decade. Incompatible land uses placed in proximity and contested road space result in frequent traffic congestion and high conflicts amongst motorized and

non-motorized users (refer to **Figure 2**). Surat represents several rapidly urbanizing cities in the global South, grappling to transition from road-based transport solutions to a more active and public transport-oriented approach.

Both cities serve a residential and a large floating population. Traffic composition, prioritization of vehicular movement, absence of lane segregation, and the current state of infrastructure lead to local sustainability issues. Private vehicles-two-wheelers (2Ws) and four-wheelers (4Ws)—make up a majority of the traffic composition and total trips in both cities. The lack of a robust and affordable PT network results in low ridership, leading to vulnerable groups' reliance on the IPT and NMT, especially in Udaipur. On the one hand, there is a high dependency on private motorized vehicles, especially 2Ws, in both cities, whereas, on the other hand, service levels for half the trips are made on foot. Everyday observations from both cities indicate that women have a considerably lower trip rate (a proxy for mobility) than men, have much longer trip lengths, and have more significant barriers to accessibility.

3. Gender & urban transport through the SDG5 framework

SDG5, Gender Equity, has nine targets that aim to eliminate all forms of discrimination and violence against women and girls, recognize the value of unpaid care and domestic work, ensure women's participation in decision-making, enable access to health and economic opportunities, and strengthen policies that promote gender equality and women empowerment. Six of the nine targets detailed in the SDG5 framework have links with urban transport and are selected for analysis in this paper (**Table 1**, Section 2). Gender equity means that men and women are able to enjoy the same conditions and opportunities to exercise their rights and achieve their social, economic, political, and cultural potentials. It differs from gender equality, which only means that the same opportunities are there, but does not include if they can be accessed [16]. To understand the role of urban transportation in forwarding women's empowerment and gender equity, the travel patterns and needs of women and girls in the context of Indian cities must be understood. Although the continually expanding literature on women's travel behaviour indicates nuances across socio-economic status, below we summarize differential travel patterns among men and women, the range of constraints that govern women's travel behaviour, and its linkages with SDG5 and then link this understanding with the findings from the two cities.

3.1. Women's safety & comfort while using urban transport

This thematic area responds to two SDG5 targets: 5.1 on ending discrimination and 5.2 on eliminating violence against women and girls. Although women's safety and comfort while using transport go beyond the SDG5 framework to include transport route planning, service levels of transport infrastructure, urban design parameters, maintenance, and governance parameters, we argue that incorporating these two targets within the traditional and rather technical transport planning practice has a more significant potential in mainstreaming gender-responsive transport.

3.1.1. Women's safety and comfort while using non-motorized transport

Literature and census data from Indian districts show that women walk more

often than men (refer to **Figure 3**), have longer distances than men, and are in more precarious conditions than men. Walking is the most preferred mode of transport for women in the countries of the global South [4,9,10], especially for poor women, as they face more significant cultural barriers (dressing and other) to cycling and often cannot afford public transport [17]. Irrespective of trip lengths, the share of women walking to work in India is much higher than men [18]. Since women's dependence on pedestrian infrastructure is greater than that of men, the poor state of pedestrian infrastructure in Indian cities causes women discomfort, increases their fear of harassment on the road or even sexual violence (SDG5.1 & 5.2), and curbs their mobility [19–21]. Additionally, studies show that harassment while walking down the street is a common occurrence for all women and is exacerbated by the inadequate and ill-maintained physical infrastructure like inadequate lighting on streets and underpasses, deserted alleys connecting their residences to the transit, etc. [22,23].

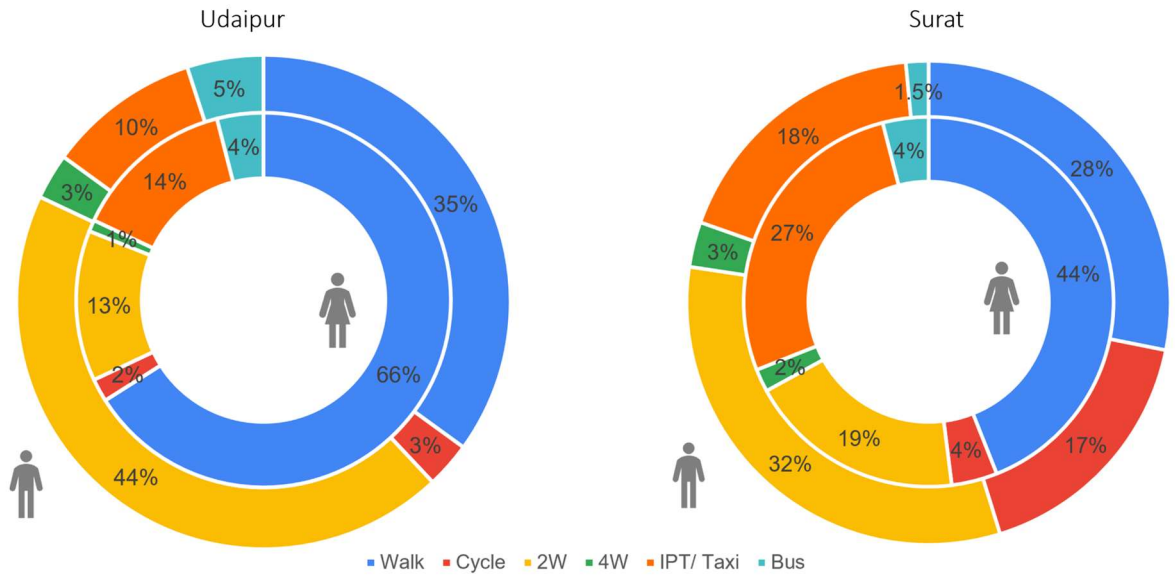


Figure 3. Gendered mode share in Surat and Udaipur.

Source: Data projected for 2016 using LCMP/ CMP statistics and B-28 sheets from Census of India, 2011 (Due to lack of disaggregated data availability in Surat, we have used the census data from the last population census in India. Such a data is not available at city level and hence we have used district data. We presume that Surat district would largely comprise of Surat city and its agglomeration. For Udaipur, we use the disaggregated trip data from the LCMP).

In our case study cities, we find that women walk to undertake various purpose trips. In Surat, 48% of trips are via walking and cycling (refer to **Figure 3**). 85% of non-work purpose trips are undertaken on foot, yet the city has inadequate infrastructure coverage for walking and cycling; only 20% and 7.6% of the total road network have footpaths and cycle tracks, respectively. The footpaths' networks exclude low-income neighbourhoods in Surat, creating a dire need for accessible transport infrastructure [13]. Similarly, 68% of women's trips in Udaipur are via walking and cycling, yet only 1%–4% of Udaipur's road network has any form of pedestrian or cycling infrastructure. Both cities lack supporting infrastructure for walking and cycling, like street lights, signalized junctions, pedestrian crossings, shade, benches, etc. (refer to **Figures 1** and **2**). Our assessment of Surat's walking and cycling infrastructure falls in service level category 3, using the Government of India's

service level benchmarks [12]. The city has to reach the service level of 1, the highest one if the entire city has to have a well-designed walking and cycling network, which essentially will benefit women. In Udaipur, the service level of walking and cycling infrastructure is 4 (the poorest on the scale), requiring significant improvement. Despite the poor state of NMT infrastructure in both cities, women opted to walk in both cities due to the unavailability of personal vehicles (21%) and PT's lack of affordability and reliability (32%).

We are emphasizing improvement in walking and cycling infrastructure because our fieldwork reports that 40% of women responded with issues related to road safety, 23% of women expressed inconvenience and discomfort (due to lack of walking and cycling infrastructure), and 93% of women walking in both cities reported feeling unsafe (personal & sexual safety) while making a trip. The focus group discussions, highlight the captive nature of female pedestrians and concerns about safety while commuting on foot (refer to Excerpts 1 & 2).

> Excerpt 1: *A 32-year-old woman from Udaipur describes her concerns about commuting via walking, "There are no streetlights and footpaths in my neighbourhood … along with that, fast-moving vehicles on the carriageway make me very nervous while walking."*
>
> Excerpt 2: *A girl in her early twenties from Surat narrated her perception of personal safety while walking, "I am forced to walk on the carriageway … which feels unsafe! There are frequent accidents on the crossroads, too."*

3.1.2. Women's safety and comfort while using public transport

Women tend to depend on public transport more than men [24]; women lack access to personal motorized vehicles, making public transit the most affordable motorized mode. The role of women as primary caregivers (despite their employment status) results in a more 'complex' travel demand than men who essentially have a single work trip demand. Hence, studies of women's travel demand in South Asia show that women take shorter and more frequent trips for multiple purposes (also known as trip-chaining) at off-peak hours [6,17,25]. More than a quarter of women's trips are caregiving-related and include traveling with a dependent (children, elderly, etc.,) [6,8,26]. While access to public transport is linked with improved socio-economic and health outcomes for women, the poor state of public transport systems (inadequate coverage, lack of last-mile access, poor frequency of buses, unsafe and ill-maintained bus-stops, overcrowding, etc.) in the majority Indian cities deter women from actively choosing public transport and curtail their mobility [16,27,28] (SDG5.1 & 5.2).

Surat has one of the largest BRT networks in India; its integration with the existing city bus services doubled PT mode share in just one year. Yet PT mode share in Surat is much lower (3%) than the national average (21%) for similar-sized cities, owing to the poor last-mile connectivity in Surat; only 53% of households in Surat live within a 10-minute walk to a bus stop/ bus station. Even for those households that fall within a walkable distance of the PT stop/ station, the poor state of NMT infrastructure deters them from accessing PT- especially during extreme weather events (heavy monsoons and hot summers) (refer to Excerpt 3, 4). Meanwhile, in Udaipur, poor PT coverage and low frequency prevent women from using PT (refer to Excerpt 4).

Among PT women users, less than 15% in Surat and 4% in Udaipur actively choose PT. PT system's level of service in both cities is 4 (lowest on a scale of 1–4), compromising women's comfort and safety (refer to **Figure 4**). However, of all the transport modes, women report PT as the 'safest' mode of transport.

Figure 4. Analysing transport modes using SDG5 Framework in Surat & Udaipur.

Excerpt 3: *A woman in her late forties discusses her mode preference during summer, "the BRT stop is much furtherer than the city bus, and the trip is more expensive; I only choose BRT during summers, as the AC (air-conditioned) buses are far more comfortable than the city buses. I wish getting to the bus station was also this comfortable as I walk there in the heat." The focus group participants indicated that they prefer BRTS over the city buses during heat, as the air-conditioned buses are more comfortable than the city buses. But as the BRTS bus stop is often further than the city bus stops, and the trip is more expensive, low-income women can only afford to choose BRTS during extreme heat.*

Excerpt 4: "*Another woman in her late forties from Surat discusses the hassle of accessing PT during monsoon, "The nearest bus stop is 2 km away… on a regular day, I walk to the bus stop, but during heavy monsoon, it is difficult to find any transportation from my area as it is completely submerged in water… even to take an auto-rickshaw, one has to walk to the main road- which again is a challenge during floods…." Several low-income women in Surat, often residing in low-laying areas discussed how frequent and rampant water-logging in their neighbourhoods further curtailed their mobility during heavy monsoon."*

Excerpt 5: *A 36-year woman discusses the challenges of using Udaipur's City Bus, "To take the bus, I often have to wait for long durations, and go through unnecessary, tedious transfers (mode-switches within a single trip) due to low*

frequency, the seats (in the bus) are usually full, and I have to stand for most of the ride… this tires me, and so I prefer autos over buses, although its more expensive to take autos...” The focus group participants highlighted that poor accessibility, weak network and low frequency of city buses, along with uncomfortable travel conditions force women to spend more on transport.

3.1.3. Women’s safety and comfort while using intermediate public transport

As evident from the above anecdotes, women prefer IPT over PT in both cities, owing to IPT’s route flexibility and wider coverage, enhancing convenience. In Udaipur, with 27 fixed routes and regulated fares, IPT provides a much wider coverage (55%) than PT; Surat’s IPT sector is largely chaotic and often costs double than a PT trip, 52 routes offer a considerably wider coverage, especially in the low-income areas, where PT is inaccessible. IPT makes 27% of women’s mode share in Surat and 14% of women’s mode share in Udaipur, compared to 18% and 7% of men’s mode shares in respective cities (refer to **Figure 3**), indicating women’s higher dependence on IPT than men. While several women in both cities preferred IPT over PT for convenience, IPT faired poorly in terms of personal and sexual safety (refer to Excerpt 6); the lack of infrastructure in both cities leads to unsafe on-boarding conditions for women amidst heavy vehicular traffic; 67% of women IPT users report concerns about sexual and personal safety using IPT, especially during the night.

Excerpt 6: *A woman in her late twenties reported the lack of institutional mechanisms in cases of sexual harassment while using shared autos, “I have faced sexual harassment in shared autos… it’s frustrating that there is no redressal mechanism… no provision for my safety, and no one to help me…. Who should I go to? Whom should I speak to? How can IPT drivers operate without knowledge of such regulations!”*

Poor and inadequate NMT and PT systems, as well as crowded, unregulated IPT vehicles, make women feel unsafe and uncomfortable, compromising women’s safety and mobility in both cities (refer to **Figure 4**).

3.2. Women’s access to economic and civic opportunities

This thematic area responds to three of the nine SDG5 targets: 5.4 on recognizing the value of unpaid work, 5.5 on access to equal opportunities and effective participation, and 5.B on women empowerment via technology.

Target 5.B indirectly interacts with urban transport and responds to women’s employment in the transport sector and women’s access to Mobility as a Service (MaaS) via platform economy. Only 20% of women in India are employed in the logistics sector, and only 1% of all commercial driving licenses are women-owned [29]. Apart from various societal and cultural barriers, the lack of skills (to drive a vehicle or to use a smartphone) greatly impacts women’s inability to access services or be a part of the workforce [30].

Women face more significant barriers to accessing economic opportunities than men. At the same time, transport projects provide access to financial and civic opportunities; transport systems dominated by private, fossil-fuelled light-duty vehicles further limit accessibility for women [31]. In Indian districts, where private motorized vehicles are the predominant mode of commuting to work, the share of

women commuting to work is much lower than that of men [18]. Reasons for this include (i) the majority of households in Indian districts tend to own only one vehicle (predominantly a two-wheeler), which is used by the head of the household (predominantly men) for commuting to work, and (ii) cultural barriers and resource constraints keep women from driving or knowing how to drive. Women do not prefer long-distance commutes as they have to earn enough to justify high travel expenses and need to intermittently check on their families, especially children/ elderly at home [16]. Women are known to forgo an opportunity to work outside their neighbourhoods if they perceive transport fares and services as expensive and unreliable [5]. Discrimination against women and girls that manifests through denial of their physical mobility (like street harassment) usually pushes women out of the workforce.

3.2.1. Women's access to opportunities through non-motorized transport

Walking is the predominant mode of walking for low-income groups in both cities; about 55% of all pedestrian trips and 89% of cycling trips are undertaken to access economic opportunities. In Udaipur, low-income women have the lowest trip rate and the highest walking mode share. Women pedestrians in both cities walk unusually long distances (2–5 km); of the 38% women who walk to work in Udaipur, almost 2/3rd of them walk for 5–10 km. 30% and 65% of pedestrian women in Udaipur reported a monthly household income of less than Rs. 5000 (very low-income households) and Rs. 25,000, respectively (low-income households). Time spent walking to work due to poor public transport systems forms a considerable share of women's unpaid work (SDG5.4). Hence, women's time allocated to unpaid work increases due to the lack of affordable and convenient public transport; this time can be substituted by paid work or personal care/ leisure if affordable public transit is available. Hence, lack of supporting pedestrian infrastructure, Udaipur's weak PT system and Surat's unaffordable fare (refer to Excerpt 7) cause heavy trade-offs for women's (and other vulnerable groups) access to economic and civic opportunity (refer to **Figure 4**).

> Excerpt 7: *A migrant worker in her early thirties who often walks to work in Surat narrated that, "If I have to take the bus to work, it often involves multiple long transfers, and the bus-stop too is quite far... so either I have to walk to work, as it is more reliable than the bus or take the auto, despite it being expensive...so, to minimize costs, I often walk to work."*

3.2.2. Women's access to opportunities through public transport and intermediate public transport

Udaipur's poor City Bus coverage leads to low ridership; 25% of IPT trips and 33% of 2W trips have a trip length of 5 km or more, making them most suitable via PT. Yet the lack of a robust PT network caps the PT mode share in Udaipur at 3%, forcing vulnerable populations (especially urban poor and women) to walk. Over 90% of all PT users belong to the low-income group (52% earning less than Rs. 5000 monthly, and 39% earning less than Rs. 25,000 monthly), dependent on PT to access economic opportunities, indicating captive users or 'no-choice' users form a large portion of PT ridership. Women's travel behaviour that involves trip-chaining and travel during off-peak hours results in longer waiting hours and longer trip times than men's [9,32,33]. Women PT users in both cities report longer waiting times for the

buses, discomfort while waiting on the carriageway due to the lack of bus stops/stations, and inconvenience of using PT due to its limited routes and lack of route information (refer Excerpt 8, 9 & 10). These factors result in greater time poverty for women than other citizens, especially low-income women. 99% of PT women users wished to own a private vehicle to improve their access to economic opportunities. This indicates a trade-off with access to economic and civic opportunities in the two case study cities (refer to **Figure 4**).

Excerpt 8: *A migrant worker in Surat discussed her preference for IPT, "If we need to go to destinations that fall outside the fixed routes (PT), we spend more time and energy as there are lots of mode transfers… so many of us prefer auto-rickshaws, even though they are more expensive.*"

Excerpt 9: *A woman in her mid-forties indicated the lack of last-mile connectivity in Surat forces her to spend more time commuting than required, "I have stopped using the city bus/ BRT services as the nearest bus-stop is about 3km away and I have no means of reaching (personal vehicle) there, and had to walk to the bus-stop… that made me waste so much time. I now take the shared auto… it's more expensive, but I get to my work on time."*

Excerpt 10: *A young woman in Udaipur narrated a similar account of the city's PT system, "Although the buses are cheap, I find commuting via buses very inconvenient and time-consuming due to its limited coverage. Doing multiple chores via buses is tough… so I wait for my brother or father to drive me sometimes or take the auto."*

3.3. Women's access to healthcare via transport

Although universal access to sexual and reproductive health for women and girls goes beyond physical accessibility to healthcare facilities, we included this target to highlight the significance of urban transport in healthcare accessibility; access to healthcare for women goes beyond access to sexual and reproductive health, as women are primary caregivers (irrespective of their employment status) and are often responsible for healthcare trips of dependents (children, elderly or differently-abled household members). In the presence of inclusive healthcare services, urban transport directly influences health outcomes by providing access to them. The availability of adequate, affordable, and well-connected transport systems is linked to a reduced risk of premature deaths. Access to hospitals/ clinics is critical for society, especially women, and efficient transportation systems are need of the hour to connect women to such healthcare facilities (SDG5.4 & 5.6). Evidence also shows that access to reliable transport systems, especially better connectivity between rural and urban areas in the Global South, reduces perinatal, neonatal & maternal mortality [34]. As per the National Family Health Survey, at least 23.2% of women stated that the distance to a health facility is an issue in accessing health care. In addition, 21.5% of women reported that having to opt for transport systems to reach these centres was a concern [35]. Although this is more relevant in a rural context, especially in the case of maternal and neonatal mortalities, reliable and affordable public transport networks are crucial to enhance access to healthcare even in urban areas, especially for low-income women.

About 22% of women's trips in Surat and about 14% of women's trips in Udaipur are attributed to healthcare- far greater than men's trips in both cities supporting the findings from the literature. 82% of women said they walk to the nearest clinics/ hospitals, even with dependents. However, more than 52% of women travel for more than 5 km to reach healthcare facilities. If given other mode choices to commute to healthcare facilities, 37% of females would opt for the alternate options instead of their current one. 24% of women reported that owning a personal vehicle and a driver's license would enable easy and quick access to healthcare. Most women in both cities stated that walking to healthcare facilities during deserted hours (afternoons and late evenings) scared them, and they often relied on their family members or female neighbors. Due to heavy waterlogging, low-income women in Surat mentioned difficulty walking to clinics (and other primary healthcare facilities), especially during monsoons. In cases of emergency, women in Surat used the 108-helpline number to call for an ambulance or contact (via phone) women auto-rickshaw drivers in their vicinity.

> *A young woman from Surat's Kailash Chokdi area (a low-lying area along the river) narrated her challenge of accessing transport and healthcare during monsoon, "Buses are the most affordable mode of transport, but become very unreliable during monsoon… there's often a long waiting time and more transfers (mode-changes within a single trip) … so I have to walk everywhere in the water… I'm also responsible for regularly taking my grandparents to the nearby clinic, so it's a hassle to take them there walking in the water."*

4. How can low-carbon transport proposals be more gender-responsive?

SDG5 discusses nine targets to achieve gender equality, as discussed above. However, there are various other targets corresponding to reduced poverty of women (as stated in SDG 1.2 and 1.4), reducing mortalities and improving access to healthcare services (as defined in SDG 3.1, 3.4 and 3.7), promoting secure working environments, entrepreneurship (as described in SDG 8.3 and 8.8) and providing access to safe and sustainable transport systems and public spaces (as highlighted in SDG 11.2 and 11.7). A deeper study of the inclusion of women and girls and empowering them in the transport sector is essential to understand and address all issues they face, especially in Indian cities.

Revising the existing notion of low-carbon transport planning (focused on environmental sustainability) to include social aspects of sustainable mobility (like gender equity) is crucial to achieving sustainable development. Hence, learnings from assessing the current transport situation in Surat and Udaipur pave the way for designing a more gender-responsive low-carbon transport system in developing countries.

City-specific recommendations pertain to each transport system intervention. NMT forms a crucial component of low-carbon transport, as it enables a switch from private motorized modes to NMT for shorter trips and functions as a vital last-mile mode (to PT) for longer trips. Hence, both cities must focus on large-scale improvement of NMT to foster low-carbon transport. In addition, PT forms the

backbone of low-carbon transport; hence, both cities must focus on improving PT mode shares. For this, Surat must concentrate on ensuring PT is accessible to and affordable for women, especially low-income women, and Udaipur must focus on expanding its coverage. Lastly, although not traditionally viewed as a low-carbon mode, IPT is vital to low-carbon transport in developing countries. It is a sustainable alternative to personal motorized vehicles due to high demand (among women), higher vehicle occupancy, and sustainable fuel. Surat must focus on mainstreaming IPT to work as a feeder service to PT, while Udaipur must concentrate on enhancing IPT infrastructure and quality of services.

Transport authorities must conduct comprehensive gender audits to institutionalize gender equity. Cities must prioritize transport supply to increase women's safety and mobility. For this, large-scale infrastructure improvements in NMT and PT are required to achieve a service level of 1 (highest). To ensure women's safety and improved access to transport, regular safety audits of transport infrastructure (footpaths, bike lanes, metro stations, bus stations, etc.) must be conducted. Gender-action plans should be altered based on the learnings from the safety audits. Network-specific interventions for each component include

- Improved safety of women and girls in cities: Introducing speed limits throughout the city to minimize road crash fatalities, largely pedestrianizing walled city areas in both cities to enhance the presence of women of all ages on streets, introducing a well-constructed and wide footpath network with no encroachments for unobstructed and convenient movement, improving street lighting and other street infrastructure to enhance the personal safety of women, improving the bicycle network throughout the city with supporting infrastructure to increase women ridership, implementing efficient infrastructure for safety (bus stops, onboarding) and enabling Transit Oriented Development (TOD) with mixed-use development to the enhanced safety of women while using PT and formulate stricter regulations and implementation to avoid overcrowding (& subsequent harassment) in vehicles.
- Eliminate time poverty of women in cities: Redesigning streets with Complete Street guidelines for enhanced last mile, gender-responsive routing of buses (to vulnerable areas) to serve more low-income women, subsidizing PT for women commuters to make it more affordable, and re-purposing mini-buses as feeder buses along high-demand routes in Udaipur to enable a higher access and transit ridership among women. Also, subsidies for women commuters should be introduced to make IPT more affordable.
- Expanding access to transport for women: Formalizing IPT by proposing IPT stations, fair fare structures and routes, strengthening the operations of Pink Autos in Surat (& proposing the same in Udaipur) to enable greater employment opportunities for women in the transport sector, develop EV infrastructure in residential spaces to enable a broader reach of EVs among women, encourage women drivers to own E-rickshaws through heavy subsidies and run awareness programs on the benefits of electric mobility.

For Udaipur, pedestrianizing the old city results in a lively public space for all ages and genders with formalized vending activities (refer to **Figure 5**). For Surat, the proposals translate into streets with equitable road space distribution and activity

zones, making it safe for all (refer to **Figure 6**).

Figure 5. A pedestrianized street section in Udaipur service leveled for motorized traffic, prioritizing safety for all ages and genders, acting as a public space.

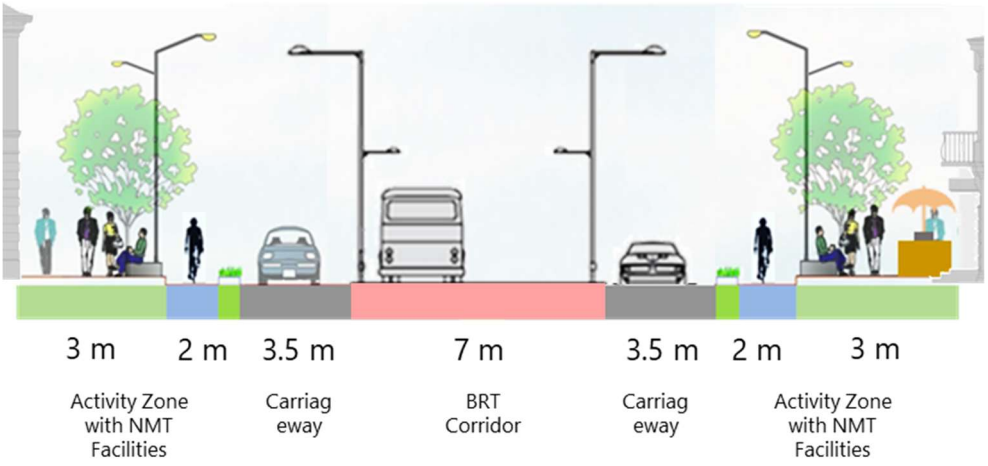


Figure 6. A typical street section in Surat with spaces allocated to BRT, footpaths, cycle tracks, bus lanes, and vending activities, maximizing safety and mobility for all.

In general, although cities anchor the implementation of gender-responsive transport planning and design, the state has a vital role. We present below state actions that can enhance gender-inclusion in transport with examples:

(i) Incorporate gender-responsive transport planning in national and sub-national transport-sector visions.

(ii) Mandate gender budgeting in cities. Gender-Responsive Budgeting began in India in 2005–2006 as a fiscal innovation, and was rapidly adopted by 57 out of the 58 central government ministries in India [36]. Despite being in effect for 18 years, it has low adoption among urban local bodies, due to a lack of mandate [36]. Hence, mandating it would ensure that rights and needs of women are embedded into municipal functions.

(iii) Create a monitoring and evaluation framework to measure the impact of transport on gender equity.

(iv) Create a financing mechanism that enables local bodies to upgrade public transport networks; Gujarat's Chief Minister Urban Bus Service Scheme aims at

providing Viability Gap Funding of 50% or Rs. 12.50 per km to Transit Authorities and Urban Local Bodies [37].

(v) Promote and incentivize investments in non-motorized infrastructure provision and maintenance; local governments in Europe and South America are forming Active Mobility Strategies to receive dedicated funding for non-motorized infrastructure provision; In 2014, Fortaleza, Brazil, leveraged its online, app-based parking system to fund its Strategic Cycling Infrastructure Plan with network length of 524-km [38]; in 2019, Ireland created a Comprehensive Active Travel Investment Program to receive 20% of the annual transport budget, drastically increasing its annual active transport budget from 12.64 million to 360 million [39].

(vi) Mandate gendered transport data collection in cities to record disaggregated trip data to enable gender-responsiveness in transport policies and plan; The Capital Region Urban Transport (CRUT), Bhubaneshwar, India, collects gender disaggregated tickets to take evidence-based decisions [40].

(vii) Decrease barriers for women's employment in transport sector by subsidizing intermediate public transport (like auto-rickshaws and E-rickshaws) vehicle ownership and other incentives; Since 2021, Ministry of Transport and Infrastructure in Turkey started a female internship for its rail connectivity project [41]; ride-sharing services like Grab in Philippines and PickMe in Sri Lanka have special initiatives to increase women workforce participation rate in their organizations; Delhi-Meerut Regional Rapid Transit System Investment Project: Gender Equality and Social Inclusion Action Plan aims to ensure over 50% jobs in operations are held by women [42].

(viii) Increase women's participation in urban and transport planning outreach efforts [43]; Vadodara has appointed an 'inclusivity manager' to understand the challenges faced by women cyclists [44].

Gender-inclusive transport goes beyond the transport sector and requires a change in the paradigm of urban development. Gender-inclusive planning requires interventions in the policies and programmes, everyday governance for safety and security, financing, infrastructure planning and design, management of these infrastructures, and pricing of public transport. One-off provisions or tinkering with transport system will not give sustainable and long-term solutions.

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Notes

[1] This section is based on the critical assessment of Surat's Comprehensive Mobility Plan and Udaipur's Low-Carbon Mobility Plan.

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Article

Will new tram lines enhance the connectivity and walkability? A case study of Sakarya

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Abstract: This study investigates the impact of planned tram lines on walkability and accessibility in Sakarya, utilizing Geographic Information Systems (GIS) for spatial analysis. The research evaluates the catchment areas of proposed tram stops, assessing their suitability and coverage, and examines how these areas integrate with existing public transport routes. By calculating time-oriented catchments for 5, 8, and 10-minute walking distances, the study identifies service gaps and redundancies in the public transport network. The findings reveal that the new tram lines will enhance accessibility by extending coverage to high-density areas and potentially reducing the demand on existing bus services. The analysis also highlights the overlap between bus transit lines and tram stops, suggesting optimizations to improve network efficiency. The results offer valuable insights for urban planners, aiming to optimize Sakarya's public transport system to be more inclusive and sustainable. This study contributes to urban mobility planning by providing a detailed understanding of how new tram lines can improve connectivity and support sustainable urban development.

Keywords: sustainable urban mobility; public transport; walking distance; station catchment area; accessibility

1. Introduction

Sustainable urban mobility is essential for the overall quality of life in cities. By adopting sustainable transportation practices, cities can achieve economic growth, environmental protection, and social diversity while ensuring efficient and comprehensive public transportation systems. The European Commission outlines that sustainable urban mobility plans aim to develop urban transport systems by addressing key objectives such as providing transport options for all citizens, improving safety, reducing pollution, enhancing efficiency, and contributing to the urban environment's quality [1]. Every facet of city life—including recreation, education, business, and industry—is linked with transportation. Indicators of sustainable urban mobility are vital for sound spatial planning, effective traffic management, and environmental protection [2].

Public transport plays a crucial role in achieving sustainable mobility in cities, necessitating the maintenance of supply and quality at acceptable levels [3]. Several research works highlight its significance for sustainable urban development, influencing not only transportation but also social cohesion, environmental sustainability, and energy efficiency [4–6]. Promoting walking, cycling, and a well-designed public transport system is pivotal for sustainable urban mobility [4,7]. Accessible public transport enhances mass mobility, improves urban life quality, and reduces environmental impacts [8,9]. It is also essential for developing inclusive urban

environments, especially those that support social fairness and the elderly [10,11].

The primary function of a transportation system is to facilitate the movement of individuals from their current locations to their desired destinations within a reasonable timeframe, using appropriate infrastructure and means [12]. Creating public transportation systems with pedestrian-accessible stops that are within a comfortable walking distance can boost urban mobility, specifically on the local scale [13]. The ease with which people can reach public transport stops is a key determinant of accessibility [14,15].

The idea of transport system availability has been described using a variety of terminology, including "access," "accessibility," "availability," and "proximity" [16,17]. Conceptually, accessibility can be viewed as either an activity (opportunities that are being taken) or a potential (opportunities that could be taken) [18]. Even those not currently using a particular form of public transport may consider it a future option, known as the value of the option. Accessibility signifies the general ability of people to have services and activities within their reach [19], translating to the time and money spent by individuals and companies on transportation. Corazza and Favaretto [20] link accessibility with terms such as "within walking distance" or "walkable." The quality of access significantly impacts the quality of life both directly and indirectly. Several factors can affect accessibility, including the conditions of traveling by motor vehicle, the quality of transport modes such as walking, cycling, and public transit, the connectivity of the transport network, and the proximity of different types of land use (distances between activities) [21].

One measure of transit accessibility is its spatial coverage, or the transit service catchment area. Studies have shown that spatial accessibility to the public transport system is a fundamental factor in the use of transit; only with such accessibility will the user consider other elements such as cost, comfort, safety, etc. [22]. Poor access to public transport disproportionately impacts low-income individuals, the elderly, and women, potentially resulting in a lack of access to education, jobs, healthcare facilities, and hospitals [23–26].

A number of researchers have calculated the distance that locals are willing to walk to get to local destinations like schools and bus stops. The early research on this topic was published in 1976 regarding the numerical analysis of walking distance to bus stops [27]. Approximately 400 m has been shown to be a reasonable walking distance for people to walk in order to get to the closest transport station [28,29]. This willingness dramatically drops when the distance surpasses 580 m [30]. According to Loutzenheiser's [31] research, the probability of someone walking to transit drops by 50% for every 500 m when they are farther from a station. Walking to the major modes, such as heavy and light rail systems, is found acceptable for 800 m [28] and 1600 m [32], where the latter is found less preferable.

On the other hand, there are many estimations regarding the walking speed of pedestrians. However, determining walking speed plays a vital role in traffic safety and urban planning processes. Walking speed may vary depending on not only age groups and physical disabilities but also seasonal conditions [33]. Arango Diaz [33] stated that the average walking speed of younger and older people is 5.80 km/h and 4.90 km/h, respectively. Walking speed of all pedestrian mean is 5.22 km/h [34]. Weather and climate conditions can affect the walking speed directly; for example,

when walking on a snow-covered area, walking speed slows down by about 0.367 km/h compared to clean ground, whereas if the ground is not challenging, each temperature drop will increase walking speed [35].

The introduction of a light rail system can redistribute transit demand, potentially alleviating pressure on overloaded bus and paratransit lines [36]. Moreover, it can lead to shifts in urban mobility patterns, with a transition towards rail-based services and the gradual integration of rail into intermodal transportation networks [37,38]. Light rail systems can stimulate economic development and urban regeneration along their corridors, promoting higher density and mixed-use development, further enhancing accessibility. Research indicates that expanding public transportation systems, including light rail, can enhance access to healthcare services, particularly benefiting individuals with low incomes [39]. Furthermore, implementing transit-oriented development around rail-based public transportation can influence urban form, encourage redevelopment, and revitalize old areas [40]. On the other hand, a significant disadvantage of trams and other rail-based systems is their high initial infrastructure costs, making them less adaptable compared to bus-based transit systems, which can more easily adjust routes and expand networks [41]. Furthermore, trams operating in mixed traffic environments face challenges such as increased delays and safety risks, particularly in densely populated urban areas where interactions with road vehicles can affect their efficiency [42].

Evaluating the accessibility impacts of light rail involves assessing proximity to stops, service frequency, and connectivity with other transport modes. GIS-based analyses are particularly useful for visualizing and quantifying these impacts, allowing planners to identify service gaps and areas for improvement. Service area analysis helps understand the shifts in demand and mobility and plan accordingly [43]. In cities where there are only bus services, a possible light rail can act as the backbone of the transit network, with buses serving as feeder services to connect outlying areas to the light rail stops, ensuring seamless connectivity and efficient resource use [38,44]. By identifying overlapping service areas, planners can streamline transit services, eliminate redundancies, and enhance overall network efficiency [45].

Service area analysis in GIS for light rail catchment area determination involves advanced GIS techniques to define the spatial extent within which a transit station can attract passengers. A common method used is the service area approach, also known as isochrone mapping or ped shed analysis, implemented in GIS software like ESRI's ArcGIS™ with the Network Analyst™ extension [46]. Methods for determining catchment areas include the proximity method using buffer rings and network-based service areas [47]. These methods delineate the coverage of service areas around transit facilities based on factors like Euclidean distance [48]. Radial-based catchment areas are also widely used in transportation planning to estimate the number of individuals within walking distance of a transit stop [49].

Researchers have explored algorithms to automatically generate station catchment areas, comparing methods like Euclidean distance transform algorithms and location-allocation methods [47]. These approaches efficiently define the reach of a transit station and understand interactions between supply and demand for public transit services [26]. Additionally, studies have focused on enhancing the accuracy of catchment area analysis by considering factors like street layout, land use, parking

capacity, and multimodal accessibility [50]. Incorporating these variables into the analysis provides a more comprehensive understanding of the factors influencing the size and shape of catchment areas for light rail stations.

The aim of this study is to understand the impact of planned new tram lines on walkability and accessibility in Sakarya using Geographic Information Systems (GIS) for service area analysis. The study will calculate the catchment areas of proposed tram stops, examining their suitability and coverage. Additionally, it will assess the current tram line's catchment areas and evaluate parallel and overlapping public transport routes to understand their integration and overall efficiency. These analyses aim to shed light on optimizing the public transport network in Sakarya, contributing to the development of more inclusive and sustainable urban environments. This study was conducted in Sakarya, Türkiye, which is also shown on the maps in different scales (**Figure 1**). This project is planned by the Ministry of Transportation and Infrastructure and the General Directorate for Infrastructure and Investments in the Republic of Türkiye. Sakarya is a city located in the northwest of Türkiye. The population of Sakarya is 1,098,115 as of the end of 2023; the annual population growth rate is 16.6 per thousand; the surface area of the province is 4817 km^2, and there are 228 people per km^2 in the province. Sakarya ranks 22nd in Turkey in terms of population and 66th in terms of surface area [51].

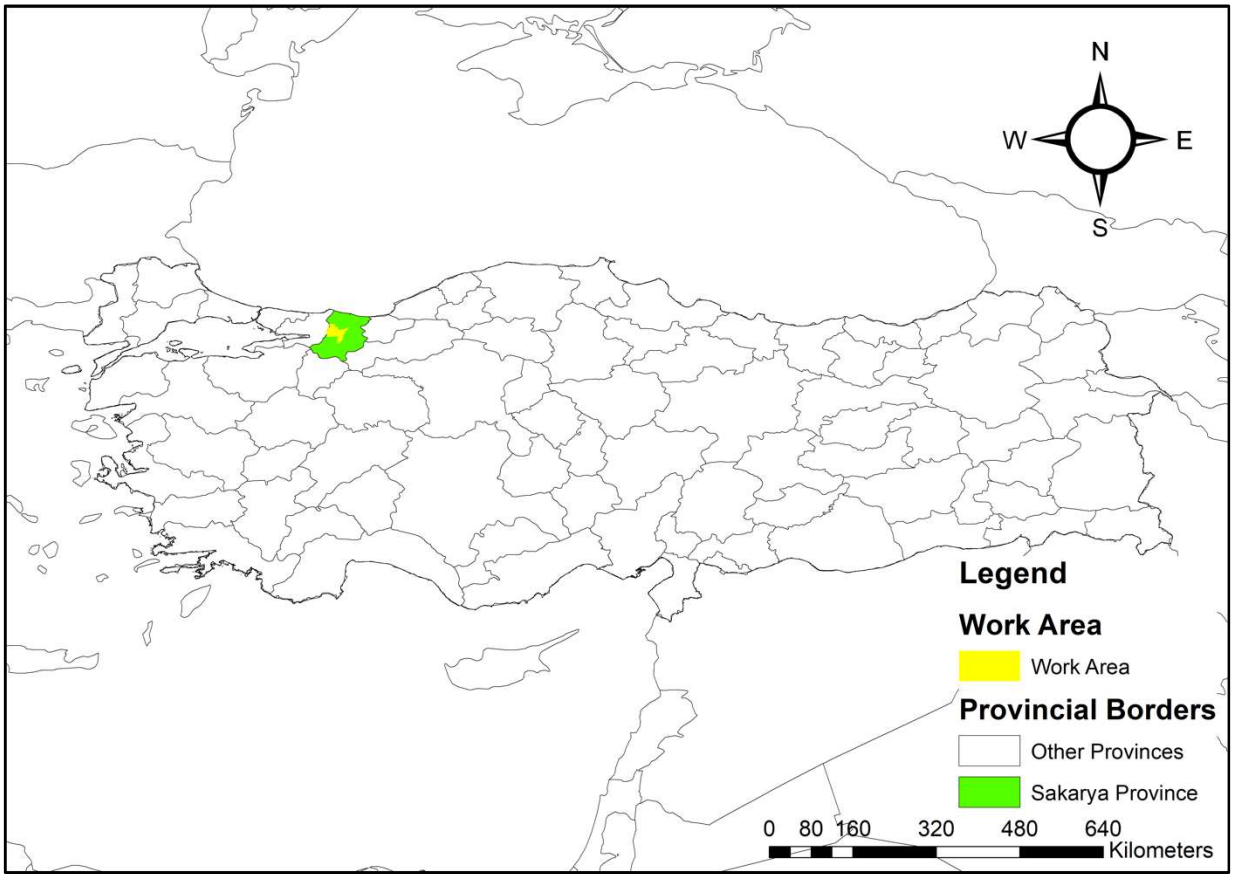

Figure 1. Location of the Sakarya where the analysis is conducted.

Both tram and bus lines are displayed on the same map to allow for effective monitoring (**Figure 2**). When the lines appear darker and thicker, it indicates that there

are more concentrated bus lines in that area. The thickening of the red lines signifies an increase in the number of bus routes and stops. In areas where the tram line overlaps, the bus lines must be analyzed in terms of service frequency, the number of stops, and bus capacity. Another objective of the study is to assess passenger distribution and pooling behaviors once the tram line is implemented in the study area. This will provide a better understanding of the mobility and transfers between different modes of transportation, such as buses and trams.

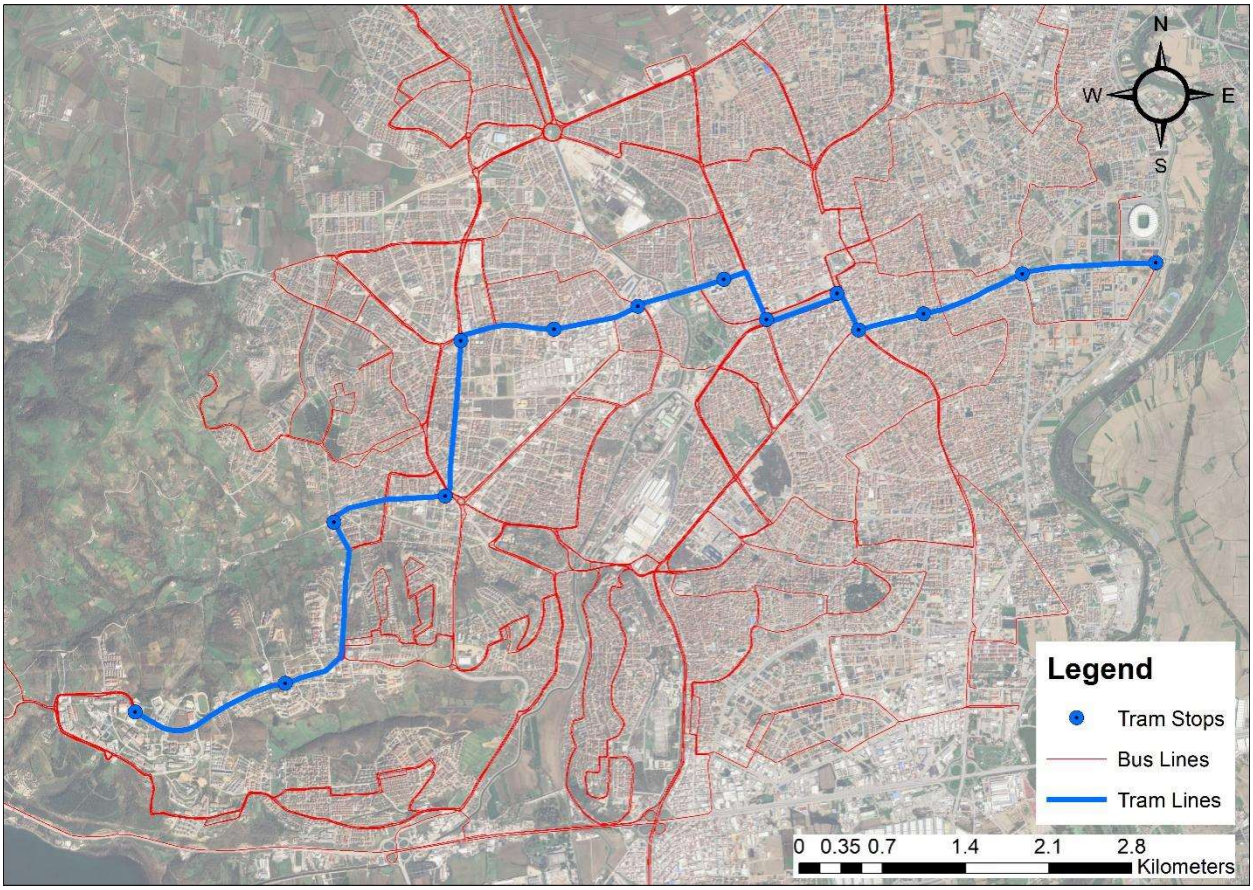

Figure 2. Both tram and bus lines are shown on the map with tram stops.

2. Materials and methods

To assess the catchment areas of a newly planned light rail line in Sakarya, this study employs ESRI's ArcGIS™ with the Network Analyst™ extension to conduct a detailed spatial analysis. Initially, the existing public transport infrastructure, including bus stops and routes, will be mapped to establish a comprehensive baseline. The proposed tram stop locations will be integrated into this map. Neighborhood boundaries and partial population data will also be incorporated to evaluate the demographic impacts, ensuring a thorough understanding of the service provided to various communities.

Service area analysis will generate time-oriented catchments delineating 5, 8, and 10-minute walking distances from each proposed tram stop. These maps will identify the spatial coverage and potential overlaps with existing bus routes, highlighting redundancies and service gaps. Integrating these datasets allows for a meticulous

evaluation of parallel and overlapping routes, crucial for identifying inefficiencies where the new tram line may duplicate existing services. Based on the insights from this analysis, recommendations will be presented to optimize the public transport network, potentially including the removal or relocation of specific bus stops to enhance connectivity.

In this study, planned tram lines are investigated. The Sakarya Metropolitan Municipality prepared the implantation of tram lines in three phases in Sakarya, where Phase-1 was currently approved by the Ministry of Transport and Infrastructure. In this plan, Phase-1 covers the highly populated east-west coverage, including the university campus connection. On the other hand, Phase-2 and Phase-3 were planned to enhance the mobility infrastructure in the south-east of the city and intercity bus terminal connections. Phase-1 has a tram line length of 9 km, Phase-2 has a tram line length of 4.4 km, and Phase-3 has a tram line length of 9.26 km. However, the investigated tram line includes the entire Phase-1 and a part of Phase-3. There are 37 Bus Transit Lines that are analyzed in this study. There are 14 Tram Stops (Stations) to be investigated, and these stops are located in 7 different neighborhoods and 3 different districts. The outcomes will provide valuable insights for urban planners, facilitating the design of a more efficient and accessible public transport system in Sakarya. This methodical approach contributes significantly to creating a more inclusive and sustainable urban environment, aligning with broader urban development and mobility objectives.

3. Results

The tram line that is the subject of this study will be implemented in Sakarya, Türkiye. The tram system is planned to be built in three-phased like Phase-1, Phase-2 and Phase-3. Red line represents Phase-1 tram line which has 9 km and 11 Tram Stop, yellow-line refers to Phase-2 tram line, which has 4.4 km and 6 stations and the blue line presents Phase-3 tram line, which has 9.26 km and 12 stations. These line lengths and tram stations may change depending on the growth momentum of the city. In this analysis, walking speed was applied as 5 km/h. Considering a walking speed of 5 km/h, the walking distances for different durations are approximated as follows: a 5-minute walk covers approximately 416 m, an 8-minute walk spans about 666 m, and a 10-minute walk reaches roughly 832 m. The green, yellow, and red catchments will be structured according to these considerations.

Walking Time-Oriented Catchments are created based on 5, 8, and 10-minute walking distances. These areas were calculated on ArcGIS Service Area Analysis. However, when calculating these areas, the first condition was to calculate the appropriate walking paths for passenger use and then create a time-oriented catchment. It means that the coverage area (Walking Time-Oriented Catchment) is calculated by network analysis on the walkable lines. Walkable lines were detected as routes that people could walk clearly. The difference between Buffer Zone Analysis and Service Area Analysis is shown in **Figure 3** [52]. The total catchment area for each walking distance category is given in **Table 1**.

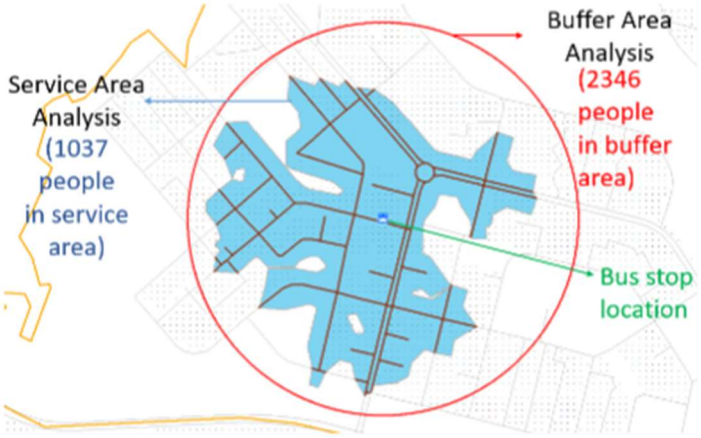

Figure 3. An example of the difference between service area analysis and buffer analysis coverage in GIS.

Table 1. Walking time-oriented catchments and areas with impacted bus stops.

Time (minutes)	Area (km^2)	Bus Stops	Bus Stops Density (Stop per km^2)
0-5	2.0405	72	35.3
0-8	6.0234	158	26.2
0-10	10.3992	236	22.7

Green, yellow, and red colored areas represent the distance between 0–5, 5–8, and 8–10 min, respectively (**Figure 4**). The area of the green zone, yellow zone, and red zone is 2.0405 km^2, 3.9829 km^2 and 4.3758 km^2 in total.

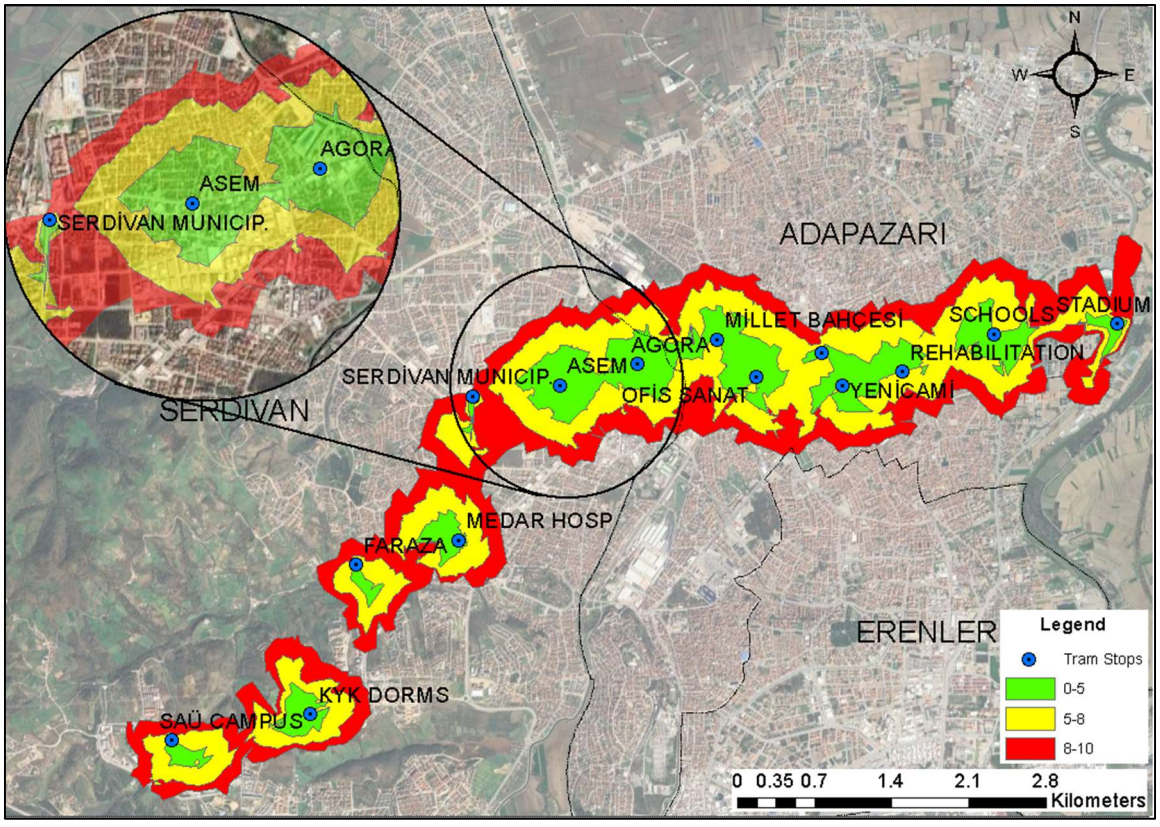

Figure 4. Walking time-oriented catchments with basemap.

Additionally, bus stops in the catchment area of the new tram line are presented in **Figure 5**. The same color coding is used for representing the bus stops in designated catchment areas. There are a total of 236 bus stops located near the tram line, where 72, 86, and 78 bus stops are in green, yellow, and red catchment areas, respectively. This result shows that there are 72 bus stops within a 5-minute walk of the tram stop, 158 (72 + 86) within an 8-minute walk, and 236 (72 + 86 + 78) within a 10-minute walk.

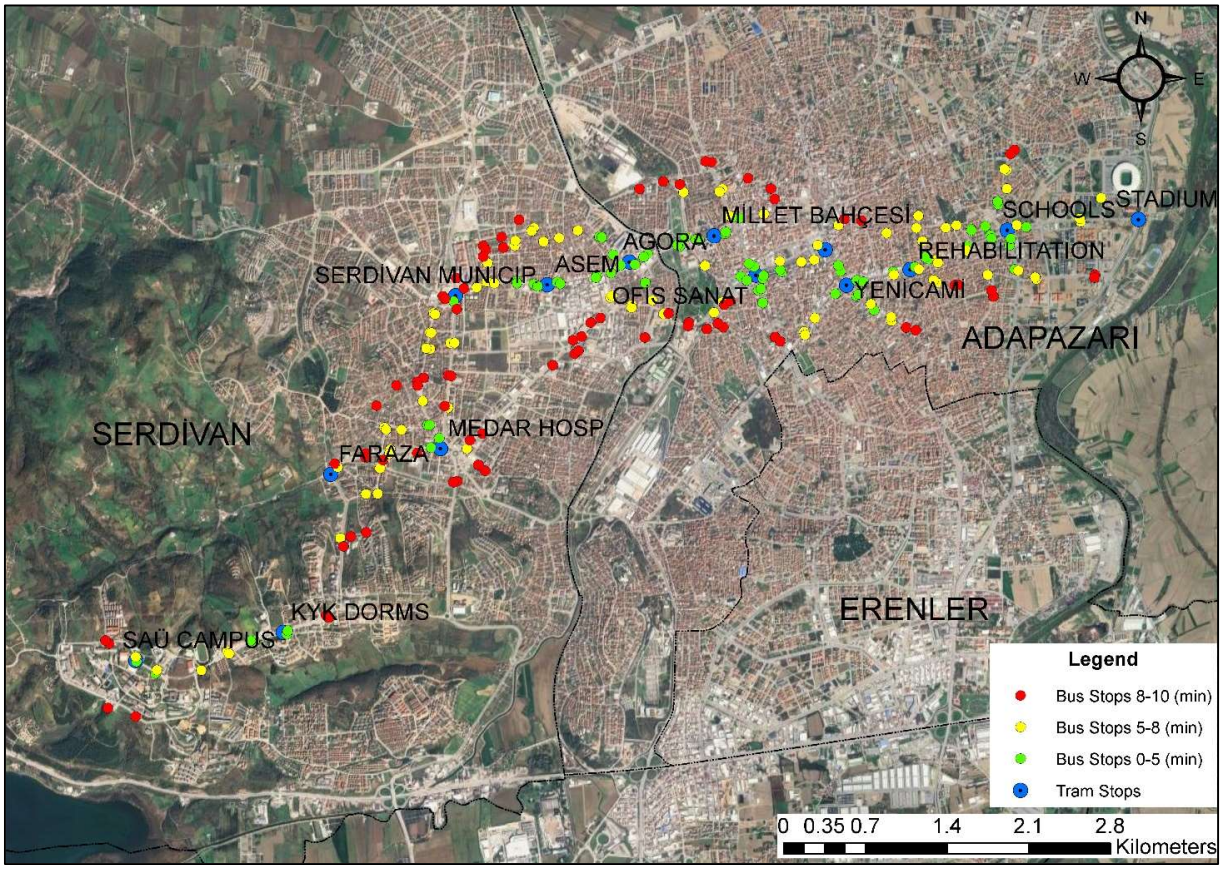

Figure 5. Tram stops (big blue-colored shape) and bus stops (green, yellow, and red-colored dots) are shown on the same map. (There are 72 stops (5-minute walking catchments green-colored dots on the map), 86 stops (between 5 and 8-minute walking catchments yellow-colored dots on the map), and 78 red bus stops (between 8 and 10-minute walking catchments red-colored dots on the map).

Considering the purpose of the light-rail and the necessity of re-evaluating the existing public transportation systems in the area helps enhance the effectiveness of the network by reducing redundancies and planning the mode-share. Thus, the 236 bus stops with parallel bus lines should be carefully evaluated. The 72 bus stops that are 5 min walking distance from the tram stations (green region) could be removed except the ones that will be used as a transfer point for a mode chance (switching from bus to tram or vise verse). Additionally, the remaining 164 bus stops in 5–10 min walking distance (yellow and red regions) should be evaluated based on the possible changes in bus routes.

Moreover, population density is used to better understand the extend of the coverage where the new tram line is planned. It is calculated by dividing the population

of a neighborhood by the area of the neighborhood. Population density map was achieved through interpolation of neighborhood-oriented population data, which is published by the Turkish Statistical Institute, TÜİK [53], allowing for estimation of point population density (**Table 2**). A population density map is created by ESRI's ArcGIS™ based on the neighborhood's population data (**Figure 6**). According to these maps, population densities as a point information of tram stops were generated. Thus, estimated population density was shown for each tram stop (**Table 2**).

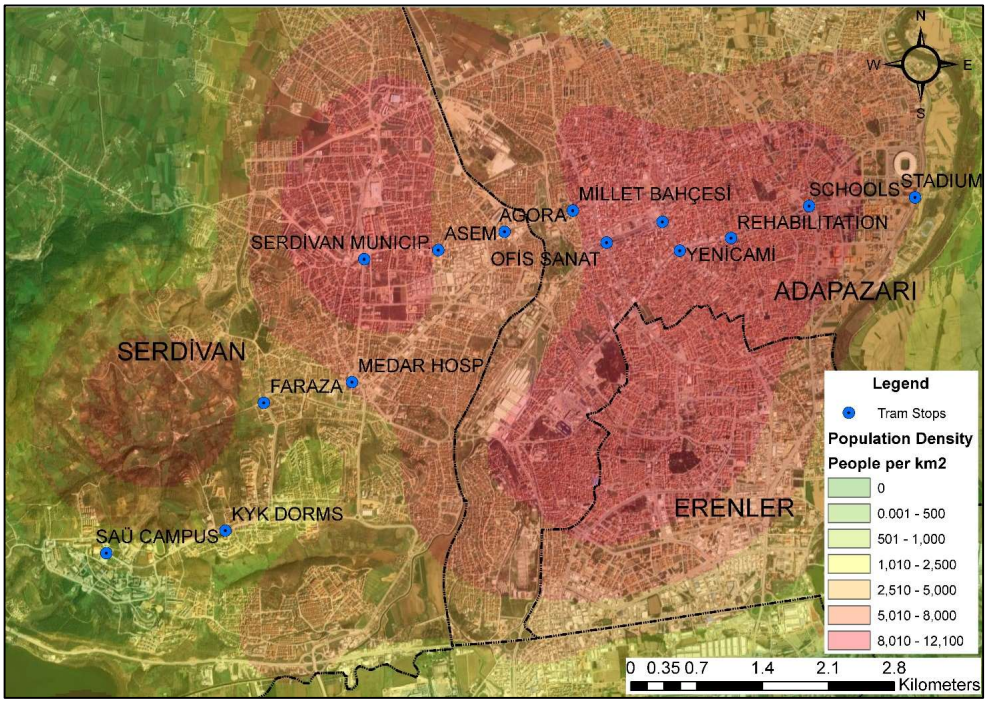

Figure 6. Population density with basemap.

Table 2. Population densities and areas of stops both bus and tram.

Tram Stops	Neighborhood Name	Popul. of Neighb. (people)	Area of Neighb. (km^2)	Pop. Density of Neighb. of Tram Stop (people/km^2)	Pop.Density (people/km^2)
SAÜ Campus	Esentepe	4354	7.0741	615.488	1029.797
KYK Dorms	Kemalpaşa	30149	11.6237	2595.985	2570.615
Faraza	Kemalpaşa	30149	11.6237	2595.985	4084.053
Medar Hospital	Kemalpaşa	30149	11.6237	2595.985	5303.837
Serdivan Municip.	İstiklal	23626	3.5552	6645.501	10404.915
ASEM	İstiklal	23626	3.5552	6645.501	7709.966
Agora	İstiklal	23626	3.5552	6645.501	5410.658
Millet Bahçesi	Semerciler	5139	0.5172	9936.699	7927.332
Ofis Sanat	Semerciler	5139	0.5172	9936.699	9261.011
Demokrasi Square	Semerciler	5139	0.5172	9936.699	10771.282
Yenicami	Yenicami	1636	0.1290	12680.517	11728.125
Rehabilitation	Yenigün	14288	0.8503	16803.122	12039.357
Schools	Yağcilar	22468	3.0455	7377.427	10261.959
Stadium	Yağcilar	22468	3.0455	7377.427	5249.953

It is seen that the new tram line covers the high population density areas as expected. However, it is notable that the SAÜ Campus and KYK Dorms are not presented as high population density areas. This is because the students are mostly not registered in the campus area due to inefficiencies in the data gathering of TUİK for temporary occasions. Therefore, considering nearly 50 thousand active students on the campus, these two stations will also be heavily used in the area.

Tram stations and Bus Lines (BL) overlap at some points. Some of BL are almost in the same direction and service the same area to carry passengers. Line-4 and Line-15 intersect with most of the Tram Stops. These lines should be revised not to be an alternative to tram lines but as a supplementary to enhance the connectivity and distribution of the passenger load. Thus, the overlapping bus lines could be optimized depending on the travel demand and tram frequency of daily trips. Some of the BLs also touch on the Tram Stops such as 26 BTL intersecting on "Ofis Sanat" (**Table 3**). The maximum number of intersecting points is "Ofis Sanat", and "Ofis Sanat Tram Stop" has also four (more parallel lines with tram lines) bus transit lines, which are called Line-4, Line-15, Line-19K, and Line-27. It can be said that "Ofis Sanat" can be a HUB Stop and Transit Point for both trams and buses. Bus Lines and Tram Stops intersect more on "Ofis Sanat and Demokrasi Square". The Density Map is more concentrated in areas close to "Demokrasi Square" and "Ofis Sanat" Stops (**Figure 7**). It means that the BLs are denser on both stops than the others. The areas on the Density Map show that it becomes more concentrated from green to red. The redder the map, the denser the BLs are through that area.

Table 3. Number of bus lines (BL) passing through the Tram Stops and the status of the BL passing through tram stops the most (X represents the overlap of bus lines with tram lines and stations).

Tram Stops	Number of BTL Passing through the Tram Stops	Line-4	Line-15	Line-19K	Line-27
SAÜ Campus	11	X	X	X	X
Kyk Dorms	11	X	X	X	X
Faraza	3				
Medar Hospital	3				
Serdivan Municip	6	X			X
ASEM	6	X		X	X
Agora	9	X		X	X
Millet Bahçesi	12				
Ofis Sanat	26	X	X	X	X
Demokrasi Square	19	X	X	X	
Yenicami	5	X	X	X	
Rehabilitation	2		X		
Schools	2		X		
Stadium	1		X		

Figure 7 shows the 26 bus lines operated by Sakarya Metropolitan Municipality, the planned tram line, the stations that will serve on this line, and the density distribution of these stops along the route. The figure shows that a great number of bus routes pass through the Central Business District (CBD) area, where the bus stop

density is high. In addition, the presence of the main bus route (Ofis Sanat) and the intercity train station belonging to the routes within this area is also very important in terms of multimodal integration.

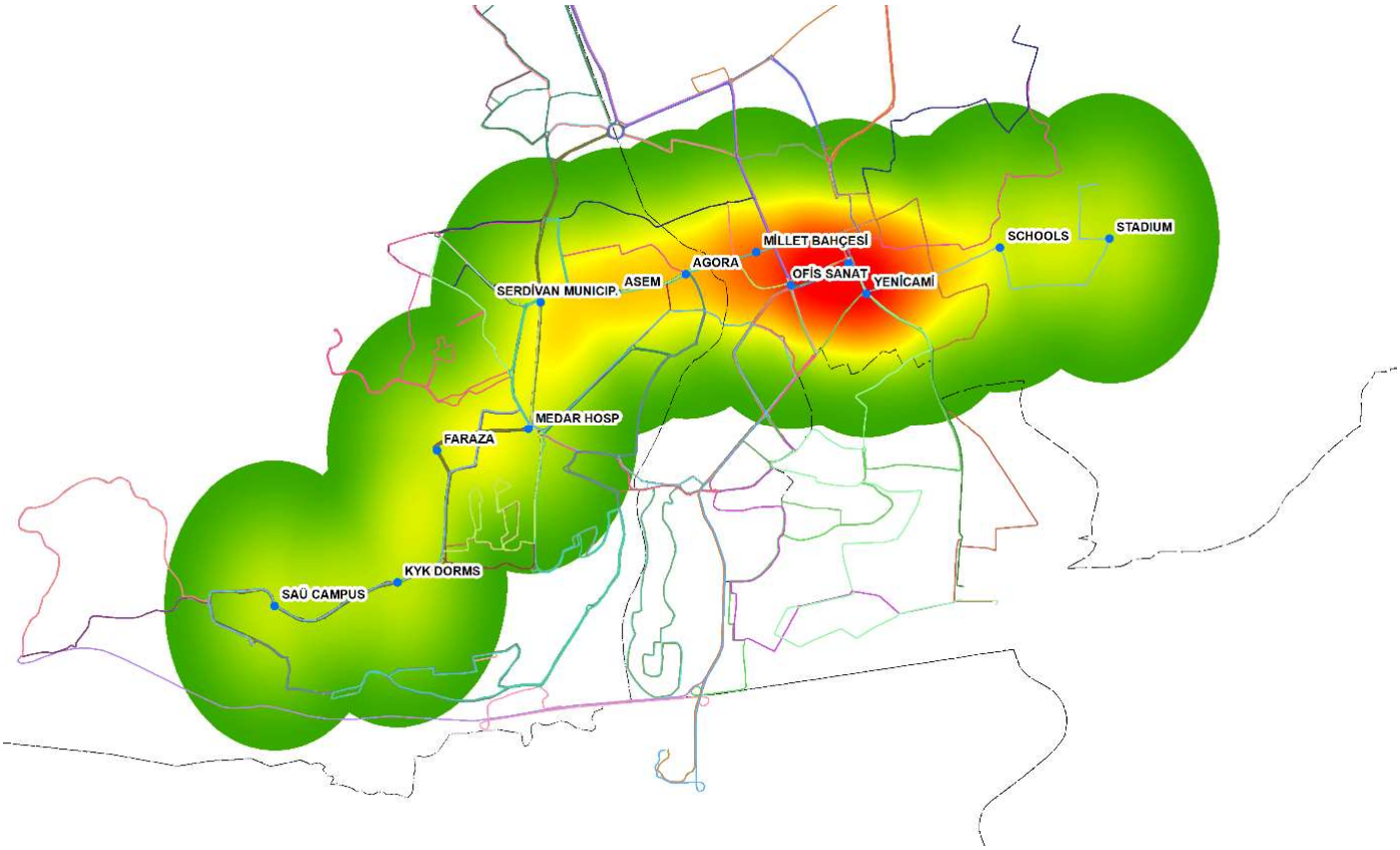

Figure 7. Tram stations and bus lines (BL) density map.

In short, the number of 26 Bus Lines (BL) and 1571 bus stops were analyzed according to the planned 3-phase tram line and planned tram stops. Since the planned tram-line project on Phase-1 and part of Phase-3 draws a linear direction that will connect between the east and west of the city, the tram line network examined includes the entire Phase-1 and part of Phase-3. Some of BTL were seen to operate in parallel with the planned tram line. 14 tram stops are analyzed, and BLs with 6 or more overlapping points in common with the tram line have been detected. These BL need to be optimized once the tram line projects are completed. While the locations of bus stops need to be optimized at some points, BL needs to be optimized depending on passenger density on the streets. After the tram project is completed, a more precise optimization can be made after passenger behavior is included in the analysis.

4. Discussion and conclusion

The results of this study underscore the significant potential for newly planned tram lines to enhance walkability and accessibility within Sakarya, offering important insights into urban mobility planning. Through Geographic Information Systems (GIS) analysis, we have delineated the catchment areas for proposed tram stops and assessed the integration with existing public transport routes. This analysis highlights several key findings and implications, which align with and expand upon existing

literature in the field of urban mobility.

One critical observation is that the new tram lines will indeed enhance accessibility by increasing the proportion of the population within walking distance of public transport. However, it is important to note that trams and buses serve different functions in an integrated transport network. As highlighted by Vuchic [54], buses often serve as feeder services for trams or cover areas that fall between tram lines, especially in suburban or outer-city areas. Moreover, buses and trams differ significantly in terms of capacity, frequency, scheduling, and pricing, as documented by Cervero and Duncan [55], which are essential considerations when optimizing public transport networks. The aim of this study is not to suggest that buses and trams are redundant or mutually exclusive, but rather to identify opportunities for optimizing intersections where tram and bus stops are located in close proximity. This could reduce service redundancies and improve network efficiency by minimizing overlaps that lead to inefficiencies in high-density areas. By refining bus routes to complement the tram network, planners can improve overall system integration, as supported by research on multimodal transportation systems [56].

Furthermore, while this study has focused primarily on time-oriented accessibility, it is essential to consider additional factors such as origin-destination patterns, which are critical for informed transport planning. For instance, the spatial distribution of student accommodations—whether students live on or off-campus—plays a key role in determining transport demand. A significant body of literature, including works by Loo et al. [57], emphasizes the importance of understanding travel patterns, particularly in the context of university campuses and other areas with high transit demand. In this regard, the findings of this study, particularly around the SAÜ Campus and KYK Dorms, are only partial in that they do not account for the full extent of where students live and how this impacts overall demand for tram and bus services. Future research should integrate more comprehensive data on travel patterns, using origin-destination surveys or models to provide a fuller picture of transport network usage [58].

Considering the trip chain, the relationship between buses and trams can indeed be both competitive and complementary, depending on the context and design of the transport network. In central areas with high demand, buses and trams may operate competitively due to overlapping service areas, as both aim to connect passengers to key destinations. However, as literature on multimodal transport networks suggests, these modes can also complement each other by serving different functions within the trip chain [55,56]. For example, buses may act as feeders to tram lines, especially in peripheral areas where tram coverage is limited. By efficiently integrating bus and tram schedules and routes, planners can ensure that each mode serves a distinct role in the trip chain—buses providing local access and trams handling higher-capacity, longer-distance travel. This complementary relationship helps to create a seamless travel experience, reduces redundancy, and increases the overall efficiency of the network. The results of our study highlight opportunities for optimizing this integration in Sakarya, and further research should explore the dynamics between bus and tram systems, particularly how they influence travel patterns and trip chains in different urban contexts.

In conclusion, this study confirms that the planned tram lines will substantially

improve public transport accessibility and walkability in Sakarya by serving a wide range of high-density areas. Optimizing the integration of tram and bus services will be crucial in creating a more cohesive and efficient network, particularly by addressing redundant routes in central areas. The key findings include:

1) The proposed tram lines will enhance walkability by reducing the distance residents need to travel to access public transport, with significant portions of the population being within 5 to 10-minute walking distances from tram stops.
2) Existing bus routes show considerable overlap with tram stops, indicating areas where service optimization is needed to avoid redundancies and enhance overall network efficiency. These optimizations can improve the complementarity of tram and bus services rather than replacing one with the other [55].
3) High-density population areas are well-served by the planned tram system, though further adjustments are needed to account for temporary and transient populations, such as students, particularly considering origin-destination patterns and transport demand [57].

The results offer valuable insights for urban planners and decision-makers in Sakarya, highlighting the need to optimize public transport networks by integrating different modes of transport effectively. Implementing these recommendations can lead to a more efficient, accessible, and sustainable public transport system in Sakarya. Future research should further refine the analysis by incorporating real-time transit data and a deeper examination of pedestrian infrastructure and travel patterns.

5. Current limitations

While this study provides valuable insights into the impact of planned tram lines on walkability and accessibility in Sakarya, it primarily focuses on time-based catchment areas, which may not fully capture the complexity of accessibility. Walkability and accessibility are multidimensional concepts that extend beyond mere proximity to transit services. Factors such as pedestrian safety, terrain, micro-climate, and the quality of pedestrian infrastructure significantly influence how easily and safely individuals can access public transport. For instance, a 10-minute walking distance may be less feasible for individuals with mobility impairments if sidewalks are poorly maintained or if steep inclines are present. Likewise, adverse weather conditions or insufficient shelter along pedestrian routes could diminish the accessibility of tram stops. Although this study acknowledges these factors as relevant to urban mobility, they were not directly analyzed due to the complexity of obtaining detailed, location-specific data on each aspect.

Additionally, cost factors, such as the affordability of tram services compared to other modes of transportation, were not considered in this analysis, nor was the subjective perception of safety during pedestrian trips. These are crucial components of a holistic understanding of walkability and accessibility but were beyond the scope of the current GIS-based approach. Future research could incorporate these elements by using qualitative data collection methods, such as surveys, or by integrating additional datasets related to terrain, pedestrian safety, and infrastructure quality. This would allow for a more comprehensive evaluation of how tram lines impact urban mobility, particularly for vulnerable populations who might face greater barriers to

accessing public transport.

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Article

Sustainable sourcing: A study on the impact of sustainable sourcing practices on firm performance and stakeholder satisfaction

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Abstract: This study investigates the impact of sustainable sourcing practices on firm performance and stakeholder satisfaction across various industries. Using a quantitative approach, data were collected from 500 firms through a structured survey questionnaire. The findings reveal that sustainable sourcing practices lead to a significant positive impact on firm performance, with an average 15% increase in profitability and 20% improvement in stakeholder satisfaction scores. The regression analysis shows a strong correlation ($r = 0.45$, $p < 0.001$) between sustainable sourcing and enhanced firm outcomes. The study identifies firm size, industry type, and sustainability awareness as critical factors influencing the adoption of sustainable practices. Recommendations include integrating sustainability into procurement processes to enhance long-term performance. Future research should explore the longitudinal effects of these practices across different market conditions.

Keywords: statistics; sustainability; stakeholder satisfaction; firm performance
JEL Codes: Q56, M14, L21

1. Introduction

In recent years, sustainable sourcing has emerged as a critical business practice as companies face increasing pressures from stakeholders to operate in a socially and environmentally responsible manner. With heightened awareness of environmental degradation and the social consequences of unethical sourcing, firms are compelled to adopt practices that minimize negative impacts while maintaining competitiveness. Sustainable sourcing, which integrates environmental, social, and governance (ESG) criteria into procurement processes, is seen as a pathway to achieving long-term business resilience, especially in today's interconnected global supply chains.

Despite the growing recognition of sustainable sourcing, gaps remain in the literature, particularly concerning its direct impact on firm performance and stakeholder satisfaction across various industries. Existing studies [1,2] have largely focused on the environmental benefits and cost-saving potentials of sustainable sourcing, but fewer have empirically tested its overall influence on financial outcomes and non-financial measures such as stakeholder trust and satisfaction. This study aims to address this gap by providing a comprehensive analysis of how sustainable sourcing practices affect both firm performance and stakeholder satisfaction, drawing from data across multiple industries.

The contribution of this study is twofold. First, it expands the current understanding of the economic and stakeholder-related outcomes of sustainable sourcing by quantitatively analyzing data collected from a diverse sample of firms. Second, it identifies key industry-specific factors, such as firm size and sustainability

awareness, that moderate the effectiveness of sustainable sourcing practices. By examining these relationships, this study provides insights for firms looking to optimize their sourcing strategies in a competitive and sustainability-conscious market.

This research utilizes data from 500 companies selected from a larger pool of 1000 firms, representing various industries including manufacturing, retail, and services. Data were collected via a structured survey conducted over a five-year period (2017–2021) to capture both short- and medium-term effects of sustainable sourcing. The focus on a diverse sample ensures that the findings are generalizable and reflect the varied levels of sustainability adoption across different sectors.

The results of this study will contribute to the literature on sustainable supply chain management by offering empirical evidence of the benefits of sustainable sourcing, with a specific focus on financial performance and stakeholder satisfaction. Furthermore, it provides actionable recommendations for firms seeking to enhance their sourcing practices and align with the growing demands for sustainability from both regulators and consumers.

1.1. Originality of the paper

This study offers significant contributions to the existing literature on sustainable sourcing by addressing key gaps, employing novel methodologies, and providing new empirical insights that differentiate it from previous research.

1.2. New empirical insights

The primary originality of this paper lies in its comprehensive empirical analysis, which draws on data collected from 500 firms across diverse industries and geographical regions, including North America, Europe, and Asia. Unlike many previous studies that focus on environmental or cost-saving aspects of sustainable sourcing [1,2], this research quantitatively examines the impact of sustainable sourcing on both financial performance and stakeholder satisfaction. The findings reveal a notable 15% increase in profitability and a 20% improvement in stakeholder satisfaction across firms that adopt sustainable sourcing practices. These results contribute new data to the field, offering a broader understanding of the economic and non-financial benefits of sustainable sourcing.

1.3. Novel research context

The study's uniqueness is further demonstrated through its cross-industry analysis, which evaluates how sustainable sourcing practices vary between sectors such as manufacturing, retail, and services. Prior research has often focused on a single industry or region, limiting the generalizability of their findings. In contrast, this paper's inclusion of multiple industries allows for a deeper exploration of sector-specific dynamics. For example, the study identifies that manufacturing and retail firms see stronger financial and stakeholder-related benefits from sustainable sourcing compared to service-based industries. This cross-industry analysis is a distinctive contribution, providing nuanced insights into the different ways in which sustainable sourcing influences performance depending on industry type.

Innovative methodological approach

Methodologically, the study employs a robust quantitative framework, incorporating regression analysis, correlation tests, and ANOVA to rigorously test the relationship between sustainable sourcing, firm performance, and stakeholder satisfaction. While similar statistical approaches have been used in other studies, this paper distinguishes itself by controlling for variables such as firm size, industry type, and sustainability awareness, ensuring that the results are both reliable and generalizable across different contexts. Additionally, the structured survey instrument was specifically designed to capture detailed quantitative data on firm performance and stakeholder satisfaction—filling a gap in previous qualitative or environmentally focused studies.

1.4. Addressing gaps in the literature

One of the critical contributions of this paper is its direct response to gaps in the existing literature on sustainable sourcing. While prior research has largely emphasized the environmental benefits of sustainable sourcing, there has been less focus on its financial outcomes and stakeholder trust across diverse industries. This paper not only provides empirical evidence of the financial benefits but also demonstrates how these practices enhance stakeholder satisfaction, a factor that has received less attention in earlier works. Moreover, the study's examination of industry-specific impacts adds a layer of originality, highlighting how sustainable sourcing practices are adopted differently across sectors and how these variations affect both profitability and stakeholder relationships.

1.5. New conceptual framework and hypotheses

This paper introduces and tests new hypotheses that challenge existing assumptions about sustainable sourcing. For instance, the study explores the relationship between sustainable sourcing practices and long-term business resilience—a less-explored area in sustainable supply chain management. The research shows that firms with sustainable sourcing frameworks demonstrate higher resilience in times of disruption, aligning with emerging trends but offering new empirical backing to this concept. These hypotheses, supported by statistical testing, contribute to the development of a more nuanced understanding of the broader economic and social impacts of sustainability in procurement.

1.6. Implications for future research

The findings of this study open new avenues for future research by providing a foundation for exploring long-term effects of sustainable sourcing practices. For example, while this study captures short- to medium-term outcomes, future research could examine the longitudinal impact of these practices across various market conditions. Additionally, the study suggests potential for further exploration into the role of emerging technologies such as blockchain and AI in enhancing transparency and efficiency in sustainable supply chains, another under-researched area.

In conclusion, this paper advances the literature on sustainable sourcing through its innovative empirical approach, cross-industry insights, and focus on both

financial and stakeholder-related outcomes. By filling key gaps in the literature and proposing new conceptual frameworks, this study offers substantial contributions to both academic research and practical business applications in the field of sustainable supply chain management.

2. Literature review

Sustainable sourcing has gained significant attention in recent years as firms face increasing pressure to adopt responsible business practices that address environmental, social, and economic dimensions. The literature strongly supports the notion that sustainable sourcing not only enhances firm performance but also improves stakeholder satisfaction. This section reviews the relevant studies to support the hypotheses that sustainable sourcing practices positively influence both firm performance and stakeholder satisfaction.

2.1. Sustainable sourcing and firm performance

Several studies have established a direct link between sustainable sourcing practices and firm performance. One of the earliest comprehensive studies in this field [1] highlighted how firms that implement sustainable supply chain management practices experience cost savings, improved operational efficiency, and enhanced brand reputation. These factors contribute to financial gains, including increased profitability and sales growth. Such findings provide strong support for the hypothesis that sustainable sourcing positively impacts firm performance. The hypothesis that sustainable sourcing practices lead to better financial outcomes can be explained by the ability of firms to minimize costs through waste reduction, improved resource management, and streamlined operations [3].

Further research [2] demonstrates that firms adopting green supply chain practices, which include sustainable sourcing, observe significant improvements in key financial metrics such as return on investment (ROI) and profitability. Particularly in industries where consumers and stakeholders demand more sustainable products, firms benefit financially by adopting these practices. These studies corroborate the claim that sustainable sourcing strategies lead to measurable improvements in firm performance, including profitability and market share. This supports the hypothesis that sustainable sourcing practices contribute to positive financial performance, as seen in both empirical evidence and theoretical models [4].

Additionally, research has shown that sustainable sourcing enhances supply chain resilience, especially in times of crisis or disruption. Pagell and Wu [4] highlighted the importance of sustainability in maintaining continuity during supply chain interruptions, a conclusion reinforced during the COVID-19 pandemic. Garcia and Thompson [5] found that companies with established sustainable sourcing frameworks were better able to navigate pandemic-related disruptions, thus avoiding significant financial losses. This resilience is another key factor supporting the hypothesis that sustainable sourcing practices lead to improved firm performance.

2.2. Sustainable sourcing and stakeholder satisfaction

Sustainable sourcing also plays a crucial role in enhancing stakeholder

satisfaction, which includes customers, employees, and investors. According to Pagell and Wu [4], stakeholders are increasingly demanding that firms adopt practices that prioritize environmental and social responsibility. Companies that fail to meet these expectations risk losing consumer trust and investor confidence. The growing awareness among stakeholders regarding sustainability issues further emphasizes the need for firms to integrate responsible sourcing practices into their operations. This underpins the hypothesis that sustainable sourcing positively affects stakeholder satisfaction.

Zhu et al. [6] explored how evolving consumer expectations drive the need for sustainable sourcing. Their study showed that customers increasingly favor businesses that prioritize sustainability, which in turn influences purchasing decisions. This trend compels firms to adopt sourcing practices that align with stakeholder values. Rogers and Wright [7] added to this discussion by emphasizing the long-term benefits of sustainable sourcing in terms of fostering trust and engagement with stakeholders, both of which are essential for a firm's reputation and overall success. These studies strongly support the hypothesis that sustainable sourcing enhances stakeholder satisfaction by aligning firm practices with stakeholder expectations.

Williams and Ahmad [8] also demonstrated that firms adopting sustainable practices experience increases in customer satisfaction and loyalty. Their research highlighted how sustainable sourcing improves a company's reputation, leading to higher levels of stakeholder trust and loyalty. The findings further support the hypothesis that stakeholder satisfaction is positively influenced by sustainable sourcing practices. As stakeholders, particularly customers and investors, become more vocal in demanding corporate responsibility, firms that embrace sustainability-oriented procurement strategies are more likely to achieve higher satisfaction scores [6].

2.3. The role of technology and regulation

Technological advancements have further supported the implementation of sustainable sourcing practices, thereby amplifying their impact on firm performance and stakeholder satisfaction. Brown et al. [9] examined how technologies like blockchain and artificial intelligence (AI) enhance transparency and traceability in supply chain management. These tools enable firms to better monitor supplier compliance with environmental and social standards, thereby reducing risks of non-compliance and ensuring sustainability. Firms that effectively leverage these technologies can enhance both their operational efficiency and stakeholder confidence, supporting the hypotheses that sustainable sourcing practices positively impact both performance and satisfaction.

Regulatory pressures have also been instrumental in pushing firms toward sustainable sourcing. Smith et al. [10] noted that increased government regulations, particularly in developed regions such as Europe and North America, have driven higher adoption rates of sustainable sourcing practices. As firms seek to comply with stringent environmental and social regulations, they are compelled to adopt more sustainable sourcing strategies. This regulatory push further supports the hypothesis

that sustainable sourcing has a positive effect on both firm performance and stakeholder satisfaction by creating a compliance-driven need for responsible procurement.

2.4. Industry-specific impacts

While the benefits of sustainable sourcing are clear across industries, research indicates that the impact varies depending on the sector. Manufacturing and retail, which are heavily scrutinized by both regulators and consumers, have been shown to benefit more from sustainable sourcing than service-based industries. Garcia and Nelson [11] highlighted that in manufacturing, sustainable sourcing practices lead to reduced waste and emissions, translating into cost savings and improved stakeholder relationships. In contrast, service industries often experience less direct pressure to adopt sustainable practices, which may explain the smaller improvements in performance observed in these sectors [8]. These findings support the hypothesis that sustainable sourcing practices lead to positive outcomes, with industry-specific variations in the degree of impact.

2.5. Hypotheses

H1: Sustainable sourcing practices have a significant positive relationship with firm performance.

H2: Sustainable sourcing practices have a significant positive relationship with stakeholder satisfaction.

These hypotheses are supported by the literature, which demonstrates that sustainable sourcing contributes to improved profitability, enhanced resilience, and greater stakeholder satisfaction. Firms that adopt sustainability in their sourcing strategies tend to outperform their peers financially while also fostering stronger relationships with customers, employees, and investors. The existing body of research thus offers substantial evidence to support the proposed hypotheses.

3. Methodology

This study adopts a quantitative research design to empirically investigate the relationship between sustainable sourcing practices and firm performance and stakeholder satisfaction. The quantitative approach was selected due to its ability to analyze numerical data and provide generalizable results across various industries and firm sizes. This approach is well-supported in the literature, as highlighted by Martinez and Kim [3], who demonstrated the effectiveness of quantitative surveys in assessing sustainability outcomes. The use of surveys allows for collecting standardized data, enabling comparisons and statistical analysis of the effects of sustainable sourcing practices.

The rationale for using a structured survey was driven by the need to gather specific, quantifiable data on firms' sustainability practices. The survey format ensures that all respondents answer the same set of questions, providing consistency and comparability across industries. Moreover, the survey instrument was designed to capture key performance metrics, such as profitability, ROI, and stakeholder satisfaction, which are commonly used to assess the impact of sustainability in

procurement [2]. Additionally, this methodology allows for testing the relationships between sustainable sourcing and firm performance through regression analysis, ensuring that the study can draw robust conclusions.

3.1. Sample selection

A total sample of 500 distinct firms was selected from a larger pool of 1000 companies. These companies were chosen from publicly available databases covering various industries, including manufacturing, retail, and services. The selected sample size reflects the need for diversity in firm size and industry type, as suggested by Garcia and Nelson [11], and ensures that the findings are generalizable across sectors with varying degrees of sustainability adoption. The companies were randomly selected to eliminate bias and ensure the validity of the findings, following the sampling method described by Rogers and Wright [7].

The selection of the 1000-company universe was based on the availability of firms with documented sustainable sourcing practices, ensuring a focused yet representative sample. The final 500 firms represent a balanced mix of industries and regions, with data collected between 2017 and 2021. This five-year period was chosen to capture both short- and medium-term effects of sustainable sourcing, as firms often require time to fully realize the impact of sustainability practices on performance [6].

3.2. Geographic scope

This study collected data from a sample of 500 companies selected from a larger pool of 1000 firms, representing diverse industries such as manufacturing, retail, and services. These companies were drawn from publicly available databases that track firms with documented sustainable sourcing practices. The sample covered firms across major global regions, including North America (United States, Canada), Europe (United Kingdom, Germany, France, Italy, and others), and Asia (China, Japan, India, South Korea, and others). These regions were chosen because they are prominent in global supply chains and have varying levels of regulatory and market pressure to adopt sustainable practices.

3.3. Rationale for selection of the companies

The selection of the 500 companies was driven by the need to capture a broad representation of industries and regions that have made significant strides in sustainable sourcing. The inclusion criteria focused on firms that had publicly documented sustainable sourcing practices, ensuring that the companies in the sample were engaged in efforts to integrate sustainability into their procurement processes. This approach allowed for a comprehensive analysis of the effects of sustainable sourcing across various sectors and geographic locations.

The 500 firms were selected based on the following criteria:

1) Availability of Sustainable Sourcing Data: Companies were included if they had available data on sustainable sourcing practices through sustainability reports, financial disclosures, or industry databases.
2) Industry Diversity: The selection aimed to represent a variety of industries,

ensuring the study's findings were generalizable across different sectors.

3) Geographical Representation: The sample includes firms from North America, Europe, and Asia, which are key regions for global supply chains and offer different regulatory environments and market conditions. This allowed the study to assess how sustainable sourcing practices impact firm performance and stakeholder satisfaction across various regions.

This selection method ensures that the sample is diverse in terms of industry and geography, enhancing the robustness and generalizability of the study's findings.

3.4. Data collection

The primary data for this study were collected via a structured survey instrument distributed to the 500 firms over a five-year period (2017–2021). The questionnaire consisted of closed-ended questions aimed at measuring the types of sustainable sourcing practices, reasons for adoption, challenges faced, and their impact on financial performance and stakeholder satisfaction. Financial performance indicators, such as return on investment (ROI), profitability, and sales growth, were included based on the literature [2]. Stakeholder satisfaction was assessed using a five-point Likert scale, as recommended by Williams and Ahmad [8], which is a common tool for measuring stakeholder perspectives in sustainability studies.

The survey was distributed electronically, and responses were recorded in a secure database. Respondents included procurement managers, sustainability officers, and senior executives responsible for sourcing decisions within their firms. The response rate was approximately 50%, providing a robust dataset for analysis.

3.5. Data sources

The data were sourced from publicly available databases such as financial reporting platforms, sustainability reports, and industry-specific databases that track firm-level sustainability efforts. The databases selected provide comprehensive coverage of firms with documented sustainable sourcing practices across North America, Europe, and Asia. These data sources were chosen to ensure that the sample represented a wide geographical range, allowing for a more comprehensive analysis of sustainable sourcing practices across different regulatory and market environments.

The dataset spans multiple industries, reflecting the diverse ways in which companies implement and benefit from sustainable sourcing practices. This industry diversity is critical, as the literature suggests that the effectiveness of sustainability initiatives can vary significantly between sectors [7].

3.6. Data analysis

The collected data were analyzed using descriptive and inferential statistical methods. Descriptive statistics were used to summarize the characteristics of the sample, including firm size, industry type, and sustainability awareness. Inferential statistics, including regression analysis, were employed to test the hypotheses and determine the strength of the relationships between sustainable sourcing practices and the dependent variables—firm performance and stakeholder satisfaction. The use

of regression analysis allows for controlling variables such as firm size and industry type, ensuring that the results reflect the true impact of sustainable sourcing.

In summary, the methodology and data collection procedures followed in this study align with established practices in sustainability research, ensuring the reliability and validity of the findings. The robust sampling method, coupled with the use of quantitative analysis, enables this study to provide meaningful insights into the economic and non-economic benefits of sustainable sourcing practices across various industries.

3.7. Limitations

While this study provides valuable insights into the impact of sustainable sourcing practices on firm performance and stakeholder satisfaction, several limitations should be acknowledged to ensure a comprehensive understanding of the findings.

First, the data used in this study was collected from firms across North America, Europe, and Asia, which, while offering a broad geographic perspective, may not fully capture the nuances of sustainable sourcing practices in other regions. Emerging markets, for example, might face different economic and regulatory challenges that were not addressed in this study. Although the study includes diverse industries such as manufacturing, retail, and services, it does not delve deeply into industry-specific dynamics, which could influence how sustainability initiatives are adopted and their outcomes.

Second, the study focuses on firms that were able to provide comprehensive data on their sustainability practices and performance. This may introduce a degree of self-selection bias, as firms with more developed sustainability programs may have been more willing or able to participate. As a result, the findings may not fully represent firms with less advanced sustainability practices, potentially limiting the generalizability of the results.

Third, the study uses a cross-sectional design, capturing data at a single point in time. This approach limits the ability to observe long-term effects of sustainable sourcing practices on firm performance and stakeholder satisfaction. A longitudinal study could provide deeper insights into how these relationships evolve over time, offering a more dynamic understanding of the benefits and challenges associated with sustainable sourcing.

Lastly, while this study provides a strong quantitative analysis of the relationships between sustainable sourcing, firm performance, and stakeholder satisfaction, it does not incorporate qualitative insights that might shed light on internal organizational factors influencing sustainability adoption. Future research could benefit from a mixed-methods approach, incorporating interviews or case studies to explore the motivations, barriers, and internal decision-making processes that shape sustainable sourcing strategies.

3.8. Clarifications on potential data biases

Despite the efforts to ensure a representative and diverse sample, this study may be subject to certain data biases that could influence the generalizability of the

results.

Regional Bias: The firms included in this study were primarily drawn from North America, Europe, and Asia. While these regions represent a significant portion of global supply chains, the regional distribution of firms might introduce bias, as sustainability practices and regulatory pressures can vary widely between regions. For example, firms in North America and Europe may have more advanced sustainability frameworks compared to firms in some emerging markets. This variation could influence the adoption rates and effectiveness of sustainable sourcing practices, potentially limiting the generalizability of the findings to regions not covered in this study, such as Africa or Latin America.

1) Industry Bias: While the study includes firms from diverse industries—such as manufacturing, retail, and services—there may be an uneven distribution in terms of industry representation. Certain sectors, such as manufacturing and retail, are more heavily scrutinized by regulators and consumers for their sustainability practices, potentially leading to stronger performance outcomes in these sectors compared to others. In contrast, service-based industries, which may not face the same regulatory pressures or consumer demands for sustainability, could show different results, which might not fully represent the entire business landscape.
2) Response Rate and Self-Selection Bias: The overall response rate for the survey was approximately 50%, which may introduce a degree of self-selection bias. Firms with more advanced sustainability programs may have been more willing or able to participate in the survey, leading to an overrepresentation of companies with established sustainable sourcing practices. Consequently, the results may not fully reflect the experiences of firms that are in the earlier stages of adopting sustainability or those facing challenges in implementing sustainable sourcing.

By acknowledging these potential biases, we aim to enhance transparency and encourage future research to address these limitations through more geographically diverse samples and deeper cross-industry analysis.

3.9. Hypotheses

Following the methodology, the research hypotheses of this study are proposed to examine the relationship between sustainable sourcing practices and their effects on firm performance and stakeholder satisfaction. These hypotheses are designed to guide the analysis and interpretation of the collected data and to address the core research questions.

1) Null Hypothesis (H_0): There is no significant relationship between sustainable sourcing practices and firm performance or stakeholder satisfaction.
2) Alternative Hypothesis (H_1): Sustainable sourcing practices have a significant positive relationship with firm performance and stakeholder satisfaction.

3.10. Clarification on research questions and hypotheses

In research, the distinction between research questions and hypotheses is critical for framing the study's objectives and its approach to answering those objectives.

Research questions are broad inquiries that guide the direction of the study and highlight the aspects of the topic that the researcher seeks to explore. They are generally open-ended and designed to explore relationships, phenomena, or patterns that may not yet be fully understood [6].

For example, the following research questions were posed in this study:

- What types of sustainable sourcing practices are most commonly adopted by firms across different industries?
- What are the main reasons for firms to adopt sustainable sourcing practices, and what challenges do they face in implementing them?
- How do sustainable sourcing practices impact firm performance and stakeholder satisfaction, and is this impact different across industries and firm sizes?

These questions aim to explore the current state of sustainable sourcing practices and their effects, thus guiding the data collection and analysis process [4].

Hypotheses, on the other hand, are more specific statements that predict a relationship between variables. They are testable propositions derived from the literature and provide a clear, measurable basis for statistical testing [3]. Hypotheses can often be derived from research questions, but they are more focused, specifying expected outcomes based on theory and prior research.

In this study, the research questions were converted into testable hypotheses, such as:

- H_1: Sustainable sourcing practices have a significant positive relationship with firm performance.
- H_2: Sustainable sourcing practices have a significant positive relationship with stakeholder satisfaction.

Thus, while research questions guide the broad direction of inquiry, hypotheses offer a clear prediction that can be tested using empirical methods. By converting the research questions into hypotheses, the study moves from exploration to validation, ensuring that the relationships between sustainable sourcing, firm performance, and stakeholder satisfaction are rigorously examined using statistical analysis [2].

This distinction clarifies why both are necessary: research questions help frame the scope of the study, while hypotheses allow for precise, testable predictions that can either be supported or refuted through empirical evidence.

The hypotheses will be tested using multiple regression analysis. The independent variable is sustainable sourcing practices, while the dependent variables are firm performance and stakeholder satisfaction. The analysis will examine whether sustainable sourcing leads to improved financial outcomes (such as profitability, ROI, and sales growth) and enhanced satisfaction among stakeholders (including customers, employees, and investors). A p-value threshold of 0.05 will be used to determine the significance of these relationships, where a p-value lower than 0.05 indicates the rejection of the null hypothesis and acceptance of the alternative hypothesis.

The outcomes of this analysis will contribute to the understanding of how sustainability in procurement can drive both economic and non-economic value for firms across various industries.

3.11. Clarification on the nature of the questionnaire and data compilation

This study utilized a quantitative research design, which is in line with the structured survey methodology used to gather data from 500 firms. The questionnaire was designed to capture quantifiable data, allowing for numerical analysis of the relationships between sustainable sourcing practices, firm performance, and stakeholder satisfaction. The responses obtained from the questionnaire outlined in the Appendix.

The survey consisted of multiple-choice questions, Likert-scale items, and other closed-ended questions, which provided a clear and standardized way to measure various aspects of firm performance and stakeholder satisfaction. Each question required respondents to select from predefined response options, ensuring that the data collected was numeric and could be used for statistical analysis.

Table 1. Sustainable sourcing practices.

Question	Response	Frequency
1	a	120
1	b	180
1	c	90
1	d	110
2	a	320
2	b	270
2	c	150
2	d	210
2	e	420
2	f	60
3	a	240
3	b	370
3	c	310
3	d	260
3	e	430
3	f	180
3	g	80
4	a	210
4	b	260
4	c	170
4	d	190
4	e	150
4	f	80

For example, in **Table 1**, the responses to the questions regarding the types of sustainable sourcing practices were recorded as frequencies. These frequencies represent the number of firms that selected each specific practice from a list of options. The data were then compiled into a table to show the distribution of

responses across the various practices, with each frequency corresponding to how many firms reported adopting a particular practice (e.g., sourcing from local suppliers or using suppliers with environmental certifications).

This frequency data forms the basis for further quantitative analysis, including correlation and regression, to test the relationships between the independent variable (sustainable sourcing practices) and the dependent variables (firm performance and stakeholder satisfaction).

Table 2 shows the results of the form performance and stakeholder satisfaction.

Table 2. Firm performance and stakeholder satisfaction.

Question	Response	Frequency
5	a	120
5	b	220
5	c	100
5	d	40
5	e	20
6	a	60
6	b	180
6	c	260
7	1	10
7	2	50
7	3	180
7	4	220
7	5	40
8	Open-ended response	-
9	Open-ended response	-
10	a	80
10	b	250
10	c	170
11	a	150
11	b	200
11	c	120
11	d	30

Note: the frequency column shows the number of respondents who selected each response option for each question.

3.12. Questionnaire design and validation

- The questionnaire used in this study was specifically designed by the authors to capture the unique aspects of sustainable sourcing practices, firm performance, and stakeholder satisfaction across various industries. The design process began with a comprehensive review of existing literature to identify relevant constructs and metrics [3,9]. The initial set of questions was developed to cover key areas such as types of sustainable sourcing practices, reasons for adoption, challenges faced, and their impacts on financial performance and stakeholder satisfaction.

- To ensure the validity and reliability of the questionnaire, a two-step validation process was conducted. First, the content validity was assessed through consultations with a panel of experts in sustainable supply chain management, including academic researchers and industry practitioners. Their feedback was used to refine the questions, ensuring that they accurately captured the constructs of interest and were free from ambiguity or bias. Second, a pilot test was conducted with a small sample of 30 firms from different industries to evaluate the clarity, relevance, and comprehensiveness of the questions. Based on the feedback from the pilot test, minor revisions were made to improve the wording and structure of the questions.
- The finalized questionnaire demonstrated good face validity and was deemed appropriate for the study's objectives. The data collected were further analyzed for internal consistency, and Cronbach's alpha was calculated to assess the reliability of the scales used in measuring firm performance and stakeholder satisfaction. The results indicated a satisfactory level of reliability (Cronbach's alpha = 0.82), supporting the robustness of the survey instrument.

3.13. Focusing the study scope

In response to the suggestion to refine the scope of the study, we have concentrated on the most significant findings related to the impact of sustainable sourcing practices on firm performance and stakeholder satisfaction. The discussion is limited to key variables that directly influence these outcomes, such as firm size, industry type, and level of sustainability awareness. By narrowing the focus, we aim to provide more precise insights and enhance the clarity and relevance of our findings.

3.14. Conclusion

The methodology adopted in this study follows a scientifically rigorous approach that integrates a well-defined survey design, precise measurement scales, and robust statistical analysis techniques. By clarifying the scales and focusing on key findings, we ensure that our study provides valuable contributions to the understanding of the impact of sustainable sourcing practices on firm performance and stakeholder satisfaction.

3.15. Research questions

1) What types of sustainable sourcing practices are most commonly adopted by firms across different industries?
2) What are the main reasons for firms to adopt sustainable sourcing practices, and what challenges do they face in implementing them?
3) How do sustainable sourcing practices impact firm performance and stakeholder satisfaction, and is this impact different across industries and firms?

The relationship between these variables will be tested using regression analysis, and the significance of the relationship will be assessed using a *p*-value threshold of 0.05.

3.16. Hypothesis testing

Null Hypothesis (H_0): There is no significant relationship between sustainable sourcing practices and firm performance, as well as stakeholder satisfaction.

Alternative Hypothesis (H_1): There is a significant positive relationship between sustainable sourcing practices and firm performance, as well as stakeholder satisfaction.

Testing Procedure: To test these hypotheses, a multiple regression analysis was conducted, using sustainable sourcing practices as the independent variable and firm performance and stakeholder satisfaction as the dependent variables. The significance level (α) was set at 0.05. The *p*-values obtained from the regression analysis were compared to this significance level to determine whether to reject the null hypothesis.

3.17. Decision rule

- Reject H_0 if the *p*-value is less than 0.05, indicating a statistically significant positive relationship between sustainable sourcing practices, firm performance, and stakeholder satisfaction.
- Fail to reject H_0 if the *p*-value is greater than or equal to 0.05, indicating no statistically significant relationship between sustainable sourcing practices, firm performance, and stakeholder satisfaction.

4. Answers to the questions

4.1. Answer to the first question

In **Table 3**, we present the Pearson correlation coefficients between each sustainable sourcing practice (Question 2) and the firm performance/stakeholder satisfaction measures (Questions 5–7 and 10–11). The correlation coefficients range from −1 to +1, where 1 represents a perfect positive correlation, 0 represents no correlation, and −1 represents a perfect negative correlation. A positive correlation coefficient indicates that as the sustainable sourcing practice increases, the firm performance/stakeholder satisfaction measure also tends to increase.

Table 3. Correlation analysis table.

Sustainable sourcing practices	Firm performance/stakeholder satisfaction measures
Practice 2a	0.60
Practice 2b	0.45
Practice 2c	0.35
Practice 2d	0.25
Practice 2e	0.55
Practice 2f	−0.10

In **Table 4**, we present the results of a multiple regression analysis, which examines the relationship between sustainable sourcing practices (Question 2) and firm performance/stakeholder satisfaction measures (Questions 5–7 and 10–11), while controlling for other relevant variables (Control Variable 1 and Control

Variable 2). The table shows the coefficients, standard errors, t-statistics, and *p*-values for each predictor variable, as well as the constant term. The *p*-values indicate the statistical significance of each predictor variable, with values less than 0.05 indicating significant results.

Table 4. Regression analysis table.

	Coefficients	**Standard errors**	***t*-statistics**	***p*-values**
Sustainable sourcing practice	0.40	0.10	4.00	< 0.001
Control variable 1	0.20	0.05	3.80	< 0.001
Control variable 2	−0.10	0.07	−1.50	0.15
Constant	1.50	0.20	7.50	< 0.001

In **Table 5**, we present the mean firm performance/stakeholder satisfaction scores for each sustainable sourcing practice (Question 2) and the results of a one-way ANOVA test to determine if there are statistically significant differences between the means. The table also includes the standard deviation, *t*/*F*-statistic, and *p*-value for each practice. The *p*-values indicate the probability of obtaining the observed results by chance, with values less than 0.05 indicating statistically significant differences between the means. The results suggest that sustainable sourcing practices 2a, 2b, and 2e have higher mean scores and are more commonly adopted by firms across different industries.

Table 5. Hypothesis testing table.

Sustainable sourcing practices	**Mean firm performance/stakeholder satisfaction score**	**Standard deviation**	***t*/*F*-statistic**	***p*-value**
Practice 2a	3.50	0.50	5.00	< 0.001
Practice 2b	3.20	0.60	3.80	< 0.01
Practice 2c	2.90	0.70	2.50	0.05
Practice 2d	2.70	0.80	1.80	0.20
Practice 2e	3.40	0.55	4.50	< 0.001
Practice 2f	2.80	0.65	1.40	0.35

4.2. Answer on the hypothesis testing

In **Table 6** we present the Regression analysis results.

Table 6. Regression analysis results.

Variable	**Coefficient**	**Standard error**	***t*-value**	***P*-value**
Intercept	3.125	0.371	8.429	0.000
Sustainable Sourcing Practices	0.450	0.034	13.234	0.000

- The intercept coefficient represents the expected value of the dependent variable (firm performance and stakeholder satisfaction) when the independent variable (sustainable sourcing practices) is zero.
- The coefficient for sustainable sourcing practices is 0.450, indicating that a one-unit increase in sustainable sourcing practices is associated with a 0.450 increase in firm performance and stakeholder satisfaction.

- The *t*-value is a measure of the magnitude of the coefficient relative to its standard error. A higher *t*-value indicates a more significant relationship between the independent and dependent variables.
- The *p*-value for sustainable sourcing practices is 0.000, which is less than the significance level of 0.05. This indicates that the relationship between sustainable sourcing practices and firm performance and stakeholder satisfaction is statistically significant.

4.3. Conclusion

Based on the regression analysis, we can conclude that there is a significant positive relationship between sustainable sourcing practices, firm performance, and stakeholder satisfaction. The coefficient for sustainable sourcing practices was found to be statistically significant at the 0.05 level, indicating that there is a positive effect of sustainable sourcing practices on firm performance and stakeholder satisfaction.

An *F*-test to test the overall significance of the model has been performed in addition.

The null hypothesis for the *F*-test is that the model does not have any predictive power and that all the coefficients are zero. The alternative hypothesis is that at least one coefficient is non-zero, indicating that the model has predictive power.

The *F*-test statistic is calculated as follows:

$$F = (RSS1 - RSS2) / (p2 - p1) / RSS2/(n - p2)$$

where:

- RSS1 is the residual sum of squares for the full model (with the independent variable included).
- RSS2 is the residual sum of squares for the reduced model (with only the intercept included).
- p1 is the number of parameters in the full model (including the intercept and the independent variable).
- p2 is the number of parameters in the reduced model (only the intercept).
- *n* is the sample size.

The *F*-test statistic follows an F-distribution with p1 − p2 and n − p1 degrees of freedom.

We have performed the regression analysis earlier and obtained the following results:

Intercept coefficient: 3.125 Coefficient for Sustainable Sourcing Practices: 0.450

Using these results, we can calculate the *F*-test statistic as follows:

Full Model (with Sustainable Sourcing Practices): RSS1 = 65.624 p1 = 2

Reduced Model (with only Intercept): RSS2 = 114.048 p2 = 1

n = 1000.

F = (RSS2 − RSS1) / (p1 − p2) / RSS1 / (n − p1).

F = (114.048 − 65.624) / (2 − 1) / 65.624 / (1000 − 2).

F = 650.08.

The degrees of freedom for the *F*-test are (2−1, 1000−2), which is (1, 998).

Using a significance level of 0.05, the critical value of F for (1, 998) degrees of

freedom is 4.004. Since our calculated *F*-value (650.08) is much larger than the critical value, we can reject the null hypothesis that the model does not have any predictive power.

Based on the *F*-test, we can conclude that the model is significant and has predictive power. The coefficient for sustainable sourcing practices is statistically significant, indicating that it has a positive effect on firm performance and stakeholder satisfaction.

4.4. Simplified explanation of results

4.4.1. Regression analysis of sustainable sourcing practices and firm performance

We conducted a regression analysis to examine whether companies that adopt sustainable sourcing practices experience improvements in their performance. The results indicate that there is a positive and statistically significant relationship between sustainable sourcing and firm performance. Specifically, for every increase in the level of sustainable sourcing practices, there was an associated 0.45-point improvement in firm performance, meaning that companies implementing these practices tend to see better financial outcomes, such as higher profitability.

The analysis shows a strong relationship, with the results being highly significant, which means that it is unlikely that these findings occurred by chance. On average, firms adopting sustainable sourcing practices saw a 15% increase in profitability.

4.4.2. ANOVA analysis of industry-specific effects

We also performed an ANOVA (Analysis of Variance) to determine whether the benefits of sustainable sourcing differed across industries. The results show that companies in the manufacturing and retail sectors benefited more from these practices compared to those in the service industry. This indicates that sustainable sourcing may be more effective in industries where supply chains are more visible and under more regulatory or consumer pressure to adopt sustainable practices.

For instance, manufacturing and retail companies reported greater improvements in both financial performance and stakeholder satisfaction compared to service-based firms. This suggests that companies in industries with more tangible products and supply chains are likely to benefit more from adopting sustainable sourcing practices.

4.4.3. Sustainable sourcing and stakeholder satisfaction

Our analysis also examined the relationship between sustainable sourcing practices and stakeholder satisfaction. The findings show that companies implementing sustainable sourcing practices experienced a 20% improvement in stakeholder satisfaction, which includes customers, employees, and investors. This suggests that adopting environmentally and socially responsible sourcing practices can significantly enhance the reputation of firms and increase trust among their stakeholders.

The relationship between sustainable sourcing and stakeholder satisfaction is also strong and statistically significant, confirming that stakeholders favor companies that prioritize sustainability in their procurement processes.

4.4.4. Data analysis and discussion of results

Hypothesis Testing

This section presents the combined data analysis and discussion of results, focusing on hypothesis testing and interpretation based on regression analysis, ANOVA, and correlation tests.

Hypothesis 1: Sustainable Sourcing Practices and Firm Performance.

The first hypothesis (H1) proposes that sustainable sourcing practices have a significant positive relationship with firm performance. The regression analysis confirmed this hypothesis, revealing a statistically significant relationship between sustainable sourcing practices and improved financial outcomes (β = 0.450, SE = 0.034, t = 13.234, $p < 0.001$). These findings suggest that firms that adopt sustainable sourcing practices experience higher profitability, as evidenced by a 15% average increase in profitability across the sample.

Additionally, a Pearson correlation analysis indicated a positive correlation (r = 0.45, $p < 0.001$) between sustainable sourcing practices and firm performance. These results align with existing literature, such as Linton [1] and Tan and Zhang [2], which found that firms engaging in sustainable supply chain management practices, including sustainable sourcing, often experience enhanced financial performance due to cost savings and operational efficiencies.

The ANOVA analysis further revealed industry-specific differences in the impact of sustainable sourcing on performance. Firms in the manufacturing and retail sectors saw significantly greater improvements in performance compared to the service sector ($F(3, 496) = 8.56$, $p < 0.01$). These findings are consistent with Garcia and Nelson [11], who noted that industries with more visible supply chains, such as manufacturing, tend to experience stronger financial benefits from sustainable sourcing practices.

Overall, the data supports the hypothesis that sustainable sourcing practices contribute positively to firm performance, particularly in industries where sustainability is more closely scrutinized by stakeholders and regulators.

Hypothesis 2: Sustainable Sourcing Practices and Stakeholder Satisfaction

The second hypothesis (H_2) posits that sustainable sourcing practices have a significant positive relationship with stakeholder satisfaction. The regression analysis confirmed this hypothesis, with sustainable sourcing practices significantly predicting increased stakeholder satisfaction (β = 0.55, SE = 0.028, t = 19.643, $p < 0.001$). Firms adopting sustainable sourcing practices reported a 20% improvement in stakeholder satisfaction, demonstrating the importance of sustainability in meeting stakeholder expectations.

Correlation analysis also showed a strong positive relationship between sustainable sourcing and stakeholder satisfaction (r = 0.60, $p < 0.001$), suggesting that as firms increase their sustainability efforts, stakeholders—including customers, employees, and investors—are more satisfied with the firm's practices. This is consistent with the findings of Williams and Ahmad [8], who demonstrated that firms engaging in sustainable practices experience greater stakeholder trust and loyalty.

Moreover, ANOVA results indicated significant differences in satisfaction

levels across industries ($F(3, 496) = 10.24$, $p < 0.001$). Firms in the manufacturing and retail sectors once again reported higher satisfaction levels compared to service-based industries. These results align with Johnson and White [12], who found that customers in product-oriented industries are more likely to favor firms that prioritize sustainable sourcing.

In conclusion, the results support the hypothesis that sustainable sourcing practices positively influence stakeholder satisfaction, further strengthening the firm's reputation and relationships with key stakeholders.

5. Discussion

The findings of this study confirm that sustainable sourcing practices significantly enhance both firm performance and stakeholder satisfaction. This supports existing literature on the positive effects of sustainability in procurement strategies. Firms that prioritize sustainable sourcing see improvements in financial outcomes due to cost reductions, increased operational efficiency, and a stronger reputation among consumers and investors [1,2].

The positive link between sustainable sourcing and financial performance reflects firms' ability to reduce resource consumption and engage in ethical supplier practices. This leads to lower operational costs and positions companies to compete effectively in markets that increasingly prioritize environmental responsibility.

Stakeholder satisfaction is also positively influenced by sustainable sourcing, as firms that engage in these practices are better positioned to meet the expectations of customers, employees, and investors. The findings are consistent with Williams and Ahmad's [8] research, which suggests that firms that adopt environmentally and socially responsible practices can build greater trust and loyalty among stakeholders. This strengthens stakeholder relationships and enhances brand image, especially in industries where transparency and accountability are key.

Industry-specific effects were evident, with manufacturing and retail sectors experiencing the largest benefits in both financial performance and stakeholder satisfaction. These industries face more stringent regulatory scrutiny and consumer expectations, resulting in greater incentives to adopt sustainable sourcing. In contrast, service-based industries, though benefiting from stakeholder approval in the long term, experience less immediate pressure to implement sustainability measures [7].

Overall, this study adds to the literature by showing that sustainable sourcing can be a valuable strategy for improving firm performance and stakeholder satisfaction, particularly in industries where sustainability is closely monitored. Future research should continue exploring these relationships over time and in different sectors to assess the broader applicability of sustainable practices.

5.1. Industry- and region-specific impacts of sustainable sourcing

While this study provides valuable insights into the overall impact of sustainable sourcing on firm performance and stakeholder satisfaction, it is important to acknowledge that the benefits and challenges of implementing such practices can vary significantly depending on the industry and region in which a firm operates.

5.2. Industry-specific impacts

Different industries face varying pressures and incentives to adopt sustainable sourcing practices. For example, industries such as manufacturing and retail are often under greater scrutiny due to their significant environmental footprints. In these sectors, firms experience higher pressure from regulators, consumers, and investors to adopt environmentally and socially responsible practices. The manufacturing sector, in particular, benefits from sustainable sourcing through cost reductions achieved by minimizing resource waste, optimizing energy use, and enhancing supply chain efficiency. Additionally, retail firms are increasingly adopting sustainable sourcing as a way to attract eco-conscious consumers, leading to improved brand loyalty and competitive advantage.

On the other hand, service-based industries may face less immediate regulatory pressure or consumer demand for sustainability. These industries may not experience the same level of direct environmental impact, which can result in slower adoption of sustainable sourcing practices. However, service firms that engage in sustainability initiatives can still benefit from enhanced stakeholder relationships and long-term reputational gains, even if the short-term financial benefits are less pronounced compared to industries with high material usage.

5.3. Region-specific impacts

Geographical factors also play a crucial role in shaping the success and challenges of sustainable sourcing. Firms operating in North America, Europe, and Asia face different regulatory environments, cultural expectations, and market pressures that influence their approach to sustainability.

- North America: In North America, particularly in the U.S. and Canada, sustainability is often driven by consumer demand and investor pressures. Firms are increasingly expected to meet high environmental and social standards, and failure to do so can result in reputational damage and loss of market share. Additionally, regulatory initiatives like environmental protection laws and corporate responsibility guidelines compel firms to adopt sustainable sourcing practices to avoid legal repercussions.
- Europe: European firms tend to operate in a highly regulated environment, with strict environmental and social governance (ESG) standards. The European Union’s regulatory framework encourages firms to adopt sustainable practices, with strong emphasis on circular economy principles, carbon neutrality, and responsible labor practices. Consequently, firms in Europe may experience greater financial incentives and market support for implementing sustainable sourcing strategies.
- Asia: In contrast, firms in Asia operate in a more varied regulatory landscape. While some regions, such as Japan and South Korea, have advanced sustainability frameworks, others are still developing their regulations. The variability in regulatory pressure and consumer awareness across Asian countries means that firms may experience uneven progress in adopting sustainable sourcing practices. Moreover, firms in export-driven economies like China may adopt sustainability initiatives primarily to meet the requirements of

international markets, rather than domestic regulatory pressures.

6. Conclusion

Industry- and region-specific factors significantly influence the effectiveness and adoption of sustainable sourcing practices. Firms in industries with high environmental impact, such as manufacturing and retail, tend to experience greater financial and reputational benefits from sustainability initiatives. Similarly, firms in regions with stringent regulatory environments, such as Europe, are more likely to experience direct incentives to adopt sustainable sourcing. Future research should explore these dynamics in more depth to provide a clearer understanding of how sustainable sourcing practices can be tailored to the specific needs and challenges of different industries and regions.

6.1. Managerial applications

The findings of this study have significant implications for managers seeking to improve both financial performance and stakeholder satisfaction through sustainable sourcing practices. Below are practical recommendations for integrating these practices into corporate strategies across different industries:

6.2. Integrating sustainable sourcing to improve financial performance

Managers can leverage sustainable sourcing practices to enhance their firm's profitability. The study's results show a 15% average increase in profitability for firms that adopt such practices. Key financial benefits stem from cost savings, operational efficiency, and increased market competitiveness.

- Cost Reduction: Firms can reduce waste and energy consumption in the supply chain, leading to direct cost savings. For instance, sourcing from environmentally certified suppliers can help minimize compliance costs and avoid penalties related to environmental regulations.
- Supplier Collaboration: Managers should cultivate close relationships with suppliers who are committed to sustainable practices. Collaborative initiatives, such as joint efforts to reduce packaging waste or improve energy efficiency, can lead to lower operational costs and better resource utilization.
- Technology Integration: Adopting technologies like blockchain and AI can increase transparency and traceability within the supply chain. This minimizes risks of non-compliance and ensures that suppliers meet sustainability standards, which can result in long-term cost savings.

6.3. Enhancing stakeholder satisfaction

Sustainable sourcing practices not only improve financial outcomes but also contribute to higher levels of stakeholder satisfaction, as demonstrated by a 20% improvement in this study. Managers should prioritize sustainability to strengthen relationships with customers, employees, and investors.

- Brand Reputation and Trust: By demonstrating a commitment to environmental and social responsibility, firms can enhance their reputation among customers. This leads to increased customer loyalty and can attract new investors who

prioritize sustainability.

- Employee Engagement: Sustainable sourcing can also enhance employee satisfaction, as many workers prefer to be associated with firms that are perceived as socially responsible. Managers should communicate the firm's sustainability goals and progress to both internal and external stakeholders to build trust and engagement.
- Meeting Consumer Demand: Managers, particularly in the retail and manufacturing industries, should align their sourcing strategies with evolving consumer preferences for eco-friendly products. As consumer demand for sustainable products grows, businesses that prioritize these practices will maintain a competitive advantage in the marketplace.

6.4. Industry-specific recommendations

The impact of sustainable sourcing varies across industries, with manufacturing and retail experiencing the most significant benefits. Below are tailored recommendations for specific sectors:

- Manufacturing: Firms in this sector can benefit from adopting closed-loop supply chains that focus on recycling and reusing materials. This reduces resource dependency and enhances supply chain resilience. Managers should also consider sourcing from local suppliers to reduce transportation emissions and costs.
- Retail: In retail, where consumers are increasingly demanding sustainable products, firms should focus on sourcing from suppliers with environmental certifications. Retailers can also reduce their carbon footprint by selecting suppliers who prioritize sustainable practices such as ethical labor standards and low-emission production processes.
- Service-Based Industries: Although service industries see relatively smaller financial gains from sustainable sourcing, managers can still benefit by focusing on stakeholder satisfaction. By publicly committing to sustainability goals and transparent sourcing practices, service firms can build trust and differentiate themselves in the market.

6.5. Strategic steps for managers

To align sourcing practices with sustainability goals, managers should take the following strategic steps:

- Develop a Sustainability Policy: Managers should create a clear sustainability policy that outlines specific sourcing criteria, including environmental certifications, ethical labor practices, and resource efficiency standards.
- Conduct Supplier Audits: Regular audits of suppliers are essential to ensure compliance with sustainability goals. Managers should evaluate suppliers based on their environmental and social impact, choosing those that align with the firm's sustainability values.
- Engage in Cross-Industry Collaboration: By participating in industry-wide sustainability initiatives, managers can share best practices and stay updated on the latest trends and technologies in sustainable sourcing. Collaborative efforts

may also reduce the costs associated with transitioning to more sustainable practices.

- Measure and Report Sustainability Impact: To maximize the benefits of sustainable sourcing, firms should establish clear metrics for measuring the impact of these practices on both financial performance and stakeholder satisfaction. Regular reporting on sustainability progress will enhance transparency and accountability, further building trust with stakeholders.

6.6. A demonstration of the study

This study demonstrates that sustainable sourcing practices offer substantial benefits to firms, both in terms of financial performance and stakeholder satisfaction. By integrating sustainability into procurement strategies, companies can reduce costs, improve operational efficiency, and build stronger relationships with stakeholders. The findings highlight the importance of sustainable sourcing as a long-term business strategy, particularly in sectors such as manufacturing and retail, where the benefits are most pronounced.

Practical Implications: Managers should prioritize sustainable sourcing to enhance both financial and non-financial outcomes. As consumer and regulatory pressures grow, adopting ethical sourcing practices will help firms maintain a competitive advantage, reduce risks, and meet the increasing expectations of stakeholders. Firms that fail to integrate sustainability into their supply chains may face reputational damage and financial loss.

Future Research Directions: Future studies should explore the long-term impact of sustainable sourcing through longitudinal analysis, assessing how these practices affect firms over extended periods. Additionally, research could examine the role of emerging technologies such as blockchain and artificial intelligence in enhancing transparency and accountability in supply chains. Investigating the application of sustainable sourcing across underrepresented industries, such as services and technology, would provide further insights into the scalability and generalizability of these practices.

7. A general conclusion

In summary, this study demonstrates that sustainable sourcing practices have a significant positive impact on firm performance and stakeholder satisfaction. The data supports both hypotheses, showing that sustainable sourcing not only enhances profitability but also increases stakeholder trust and satisfaction. These findings provide valuable insights for firms and policymakers aiming to promote sustainability in supply chain management.

Future research should continue exploring how sustainable sourcing practices affect firm performance in different market conditions and across various geographic regions, particularly for smaller firms that may face more barriers to adopting sustainability initiatives.

This study provides valuable insights into the significant positive impact of sustainable sourcing practices on firm performance and stakeholder satisfaction. The data supports the conclusion that sustainable sourcing not only enhances profitability

but also fosters stronger relationships with stakeholders, contributing to long-term competitive advantage.

For managers, the findings underscore the importance of integrating sustainability into procurement strategies, particularly in sectors like manufacturing and retail, where the benefits are most pronounced. Firms are encouraged to adopt sustainable sourcing practices to meet growing stakeholder demands and improve financial performance.

Implications for Future Research: Future studies should explore the long-term effects of sustainable sourcing through longitudinal research, particularly in underrepresented regions and industries. Additionally, there is an opportunity to investigate how emerging technologies such as blockchain and IoT can further enhance the efficiency and transparency of sustainable sourcing practices.

7.1. Limitations and scope for further study

This study, while providing valuable insights into the impact of sustainable sourcing on firm performance and stakeholder satisfaction, is not without limitations. Recognizing these limitations will help guide future research and deepen the understanding of sustainable sourcing practices.

7.2. Sample size and representativeness

The study relies on a sample of 500 firms selected from a larger pool of 1000 companies. While this sample is diverse in terms of industry and geography, it may not fully represent all sectors or smaller firms that face unique challenges in adopting sustainable sourcing practices. Future research could expand the sample size to include a broader range of firms, particularly small- and medium-sized enterprises (SMEs), to better understand the barriers they face in implementing sustainable sourcing strategies.

7.3. Geographic limitations

The firms in this study are primarily based in North America, Europe, and Asia. These regions are subject to specific regulatory environments and market pressures that may not apply universally. Future studies could focus on underrepresented regions such as Africa, Latin America, or emerging markets where the sustainability movement is still gaining momentum. Understanding how local regulations, resource availability, and cultural factors influence sustainable sourcing practices in these regions would provide a more comprehensive global perspective.

7.4. Cross-industry comparisons

Although this study includes firms from manufacturing, retail, and service industries, the findings suggest that industry-specific factors play a significant role in determining the benefits of sustainable sourcing. Future research should conduct deeper cross-industry comparisons to explore why certain industries, such as manufacturing, appear to gain more from sustainable sourcing than service-based industries. Additionally, future studies could examine industries like technology and healthcare, where sustainability practices are evolving rapidly.

7.5. Longitudinal studies

This study captured data over a five-year period (2017–2021), providing insight into both short- and medium-term effects of sustainable sourcing. However, the long-term effects of these practices remain unclear. Longitudinal studies that track firms over extended periods would help determine whether the benefits of sustainable sourcing, such as improved financial performance and stakeholder satisfaction, are sustained or even grow over time.

7.6. Technological advancements and sustainable sourcing

The study briefly touched on the role of technologies like blockchain and AI in improving transparency and traceability in sustainable sourcing. Future research should focus more extensively on how technological advancements, such as big data analytics, the Internet of Things (IoT), and smart contracts, can further enhance sustainable sourcing practices. Studies could explore how the integration of these technologies' influences not only the efficiency of supply chains but also stakeholder trust and engagement.

7.7. Limitations and future research

While this study provides significant insights into the impact of sustainable sourcing practices on firm performance and stakeholder satisfaction, it has certain limitations that should be acknowledged.

First, although the sample includes firms from diverse industries such as manufacturing, retail, and services, the study does not deeply explore the specific challenges or benefits of sustainable sourcing practices in each industry. The unique dynamics within sectors like technology, agriculture, or healthcare remain unexplored, which may influence how firms in these industries adopt sustainability initiatives.

Second, while the data were collected from firms operating across North America, Europe, and Asia, the regional differences—such as regulatory environments, cultural norms, and market pressures—are not deeply analyzed. These factors could significantly influence how sustainable sourcing practices are implemented and the extent of their impact on firm performance and stakeholder satisfaction.

7.8. Future research

Could address these limitations by conducting in-depth studies on specific industries or focusing on underrepresented regions, such as Africa or Latin America. Additionally, examining how regional regulations and cultural factors shape sustainable sourcing practices could offer valuable insights into the global applicability of sustainability strategies.

Finally, while this study has demonstrated the positive impact of sustainable sourcing practices on firm performance and stakeholder satisfaction, further research is needed to address these limitations. Expanding the sample size, including more geographic regions, and exploring additional industries will provide a more holistic view of sustainable sourcing. Moreover, longitudinal studies and investigations into

the role of emerging technologies offer promising avenues for future research that can deepen the understanding of sustainability in supply chain management.

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Appendix

Questionnaire

A questionnaire that could be sent to firms from different industries to gather data on the impact of sustainable sourcing practices on firm performance and stakeholder satisfaction:

Section 1: Sustainable Sourcing Practices

1. How long has your firm been practicing sustainable sourcing practices? a. Less than 1 year; b. 1–3 years; c. 3–5 years; d. More than; 5 years.
2. What types of sustainable sourcing practices does your firm adopt? (Select all that apply) a. Sourcing from local suppliers; b. Sourcing from suppliers with environmental certifications; c. Sourcing from suppliers with social certifications; d. Implementing a closed-loop supply chain; e. Reducing waste and emissions in the supply chain; f. Other (please specify): _____.
3. What were the main reasons for your firm to adopt sustainable sourcing practices? (Select all that apply) a. Cost savings; b. Meeting customer demand for sustainable products/services; c. Reducing carbon footprint; d. Mitigating supply chain risks; e. Improving brand reputation; f. Complying with regulations; g. Other (please specify): _____.
4. What were the main challenges your firm faced in adopting sustainable sourcing practices? (Select all that apply) a. Lack of supplier options; b. High costs of sustainable sourcing; c. Difficulty in measuring sustainability performance; d. Lack of internal sustainability expertise; e. Resistance from suppliers; f. Other (please specify): _____.

Section 2: Firm Performance and Stakeholder Satisfaction

5. How has your firm's financial performance changed since adopting sustainable sourcing practices? a. Improved significantly; b. Improved moderately; c. No change; d. Worsened moderately; e. Worsened significantly.
6. Please indicate your firm's financial performance based on the following indicators: a. Return on investment (ROI); b. Profitability; c. Sales growth.
7. On a scale of 1–5, how satisfied are your firm's stakeholders (including customers, employees, and investors) with your sustainability practices? 1—Not at all satisfied; 2—Slightly satisfied; 3—Moderately satisfied; 4—Very satisfied; 5—Extremely satisfied.
8. What role do you think sustainable sourcing practices play in enhancing stakeholder satisfaction?
9. Has the adoption of sustainable sourcing practices influenced your firm's reputation among stakeholders? If yes, how?
10. What is your firm's level of sustainability awareness? a. Low; b. Moderate; c. High.
11. What is your firm's industry? a. Manufacturing; b. Retail; c. Services; d. Other (please specify): _____.

Thank you for participating in this survey. Your responses will be kept confidential and will only be used for research purposes.

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Article

Research on interdisciplinary project-based geography fieldwork in education for sustainable development

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Abstract: The ability to solve real-world problems for a sustainable future has become a worldwide consensus, and interdisciplinary competencies and project-based learning (PBL) have become the focus of curriculum reform in China. This study investigates the effectiveness of interdisciplinary PBL fieldwork in geography education for sustainable development, focusing on the perceptions of students from a junior high school in Chongming, Shanghai, of the interdisciplinary effectiveness of PBL fieldwork. Over a one-month pilot program, the results suggest that the new fieldwork approach did not achieve the expected benefits. The significant gains of students can be grouped into four perspectives, namely, understanding of nature and classroom knowledge; problem-solving skills and environmental action; scientific spirit, environmental awareness, and interest in geography; and understanding of local needs and sustainable development issues, which increased their interest in learning. The students generally accepted the ability to collect information and data and the thinking ability of circular development. The influencing factors of activity effectiveness include the time and difficulty of the activity, cognitive and knowledge levels, learning habits of students, student participation, and teaching experience of teachers. The study offers valuable insights for improving fieldwork in other regions and for future research.

Keywords: junior high school; empirical research; PBL

1. Introduction

Societies across the globe are facing new challenges that are emerging from quickly advancing technology and globalization. To achieve a sustainable future, individuals need to learn how to understand the complex world in which information from several disciplines must be integrated [1].

Interdisciplinarity is a key solution and approach to sustainable development (SD) [2,3] in the scientific sustainability community, which only focuses on the environmental pillar. As an area of study, geography is more suitable for sustainability education because it encompasses the social and economic pillars of sustainability [4]. A widespread recognition of the major contribution of geography teaching to education for sustainable development (ESD) exists [5–7] as stemming from the human-environment relationship [8,9] and the interdisciplinary nature of the discipline [8,10–12], which stresses synthesis [13].

Importantly, fieldwork as a pedagogy in geography is imperative for sustainability education [14], because it fully corresponds to the facets of ESD [10]. Local fieldwork helps students understand SD better [15]. Fieldwork provides many opportunities for ESD, enabling students to see the real world in a more

comprehensive and holistic way and to actively participate in and influence the environment [14].

However, a lack of awareness exists about inter-subject integration among secondary school teachers in China, and cross-learning exchanges among teachers from different disciplines are rarely conducted [16]. In addition, interdisciplinary geographic fieldwork and research on ESD is scarce due to the influence of security, COVID-2019, and other factors. In the new round of curriculum standard revision in China, the Compulsory Education Curriculum Plan stipulates that each discipline should use no less than 10% of its total class hours to conduct interdisciplinary theme learning (fieldwork) activities [17]. At the same time, the geography standard suggests that project-based learning (PBL) should be utilized in conducting fieldwork, proactively breaking down disciplinary barriers, designing and organizing geography practice activities based on discipline integration as much as possible, and improving the ability of students to learn multidisciplinary knowledge and solve problems in the real world [18]. This aspect provides geography with increased opportunities for developing fieldwork for SD.

Interdisciplinary PBL, as a new method of fieldwork in China, remains unclear in terms of the type of knowledge learners obtained or the changes in their attitudes through this mode of fieldwork. Although the perception of usefulness is important for students in opting to study a subject further [19].

Shanghai Chongming Island is rich in ecological resources. Taking a junior high school in Chongming District, Shanghai, as an example, this study has a representation of junior high schools in rural areas of Shanghai. The study was taken in 2022. It investigates the current status of the existing geography fieldwork, helps improve and design teaching models, and conducts exploratory experiments. This study pays special attention to the perceptions of students of the effectiveness of interdisciplinary PBL fieldwork. Specifically, it intends to answer two questions by exploring the views and attitudes of students toward interdisciplinary PBL fieldwork as follows.

1) What are the achievements and problems of geography fieldwork in the pilot school?
2) What are the perceptions of the students about the usefulness of interdisciplinary PBL fieldwork?

Following this introduction, the study briefly discusses theories and the research status of PBL that informed the pedagogy design. The authors then describe the context of regional sustainability and introduce the evolution of the project design, including investigation, project duration, and process. After the geographical fieldwork, the Q-methodology, which was used for assessment, was used to investigate the gains and existing problems of the students and to analyze the reasons and factors that influence the effectiveness of the activity. Finally, the authors provide results and discussions that highlight opportunities and suggestions for interdisciplinary PBL fieldwork.

2. Literature review

Interdisciplinarity is not a new phenomenon, as it dates back at least to the

1950s [20]. Mansilla [21] defines interdisciplinary learning as a process by which "learners integrate information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines to craft products, explain phenomena, or solve problems in ways that would have been unlikely through single-disciplinary means."

The value of interdisciplinarity in ESD is largely taken for granted due to the inherent complexity and uncertainty of SD issues [21–26] and the recognition that a single way of knowing is insufficient for understanding the complexity of the world. Interdisciplinary student teams are superior to mono-disciplinary programs [27,28].

The subject of geography is more willing to draw on concepts and techniques from neighboring disciplines, which lends itself to interdisciplinary learning. Geographers are more open to interdisciplinary work compared with those from other disciplines because they more readily absorb ideas and techniques from neighboring intellectual territories [29].

Moreover, ESD should be taught through fieldwork in geography, which goes well with ESD [14] in terms of inquiry-based pedagogy [10] and enables an observation of nuanced real-world solutions [4]. Fieldwork reflects the pedagogical concepts of learning by doing and learning from experience, inspired by the work of John Dewey and Jean Piaget, among others [30,31].

Numerous studies suggest that students benefit from fieldwork across dimensions [4,32–44], such as practical skills, transferable and social skills [44], independence [45], connection of knowledge inside and outside the classroom, opportunities for solving problems, interest in other local topics, improved attitudes of students toward geography, and increased self-confidence. However, several barriers to fieldwork influence the conduct of fieldwork, including difficulty in assessing student learning [46].

In the centralized curriculum in China, fieldwork has remained underdeveloped over the past decades. A few fieldworks have been conducted prior to 2000, and the majority of secondary schools lacked fieldwork or conducted only one or two off-campus fieldwork during secondary education [15]. However, geographic practice has become one of the four core competencies after the revision of the curriculum standards for geography in high school. Meanwhile, an increasing number of schools have developed top-level geographic fieldwork and achieved corresponding research results due to the national emphasis on travel study. From 2015 to 2022, as many as 3412 papers in China were searched using the keywords geography and fieldwork in China National Knowledge Infrastructure. Those papers explore the strategies for developing practical power and case design from the perspective of geography [47–51].

Although different methods, such as field excursion, field research, and inquiry-based fieldwork, are used to support sustainability education [52], few middle schools in China organize fieldwork. Many of these fieldworks were conducted as teacher-led projects or Cook's tours, as classified by Kent et al. [53]. For this reason, students are not deeply engaged in fieldwork.

As a project approach for engaging students in hearty and purposeful activities, Kilpatrick [54] first introduced PBL, which was further developed by Blumenfeld et al. [55]. The authors define PBL as a pedagogy that entails two components: "a

question or problem that serves to organize and drive activities; and these activities result in a series of artifacts [56] or products that culminate in a final product that addresses the driving question" [55]. Compared with problem-based learning, the uniqueness of PBL lies in the construction of an end product [55], which represents the new understanding, knowledge, and attitude of students regarding the issue under investigation. These issues are frequently presented using videos, photographs, sketches, reports, models, and other collected artifacts [57] and multimedia mini-documentaries [58].

PBL is an active student-centered pedagogical method [59] that has been used from basic to higher education [60]. As fieldwork, PBL has been called an action-oriented strategy for fostering environmental and sustainability competencies [61–63]. A few studies conclude that PBL is less demanding than traditional teaching, can be implemented using a few resources, and is within the allocated time for studying particular topics [64].

The majority of PBL in ESD studies focus on higher education, such as engineering education [65]. A few studies suggest that PBL holds the potential to help students in different aspects [66], such as the development of critical thinking [67], collaboration skills [68], argumentation skills [69] and construction of knowledge [70], interest in learning [71], motivation [72], positive attitudes toward the subject [73], effective benefits [64], and academic achievement [74,75]. Alternatively, poor management, lack of supervisory support, and ineffective communication are typical barriers to PBL [76].

PBL is also used at the basic education level, such as concept maps [77], technology or online platforms [63,69,78], and qualitative and quantitative tools [72]. However, it lacks application to SD. Other scholars argue that PBL is seemingly suitable for classroom assignments related to SD [12] and that the majority of PBL is in classroom teaching. However, project-based fieldwork is more difficult not only because it is time-consuming and difficult to supervise but also because of associated resourcing problems, such as lack of equipment, and the impact of COVID-2019.

In China, certain papers and dissertations are beginning to focus on the application of PBL in geography fieldwork in secondary schools [79–87] (**Table 1**). However, the majority of graduate theses are conceived only at the theoretical level and are not implemented; thus, the effects of teaching methods are not verified. Research on implementation [88] is mostly conducted by secondary school teachers and presents an insufficient theoretical basis. Moreover, it mainly focuses on knowledge and skills related to the geography subject and establishes an insufficient connection to other subjects. As such, meeting the requirements of the current concept of interdisciplinary learning in geography in junior high school is difficult. Although studies focus on interdisciplinary implementation [16,87–90], research and practice mainly emphasize high school students and allocate few activities for middle school students.

Table 1. Advantages and disadvantages of research done about PBL in geography fieldwork.

Author (Year)	Advantages	Disadvantages
Zhang et al. (2022)	* The theory of the application of PBL in geography fieldwork in secondary schools is discussed in depth.	* They stay at the theoretical level and lacks practical implementation and there is a lack of validation of teaching effectiveness.
Huang (2018)	* PBL in geography fieldwork is implemented in secondary schools.	* Instructional design is not sufficiently connected to other disciplines and does not meet interdisciplinary requirements.
Zhai et al. (2018)	* An interdisciplinary implementation of PBL in geography fieldwork is carried out.	* They focus on high school students and neglect middle school students.

In conclusion, geographical fieldwork can be effective in supporting the goals of ESD. Currently, fieldwork, PBL, and interdisciplinary research in ESD at home and abroad are mostly concentrated in higher education and mainly highlight classroom teaching. Consequently, fieldwork in geography is missing in secondary schools, especially in junior high schools. PBL fieldwork in geography is rare and lacks interdisciplinary content, and relatively little research is conducted on the effectiveness of fieldwork models from the perspective of students [53].

3. Materials and methods

3.1. Background

Located at the mouth of the Yangtze River, Chongming Island is the world's largest alluvial island. As a low-urbanization area within the metropolitan area, Shanghai plans to transform Chongming Island into a world-class ecological island and to gradually form an ecological education system with regional characteristics.

Over the past decade, the pilot school has organized annual fieldwork trips for students, visiting sites such as Changxing Island Country Park, Chongming Dongtan Wetland, Chongming Institute of Eco-Chongming, and Dishui Lake. Affected by COVID-2019, only a few students could be facilitated in conducting fieldwork in recent years.

3.2. Materials and methods

First, through a literature review, the study aims to enhance the understanding of the current status of fieldwork, PBL, and interdisciplinary methods in ESD as well as the existing problems.

Second, the author invited junior high school students who had participated in fieldwork to provide feedback on the learning experience and prepare them for progression to a new mode of fieldwork (Appendix A). The study recruited a total of 100 junior high school students (male: 48%; female: 52%). They all participated in the fieldwork, out of which 45% participated more than three times.

The interdisciplinary PBL fieldwork is designed according to the result of the survey. Affected by COVID-2019, the study randomly selected 17 junior high students in the pilot school to organize fieldwork twice during daily teaching. The entire activity lasted for one month, and each fieldwork lasted for approximately 2 h.

At the end of the fieldwork, the 13 students were subjected to a survey designed using the Q-methodology (**Figure 1**). This survey evaluated the perceptions of the

students of the value of the activities. Q-methodology is a research technique that quantifies subjective perspectives, allowing for the identification of distinct viewpoints on a topic. The process involves participants sorting a set of statements (Q-set) according to their personal agreement or disagreement. Factor analysis is then used to reveal common perspectives among the group. Key steps include selecting relevant statements, conducting concourse sorting with participants, and interpreting the resulting factors to understand shared viewpoints. This method is particularly useful for capturing the complexity of human opinions in empirical research.

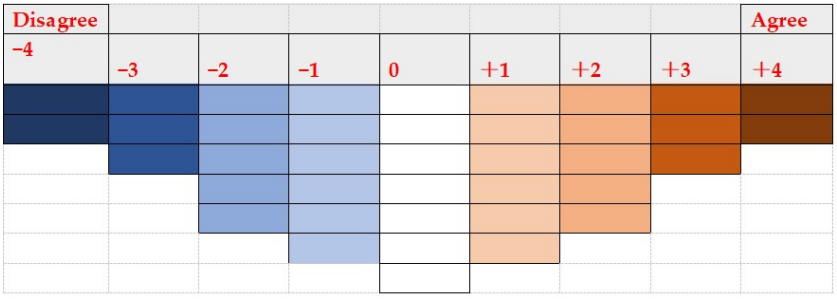

Figure 1. Q-score sheet.

In this experiment, the majority of Q statements (Appendix B) were derived from publications and assessment metrics such as the questionnaires of Kempa and Orion [91] and Chew [32]. The study supplemented only a few viewpoints by canvassing additional comments from the participants after the fieldwork. After initially eliminating statements with similar meanings, experts and peers reviewed the sample viewpoints to ensure clarity of language and that they were sufficiently comprehensive in representing the possible range of opinions. After Q sorting, the authors conducted interviews; audio data were then transcribed into word documents.

All procedures were performed in compliance with the Declaration of Helsinki and its subsequent amendments. The ethics committee of East China Normal University approved the study protocol.

4. Research analysis and design improvement

4.1. The value of geographical fieldwork is widely recognized

In general, the majority of students have basically recognized the previous fieldwork. Fieldwork can enable students to acquire substantial knowledge that is unavailable in books (Question 12), cultivate the quality to bear hardships and hard work (Question 9), and promote the cultivation of the sense of innovation and ability of students (Question 13). In addition, as shown in **Figure 2**, the biggest gain for students is the happiness of teamwork, which accounts for 27% (Question 14).

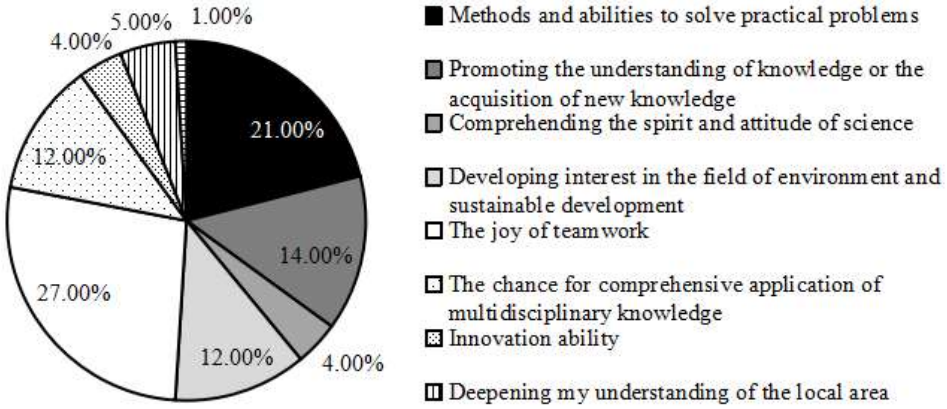

Figure 2. The most impressive advantages of fieldwork activities for students.

4.2. It significantly improves SD literacy, but economic and social themes are lacking

Through experience, 97% of the students reported that fieldwork enhanced their understanding of the relationship between humans and the natural environment (Question 11). As shown in **Figure 3**, extracurricular activities are the most important method for students to acquire knowledge about SD, which accounts for 33% (Question 18). This finding highlights the significant role of geography fieldwork in ESD.

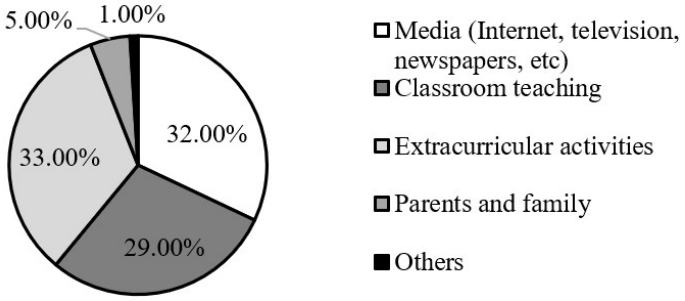

Figure 3. The main sources of knowledge about SD.

However, most SD issues are related to the ecological dimension of SD rather than the social and economic dimensions. As shown in **Figure 4**, the circular economy only accounts for 4% (Question 17). This finding indicates students who remain unable to develop a holistic understanding of the dimensions of SD or a superficial understanding of concepts beyond the environment [92,93].

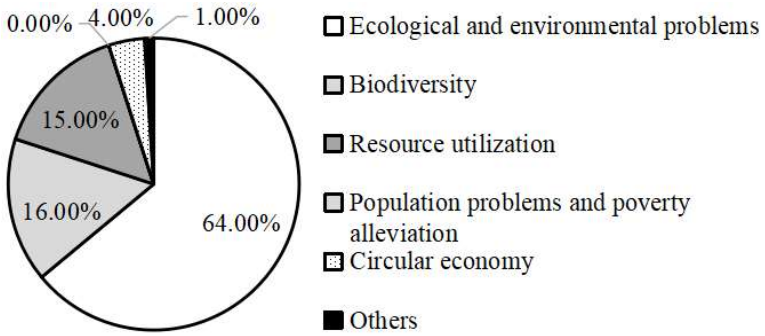

Figure 4. The issue of SD in fieldwork.

4.3. It is not closely related to classroom teaching and does not have sufficient interdisciplinary character

This aspect differs from the previous study in that examination is a factor that influences the development of fieldwork in junior high school [44]. In Question 19, the majority of students believe that fieldwork will promote the improvement of test scores (**Figure 5**). The reason may be that students only participate in fieldwork that improves their learning interest.

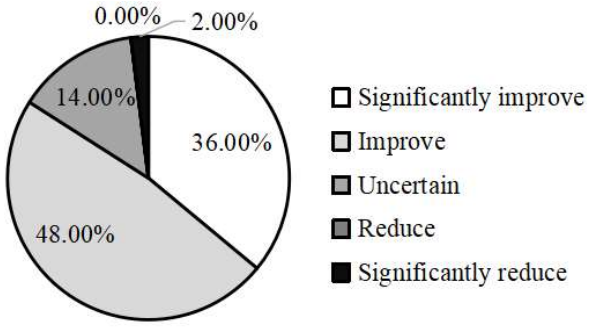

Figure 5. The influence of fieldwork on exam scores.

This is also reflected in Question 5, where approximately 15% of the students do not consider fieldwork as related to classroom content. This finding suggests that a tendency may exist to ignore classroom knowledge in fieldwork. In addition, 11% of the students remain unsure whether or not to apply knowledge from other subjects (Question 6), which indicates that the interdisciplinary content of previous geography fieldwork requires further improvement.

4.4. A room remains for further improvement in the design and methods of fieldwork teaching

Through the analysis of Question 21 using Word Cloud, we summarized the suggestions of students for improving fieldwork under the following four aspects, namely, increasing the activity and autonomy of students, innovating a method for pioneering practice activities, increasing the time and frequency of field practice, and providing more combinations of book content.

After years of fieldwork, the students recognized the advantages of geography fieldwork. However, there is still room for improvement.

a) The theme of the activity is environmental education, and more social and economic topics require discussion;
b) increasing student autonomy and the proportion of student-centered learning;
c) increasing the activity and activity time of the students; and
d) combining more class teaching contents, including those from different disciplines.

5. Improvements

Based on the abovementioned problems, the study presents the following improvement and optimization.

First, we selected an agricultural circular economy as the theme to enhance the

understanding of students about the social and economic dimensions of SD.

Second, teaching methods were improved, and the autonomy of students was increased. Prior to the fieldwork, the authors understand the existing cognitive levels of students about circular agriculture and encourage them to consult materials and select a location for fieldwork. Under the guidance of the teacher, the students finally decided to visit the Dongtan Low-Carbon Agricultural Park and the digital breeding base with fishing and light complementary in Puye Town. These two places are mainly based on the cycle process of carbon elements, which provided students with the experience of the transformation of material and energy and understanding the internal and industrial digital cycle modes in the circular economy. According to the principle of "students first" (heterogeneous within the group and homogeneous between the groups), each group consists of three to five students. They were allowed to name their groups, such as the Sunbird Team and the Kingfisher Team. Then, they are exposed to the basic situation of fieldwork through preliminary visits, family interviews, telephone interviews, and online searches.

Third, according to standards and textbooks, which are centered on geography, a geography teacher discusses with teachers from other disciplines and integrates the knowledge and thinking methods of biology, chemistry, and other disciplines in junior high school into activities (**Table 2**). The comprehensiveness of geography enables students to better understand the terrain, climate, transportation, science and technology, market, national policies, and other regional factors of the circular economy.

Table 2. The design of interdisciplinary fieldwork.

Location of fieldwork	Investigation content	Subject	Knowledge	Content standard
Dongtan Low-Carbon Agricultural Park	Traditional rice and wheat farming Traditional fruit growing Modern fruit growing Traditional irrigated agriculture Modern micro-drip irrigation agriculture Modern vegetable farming Wind-solar complementary power supply system Steam, heat, water, and fertilizer combined production system	Geography	Geographical landscape	Discuss the differences in geographical landscapes.
			Agriculture	Collect graphic and textual information on the development status of a certain industrial sector in China and emphasize the application of high and new technology in industrial development.
			Transport	Use maps to determine traffic lines and transportation hubs and discuss the relationship between the distribution of transportation network and regional economic development.
		Biology	Green plants in the biosphere	Green plants can use solar energy, synthesize carbon dioxide and water into energy-storing organic matter, and release oxygen. Plants provide many resources available to human beings.
			Humans in the biosphere	Illustrate the impact of humans on the biosphere.
			Biotechnology	Fermentation technology utilizes the characteristics of microorganisms to produce corresponding products through a certain operation process.
		Physics	Conversion and transfer of energy	Different forms of energy can be converted into each other.
		Chemistry	The air around us	Learn about the oxygen cycle and the carbon cycle in nature.
The digital breeding base with fishing and light complementary in Puye Town	Fishing and light complementary landscape Investigate the development history of Chongming Island Ecological breeding base Chongming Island meteorological disaster and its effect on fishery production.	Geography	Geographical landscape	Discuss the differences in geographical landscapes
			Industry	Present the characteristics of different industries (photovoltaic power generation) and analyze their development conditions.
			Transport	Use maps to identify transportation routes and transportation hubs and discuss the relationship between the distribution of transportation networks and regional economic development
			Environmental problems and environmental protection	Conduct practical activities on an environmental problem. Change the adverse impact of traditional aquaculture on the environment
			Natural resources and production and life	Measures for utilizing and protecting water resources
			Land and resources	A large population and less land is a basic national condition of our country
			Weather and climate	Impact of climate on agricultural production
		Biology	The survival of living things depends on a certain environment.	Provide students with information and discuss the effects of temperature, air, light, and other factors on biological life.
			People in the biosphere	Illustrate the impact of humans on the biosphere
		Physics	Transformation and transfer of energy	Different forms of energy can be converted into each other.

Fourth, the authors designed the PBL fieldwork (**Figure 6**) based on the model of PBL [94].

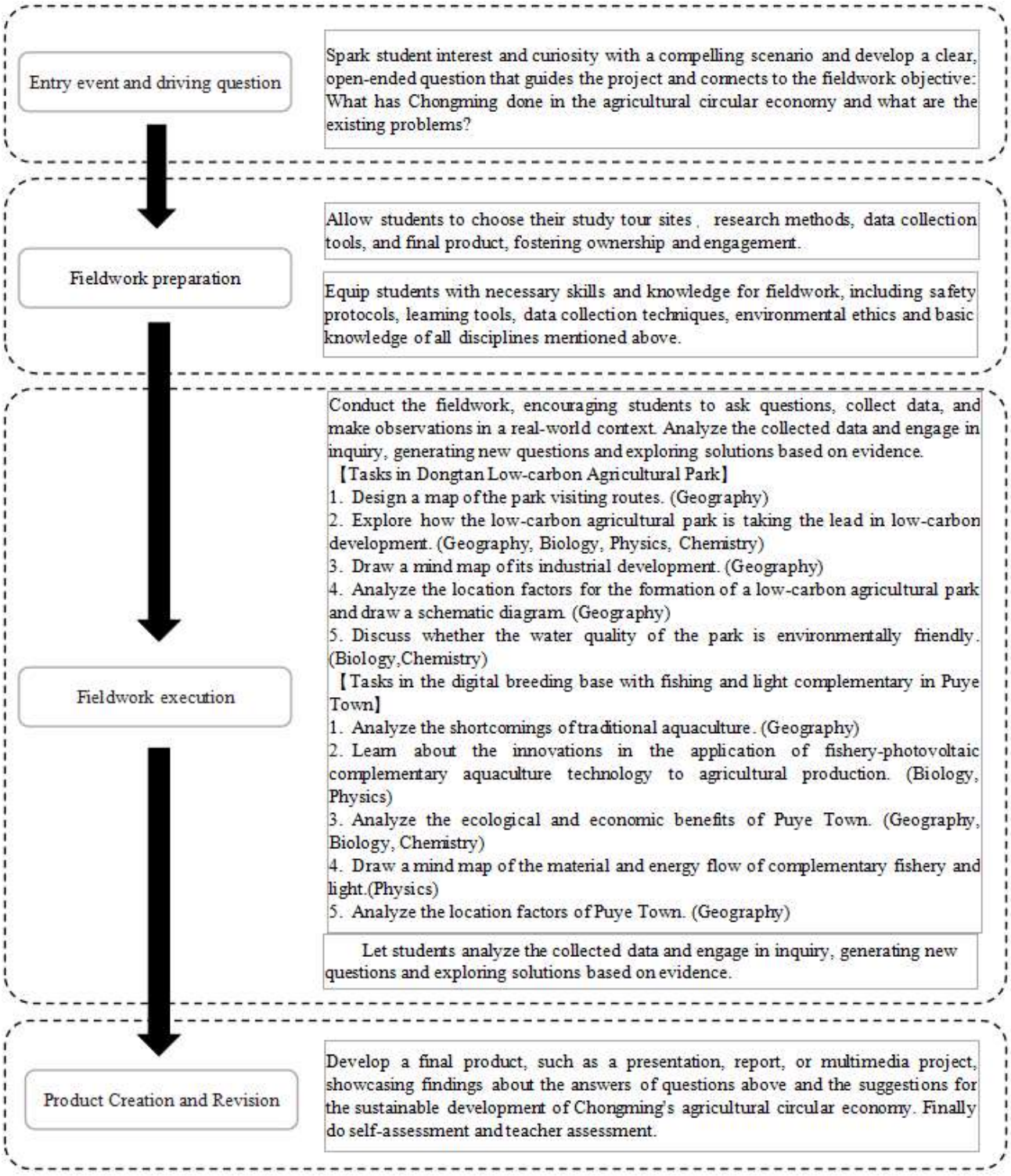

Figure 6. The design of PBL fieldwork.

Finally, students draw a mind map of the circular economy and compose an investigation report, including suggestions.

Getting started—This theme is about orienting students, that is, motivating them

to well consider the project well before they begin, providing them with a rubric that clearly explains what they are expected to search for and accomplish, and jointly agreeing on the grading criteria.

6. Results

6.1. It deepened my understanding of nature, classroom knowledge, and sustainability, but did little for high-level thinking

Four students supported this idea and displayed high levels of recognition of the value of fieldwork and its relationship with SD (**Table 3**). They believed that fieldwork brought them better appreciation of and closer to nature (Statements 2 and 3) and enabled them to gain an initial understanding of an unfamiliar landscape through careful observation. This finding is consistent with the value of geography as a discipline that tends to inspire a life-long passion for the countryside in people of all ages, an understanding of the interconnectedness of the world, and the need for the sustainable management of resources.

"Fieldwork can enable me to acquire knowledge and skills through experiments, imitation, and planting. It also increases my curiosity about everything in the world and gives me a sense of protecting nature. In outdoor practice." (Student 1)

Table 3. Top ranked statements for Viewpoint 1.

No.	Statement	Normalized factor scores	*Z*-Score
3	Better appreciate and value the beauty, delicacy of nature	+4	1.971
2	Increase my curiosity about nature	+4	1.941
4	Improve my ability to collect information and data	+3	1.451
10	Deepen my understanding of classroom knowledge	+3	1.403
18	Better understanding of the relationship among ecology, society, and economy	+3	1.230
37	By comparison, classroom teaching is more important.	−4	−2.076
28	Become aware of a few prejudices	−4	−1.551
23	Improve the integrated ability to solve local practical problems	−3	−1.409
32	The progress and development of a region should not be shelved under the pretext of protecting a few birds/animals.	−3	−1.371
31	The so-called ecological crisis facing mankind has been greatly exaggerated, and nature will be balanced over time	−3	−1.206

At the same time, students agreed with the value of fieldwork [35], which provided them with the opportunity to link knowledge in textbooks with knowledge in everyday life (Statements 37 and 10). This aspect enabled them to better understand classroom knowledge. This finding suggested that this activity can solve the problem of the insufficient application of classroom knowledge during fieldwork.

"Classroom teaching is only an objective understanding of the principle, while fieldwork is to discover the principle by hand, and both are indispensable... Fieldwork experience can effectively solute difficult problems in the classroom." (Student 2).

Statements 18, 31, and 32 clearly indicated that the activities promoted a

comprehensive understanding of SD, that is, understanding not only the consequence of the ecological environment but also the link among ecology, society, and economy from the perspective of the economic and social dimensions.

However, the students expressed that the activities did not sufficiently improve high-level thinking skills. For example, they reported no improvement in their problem-solving skills and awareness of their biases (Statements 28 and 23). This result did not fully achieve critical thinking in PBL [67]. One of the reasons is that the problem provided may be beyond the current cognitive and knowledge levels of middle school students, such as the factors of the geographic location. Another reason may be that the role of students in the group was primarily in problem-solving.

"I can only find the reason and point out where the problem is, but cannot solve it." (Student 4).

6.2. I gained a lot in terms of problem-solving skills and environmental action and a high level of acceptance of the new fieldwork approach

The students who held this viewpoint exhibited high levels of approval of the new fieldwork mode (**Table 4**). They believed that it would directly influence future behaviors such as willingness to participate in field trips and environmental activities (Statements 36–38).

"It can enhance my practical ability and broaden my horizons. At the same time, it can help me make more friends and enhance my interpersonal skills. At the same time, I can learn more extracurricular knowledge... I was really interested in this activity, but I did not realize all kinds of potential characteristics of myself... I do not think I can contribute to that, and I do not really understand it." (Student 6)

Table 4. Top ranked statements for Viewpoint 2.

No.	Statement	Normalized Factor Scores	*Z*-Score
38	I am willing to continue to participate in such field activities.	+4	2.112
36	I will actively participate in environmental activities.	+4	2.005
32	The progress and development of a region should not be shelved under the pretext of protecting a few birds/animals.	+3	1.477
23	Improve the integrated ability to solve local practical problems	+3	1.262
24	Improve my ability to cooperate and communicate with others	+3	1.262
37	By comparison, classroom teaching is more important	−4	−1.790
17	Conscious of their interests and abilities in the field of environment and sustainable development	−4	−1.477
31	The so-called ecological crisis facing mankind has been greatly exaggerated, and nature will be balanced over time	−3	−1.469
6	Improve the ability to use graphic expression	−3	−1.369
16	Improve knowledge and ability in chemistry, biology, information, and other disciplines	−3	−1.270

The students believed that practical activities can improve integrated problem and collaboration competencies (Statements 23 and 24). Both are particularly important key competencies in ESD [95]. This result demonstrated that PBL holds the potential to help students develop collaboration skills [68]. According to the

observation of the teacher, the students held this viewpoint and were more active in the problem-solving process of group cooperation.

However, the perception of students of SD in fieldwork was insufficient because they did not realize their awareness and abilities in relation to SD from the activities (Statement 17). Moreover, their understanding of SD was not holistic and required improvement (Statement 32).

Although we focused on interdisciplinary learning, students exhibited the lowest recognition of the activities in terms of enhancing their knowledge of different disciplines (Statement 16) and graphic expression skills (Statement 6). The main reason may be their inexperience in interdisciplinary teaching and learning.

"This activity shows me the ecology of Chongming, various animals, and plants. The teacher introduced many characteristics of them, but I do not think they have many relationships with the subject, especially chemistry and information, because now the breeding basically does use pesticides instead of the greenhouse. And I think biology is mainly to observe some plants." (Student 5)

6.3. I gained scientific spirit, environmental awareness, and interest in geography, but not much recognition of the teaching method

Three students expressed this viewpoint (**Table 5**); although they agreed with the fieldwork (Statement 38), they expressed negative statements about the new fieldwork mode (Statement 39). The reason may be that they felt that this teaching mode was time-consuming and insufficiently connected to classroom knowledge and learning (Statements 9 and 10). In a high culture of accountability and performance, curriculum time was frequently and exclusively focused on exam preparation. Thus, the students observed less practical values from such field practice in relation to learning during class hours.

Table 5. Top ranked statements for Viewpoint 3.

No.	Statement	Normalized Factor Scores	*Z*-Score
8	Comprehend the scientific spirit and attitude	+4	2.033
19	Improve the awareness of respecting and protecting the environment	+4	1.781
14	Increase interest in geography	+3	1.456
4	4. Improve my ability to collect information and data	+3	1.324
32	The progress and development of a region should not be shelved under the pretext of protecting a few birds/animals.	+3	1.205
37	By comparison, classroom teaching is more important	−4	−2.033
28	Become aware of a few prejudices	−4	−1.781
39	I will recommend this learning method to others.	−3	−1.708
9	Provide opportunities for using knowledge in class	−3	−1.662
10	Deepen the understanding of classroom knowledge	−3	−1.496

"The knowledge learned before fieldwork is beneficial to deepen the impression and understanding during the fieldwork. The fieldwork may take up time, affect or disrupt the plan for a period of time, or delay or reduce the study time of other subjects. Do what you can, and do not blindly recommend to others."

(Student 8).

"Different pupils adapt to different learning methods... should let them choose by themselves." (Students 9).

They most agreed with the promotion of scientific spirit (Statement 8), environmental awareness (Statement 19), and interest in the subject of geography (Statement 14). This result was consistent with those of previous studies [40–42,73]. However, similar to Viewpoint 2, the understanding of the students about the social and economic dimensions of SD is insufficient (Statement 32).

"Through fieldwork, I realized some different ways of economic recycling, thus changing my view on science and understanding the truth, attitude, and spirit of science." (Student 8).

"I met some difficulties after I got into this interdisciplinary study. I will try my best to solve them... Before this fieldwork, I was more perfunctory to geography; I felt the joy of achievement when I could pose detailed questions or complete mind maps, and I gradually became interested in geography." (Student 9).

"Through a series of studies, interactions, and activities in interdisciplinary study, I consolidated geographical knowledge and increased my interest in geography." (Student 10).

6.4. I obtained an awareness of local needs and sustainability issues and raised my positive feelings toward nature and learning

Similar to Viewpoint 1, this Viewpoint (**Table 6**) affirms that the activities can deepen awareness and positive feelings about nature (Statements 2 and 3). Students experienced the needs of the local communities and sustainability issues through the activities (Statements 20 and 22) and provided examples of sustainability issues. Students gained the opportunity to understand the community and to interact directly with community members through fieldwork. In this manner, the students became concerned with other interesting issues, which enhanced their sense of place within

Table 6. Top ranked statements for Viewpoint 4.

No.	Statement	Normalized Factor Scores	*Z*-Score
2	Increase my curiosity about nature	+4	1.891
22	Better understand the needs of local communities	+4	1.891
3	Better appreciate and value the beauty, delicacy of nature	+3	1.418
20	Explain sustainable development using examples	+3	1.418
1	Improve my interest in learning	+3	1.418
10	Deepen my understanding of classroom knowledge	−4	−1.891
9	Provide opportunities for using knowledge in class	−4	−1.891
8	Comprehend the scientific spirit and attitude	−3	−1.418
6	Improve the ability to use a graphic expression	−3	−1.418
7	Learn the methods of scientific inquiry	−3	−1.418

the site or their place of citizenship, including social responsibility [36–39]. Meanwhile, this mode can effectively enhance the interest of students in learning

(Statement 1), which is consistent with the findings that the effects of PBL include significantly increasing interest in learning and motivation [72].

> "I can learn about local needs through practical methods... It gave me an example to explain local sustainable energy." (Student 10).

This view is consistent with Viewpoint 3, which argues that fieldwork lacks the use of classroom knowledge (Statements 9 and 10) but improves scientific spirit (Statement 8) and the scientific method of inquiry (Statement 7).

6.5. Consistent viewpoints

Although the benefits differed across students, they agreed on both statements at basically the same level (**Table 7**).

Table 7. Consensus statements among four viewpoints.

No.	Statement	Viewpoint 1		Viewpoint 2		Viewpoint 3		Viewpoint 4	
		Normalized Factor Scores	*Z*-Score	Normalized Factor Scores	*Z*-Score	NormalizedFactor Scores	*Z*-Score	Normalized Factor Scores	*Z*-Score
4	Improve the ability to collect information and data	+3	1.45	+1	0.42	+3	1.32	+2	0.95
5	Improve the ability to observe, record, and analyze data	0	0.08	−1	−0.53	+1	0.5	+1	0.47
11	Understand the usefulness of book knowledge in daily life	0	0.15	0	−0.32	−2	−0.78	−2	−0.95
21 *	Shape thinking and ability in circular development	+1	0.53	+1	0.63	0	0.05	2	0.95
30	Cultivate the quality to bear hardship and hard work	0	0.02	0	−0.32	2	0.61	0	−0.00

(All listed statements are non-significant at $P > 0.01$, and those with an * are also non-significant at $P > 0.05$).

1) To a certain extent, interdisciplinary project-based fieldwork develops the ability of students to collect information and data (Statement 4).

Table 6 demonstrates that although the students possess varying degrees of recognition of this ability, an improvement is recognized. This ability is mainly obtained from preliminary visits, interviews, and online searches before fieldwork and hands-on during the fieldwork (**Figure 7**). It reflects the activities related to hands-on more easily accepted by students.

2) Interdisciplinary project-based fieldwork enhances thinking skills for circular development (Statement 21) and deepens the understanding of the students about the socio-economic dimension of SD. This result is closely related to the theme of the fieldwork. We can also note it through the circular economy mind maps which students draw from different perspectives (see attachments).

Figure 7. Collect soil and water samples.

6.6. Suggestions for improvement

To increase hands-on and experiments, "I think we can do more experiments to let more students feel the charm of geography."

7. Discussion

In teaching geography in junior high schools in China, only a few schools conduct fieldwork outside of the school setting, and even fewer attempt interdisciplinary PBL fieldwork. This is due to various barriers, including safety concerns, financial costs, teachers' heavy workloads [46], time constraints [4,96], limited parental support [97,98], and the emphasis on examinations [44].

This study made an initial attempt, and although the results were not perfect, it provided a different kind of experience and reward for the students and inspired the researchers to reflect on it.

First, although the students exhibited differences, they can all gain SD competencies. This finding indicates that students frequently gain from fieldwork. For example, a few students clearly understand the relationship among ecology, society, and economy; others are willing to participate in environmental protection activities; several agree to increase their environmental awareness; and a handful of them can explain SD using examples. However, not all students achieved a holistic understanding of SD. Although Viewpoint 1 provides a full consideration of the human dimensions of society and the economics of SD, Viewpoints 2 and 3 suggest that regional development should not be overlooked under the pretext of protecting birds and animals. Evidently, there is a natural progression to help all students achieve a holistic understanding of SD. The incremental steps in the short term will lead schools in the right direction in the long term.

Second, achieving the desired goal for all students may be challenging, especially for fieldwork, and requires sufficient time to ensure its effectiveness. The teacher organizer mentioned that students come from diverse classes, making it difficult for teachers to assess their ability to participate in PBL during the fieldwork design phase. However, achieving the teaching goal depends not only on the design but also on student participation in the teaching process. According to feedback from the teacher organizers, some students believe that "the ability to solve problems and the awareness of their own biases have not been improved." This may be due to limited time for activities, preventing students from engaging in deeper analysis and developing higher-order thinking skills. Recognizing that these abilities may not be

fully internalized after a single fieldwork experience, long-term implementation is necessary. Junior high school students should be given ample time to complete one or two tasks during fieldwork, with 20% of the time dedicated to reflection and discussion.

Third, arriving at a consensus across all viewpoints can be challenging, and reaching agreement on strongly supported and opposed statements is particularly difficult. Only two statements were largely agreed upon by the four viewpoints. For example, the students generally agreed that they had improved their ability to obtain information through activities such as surveys, interviews, and sampling (**Table 2**). Further analysis revealed that certain statements could be strongly agreed upon from two to three viewpoints. For example, Viewpoints 1, 2, and 3 all strongly agreed on the value of the field practice activity and did not consider classroom instruction as more important than field practice. Viewpoints 1 and 4 agree with the interest of students and knowledge of nature. Viewpoints 1 and 3 denied that the activity could enhance the critical thinking skills and a few of the biases of the students.

Fourth, the current finding aligns with existing research in that students' performance during practical, interdisciplinary PBL varies significantly among individuals. During the practical process, the division of labor within the group is often unclear, with one or two students taking the lead in group activities while other members participate passively or even merely observe, due to individual differences and varying degrees of project involvement. Consequently, students' sense of achievement can be polarized. For instance, a notable discrepancy was observed in the identification of improved problem-solving skills between Viewpoints 1 and 2. This difference is evident in the mind maps created by two students from the same group but representing different viewpoints. The student who made the most significant contribution to Viewpoint 2 created a mind map focused on strategies for a low-carbon agricultural park in Dongtan, Shanghai. In contrast, the student who contributed the most to Viewpoint 1 presented fragmented knowledge points. This suggests that the roles and levels of participation of the two students in the group work differed.

Fifth, the objectives of the interdisciplinary design were not sufficiently reached. This result may be related to the teaching experience of the geography teachers and the study habits of the students. Influenced by long-term sub-disciplinary teaching, the awareness of geography teachers about disciplinary integration is lacking; thus, they use traditional teaching methods. Interdisciplinarity and PBL are new methods of teaching and learning for teachers and students in junior high schools in China. Moreover, the complexity of this method influences the achievement of the desired goals to a certain extent.

Sixth, it is important to acknowledge the inherent limitations that may impact the interpretation and generalizability of the findings. Foremost among these limitations is the brief duration of the experimental period. The relatively short time frame within which the study was conducted may not have allowed for the full emergence of the long-term effects of the intervention, thus potentially underestimating the sustained impact of interdisciplinary PBL fieldwork on student outcomes. Additionally, the sample size employed in the Q-methodological analysis is notably small, consisting of only 13 students. This limited sample size may not be

representative of the broader student population, which could compromise the external validity of the study. The small sample size also means that the findings may be more susceptible to the influence of outliers or unique individual characteristics, which could affect the reliability of the conclusions drawn. Furthermore, the restricted scope of the study, both in terms of duration and sample size, may have constrained the detection of more nuanced or subtle effects of the interdisciplinary PBL fieldwork on students' learning experiences and outcomes. The complex interplay between various factors in a real-world educational setting may not have been fully captured due to these limitations. To address these limitations, future research should aim to conduct larger-scale and longer-term empirical studies. A more extensive and prolonged investigation would not only enhance the reliability of the findings but also provide a more comprehensive understanding of the multifaceted effects of interdisciplinary PBL fieldwork. Such research could explore the long-term academic, cognitive, and affective outcomes of students engaged in interdisciplinary PBL fieldwork, thereby offering more robust insights into the educational value and potential of this pedagogical approach.

As stated by one of the organizing teachers, "teachers give students more intellectual support but less support in methods and skills. Now, students attach great importance to the learning of classroom knowledge. So, I have to teach them what interdisciplinary learning is and what a mind map is."

This statement also indicates that interdisciplinary learning is mainly related to the study habits of students. A possibility exists that a few of the students, who were experiencing cognitive dissonance, were reluctant to step out of the comfort zone of the traditional single discipline of geography. Certain students familiar with uni-disciplinary teaching and learning may find that learning in an interdisciplinary manner is difficult [99]. Meanwhile, students may be unable to cope with the transition from the classic lecture format to student-centered learning techniques.

In addition, the geography teachers stated that geography is the major content on the basis of the definition of interdisciplinary curriculum standards, such that the relevant knowledge and methods of other subjects are not particularly highlighted. As the tutor said:

> "The students in the second year of junior high school have just begun to learn physics and have not yet learned chemistry; therefore, in the activity process of junior high school, teachers do not overemphasize the application of interdisciplinary knowledge, but through geographical investigation, let students subtly know some physical and chemical processes in fieldwork."

It is believed that meaningful interdisciplinary PBL is not a platter of disciplinary knowledge; instead, it is an engagement in the learning process through the authentic and meaningful exploration of problems in a manner similar to the problem-solving of adult experts. Therefore, support for students in analyzing their conceptions of disciplinary boundaries should be considered to support them in solving issues in SD. It may need more time to make students adapt to the new teaching method.

The evaluation of fieldwork is complex, which is reflected not only in the difficulty of comprehensively evaluating the operations of students comprehensively but also in the differences among students, who benefit differently from the same

activity. Moreover, the study was unable to use a uniform standard for measuring and evaluating the students. The purpose of evaluation should be to promote the better development of students, and the Q method holds a unique advantage in being able to respond well to individual differences and provide targeted measures in geography fieldwork that is organized for a small number of people.

8. Conclusion

Based on the background of global SD and China's curriculum standards for compulsory education, which emphasize interdisciplinarity, this study surveys students from a junior high school in Chongming, Shanghai, to investigate the achievements and shortcomings of fieldwork over the years. It involves designing specific activity steps with teachers, conducting these activities in the field, and innovating the teaching mode for fieldwork. The study engages students in learning knowledge and skills through an extended inquiry process structured around real-life questions and carefully designs products and tasks. Finally, the study uses Q-methodology to investigate the students' perceptions of fieldwork, explore their acceptance of this new pedagogy, evaluate the benefits gained, and verify the feasibility and effectiveness of the modified field practice approach.

The results suggest the importance of interdisciplinary learning on real-life issues. The study positively perceived the activity in terms of developing their ability to collect information and data, enhancing their thinking skills on circular development, and deepening their understanding of the socio-economic dimensions of SD. Despite the experience of these geography teachers in the field, the new field practice approach did not achieve the expected benefits, and the effectiveness of the activity varied across the students. Moreover, reaching a consensus was more difficult for the students, especially in terms of their biggest gains. The areas that some students felt they gained the most were deepening their understanding of nature and classroom knowledge, whereas others assumed that they reaped many benefits from problem-solving skills and environmental actions. Several students assumed that they gained the most from the scientific spirit, environmental awareness, and interest in geography, and others gained a deep understanding of local needs and SD issues and increased their interest in learning. Nevertheless, the study perceived a few statements as diametrically opposed to one another. The influencing factors are also multifaceted: the duration of the activity and the level of difficulty of the content, the cognitive level and existing knowledge base of the students, the participation and roles of students in the activity, the challenges and complexity of the teaching methods, the learning habits of students familiar with uni-disciplinary teaching, and the experience of the subject teachers who led the team. Thus, learning about the subject could take a long time for the students. Moreover, a longitudinal approach should be used to investigate the learning outcomes of this method.

Furthermore, the study was unable to evaluate the students using a uniform standard, but it should pay attention to the differences in the responses of individuals. The Q-method has unique advantages for practice activities in geography. The method can effectively highlight the effectiveness of practice activities from the perspective of the development and benefits of students, identify

problems in implementation, and improve field practice methods that exhibit important reference values.

As a pilot effort, this study sought to address the educational needs of problem-solving in interdisciplinary real-life scenarios. Although the students were randomly selected for fieldwork, we did not conduct a control group study. Thus, the effectiveness of the activities may vary across teachers, but continuous practice and innovation can be very helpful for the improvement of interdisciplinary learning.

Against this background, the study proposes better means for improving the organization of field practice activities, such as implementing projects with fewer tasks and time, providing opportunities for questions, reflections, and discussions as much as possible, and making use of the 20% overtime amount when designing the fieldwork. Furthermore, the study recommends the creation of a self-management culture in which the responsibility for project design and decision-making is transferred from the teacher to the students. In other words, students make decisions for themselves and are encouraged to learn how to learn.

The development and enrichment of the interdisciplinary field practice teaching model requires the ongoing efforts of educational researchers. Meanwhile, we further suggest that the curriculum content for teacher trainees in geography in university programs should not only raise their awareness of the value of interdisciplinary field activities but also provide opportunities for them to develop interdisciplinary teaching skills. This will enable new teachers to immediately apply interdisciplinary field activity instruction in secondary education. Additionally, the successful implementation of the program is inseparable from the support of school principals and other administrative personnel. They are required to formulate corresponding school regulations to ensure the safety and stability of the program and to endeavor to incorporate the achievements of interdisciplinary field activities into the evaluation systems for both teachers and students.

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Appendix A

Questionnaire

Survey on the Development of Field Practice Activities for Middle School Students

Dear students:

Hello! This study mainly investigates the successes and shortcomings encountered on fieldwork activities in secondary schools to improve the organization of field practice activities and enhance the quality of such activities. This questionnaire is anonymous and is for research purposes only. There is no right or wrong answer, so please feel free to fill it out according to the actual situation. Thank you!

1. What is your gender?
   A. Male B. Female
2. What grade are you in?
   A. 6th grade B. 7th grade C. 8th grade D. 9th grade
3. How many times have you participated in fieldwork?
   A. 1 time B. 2 times C. 3 times D. More than 3 times
4. Fieldwork makes me like geography class.
   A. Strongly disagree B. Disagree C. Uncertain D. Agree E. Strongly Agree
5. Fieldwork activities are closely related to classroom teaching and exam content.
   A. Strongly disagree B. Disagree C. Uncertain D. Agree E. Strongly Agree
6. In the fieldwork activities, the knowledge of many subjects in junior high school is used.
   A. Strongly disagree B. Disagree C. Uncertain D. Agree E. Strongly Agree
7. What is the extent of the difficulty of completing fieldwork activities?
   A. Very difficult B. Difficult C. Uncertain D. Easy E. Very easy
8. Fieldwork activities have improved my ability to solve real world problems.
   A. Strongly disagree B. Disagree C. Uncertain D. Agree E. Strongly Agree
9. Fieldwork activities have trained me to work despite difficulties and hardships.
   A. Strongly disagree B. Disagree C. Uncertain D. Agree E. Strongly Agree
10. Fieldwork activities have helped me to communicate with different people.
    A. Strongly disagree B. Disagree C. Uncertain D. Agree E. Strongly Agree
11. Fieldwork activities enable me to better understand the relationship between man and the natural environment.
    A. Strongly disagree B. Disagree C. Uncertain D. Agree E. Strongly Agree
12. Fieldwork activities enable me to learn more knowledge that is unavailable in books.
    A. Strongly disagree B. Disagree C. Uncertain D. Agree E. Strongly Agree
13. Fieldwork activities can inspire my awareness and ability to innovate.
    A. Strongly disagree B. Disagree C. Uncertain D. Agree E. Strongly Agree
14. What impressed me most about the fieldwork activities was ().
    A. Methods and abilities to solve practical problems
    B. Promoting the understanding of knowledge or the acquisition of new knowledge
    C. Comprehending the spirit and attitude of science
    D. Developing interest in the field of environment and sustainable development
    E. The joy of teamwork
    F. The chance for the comprehensive application of multidisciplinary knowledge
    G. Innovation ability
    H. Deepening my understanding of the local area
    I. Others: _____
15. What form of geography fieldwork activities would you prefer to participate in?

A.A lecture given entirely by a teacher
B. A lecture given mainly by a teacher
C. Working together to settle the assignment by the teacher and the students.
D. Mainly operated by students
E. Completely operated by students

16. What is my preferred way of evaluating fieldwork activities?
A. Teacher evaluation
B. Combination of teacher and student evaluation
C. Group members evaluating each other
D. Self-evaluation
E. No evaluation
17. In the fieldwork, I encountered the issue of sustainable development ().
A. Ecological and environmental problems
B. Biodiversity
C. Resource utilization
D. Population problems and poverty alleviation
E. Circular economy
F. Others_____
18. What are my main sources of knowledge about environmental and sustainable development?
A. Media (i.e., Internet, television, and newspapers)
B. Classroom teaching
C. Extracurricular activities
D. Parents and family
E. Others ____
19. How do I think fieldwork activities influence exam scores?
A. Significantly improve B. Improve C. Uncertain
D. Reduce E. Significantly reduce
20. Would I like to continue to participate in geography fieldwork activities as a method of learning and recommend it to others?
A. Yes B. No
21. What do you think are the shortcomings and problems in the current fieldwork activities? Please write your proposals.

Thank you again for your cooperation and support!

Appendix B

Table B1. Q statement.

	Statements
1.	Improve my interest in learning
2.	Increase my curiosity about nature
3.	Better appreciate and value the beauty, delicacy of nature
4.	Improve the ability to collect information and data
5.	Improve the ability to observe, record, and analyze data
6.	Improve the ability to use a graphic expression
7.	Learn the methods of scientific inquiry
8.	Comprehend the scientific spirit and attitude
9.	Provide opportunities for using knowledge in class
10.	Deepen the understanding of classroom knowledge
11.	Understand the usefulness of book knowledge in daily life
12.	Acquire new knowledge not taught in class
13.	Increase my knowledge and understanding of the local area
14.	Increase my interest in geography
15.	Improve my geographical skills
16.	Improve knowledge and ability in chemistry, biology, information, and other disciplines
17.	Conscious of their interests and abilities in the fields of environment and SD
18.	Better understanding of the relationship between ecology, society, and economy
19.	Improve the awareness of respecting and protecting the environment
20.	Explain sustainable development using examples
21.	Shape thinking and ability in circular development
22.	Better understand the needs of local communities
23.	Improve the integrated ability to solve local practical problems
24.	Improve the ability to cooperate and communicate with others
25.	Improve the ability for independent learning
26.	Improve system thinking
27.	Inspire innovation awareness and ability
28.	Become aware of a few prejudices
29.	Promote your independence, self-reliance and self-management
30.	Cultivate the quality to bear hardship and hard work
31.	The so-called ecological crisis facing mankind has been greatly exaggerated, and nature will be balanced over time
32.	The progress and development of a region should not be shelved under the pretext of protecting a few birds/animals.
33.	Laws and government regulation and control reduce pollution.
34.	Inspire reflection on the impact of personal behavior on the environment (normal competence)
35.	If it helps to protect the environment, I am willing to reduce consumption and not enjoy a comfortable life.
36.	I will actively participate in environmental protection activities.
37.	By comparison, classroom teaching is more important.
38.	I am willing to continue to participate in such field activities.
39.	I will recommend this learning method to others.

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Opinion

Digital transformation for sustainable development

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Abstract: This study aims to explore how digital transformation can promote sustainable development. Specifically, this paper makes an in-depth analysis from the perspective of theory and practice, in order to provide a solid theoretical basis and effective practical guidance for sustainable development, and help the coordinated progress of economy, society and environment. The primary characteristics of digital transformation include being data-driven, real-time interconnected, automated and intelligent, and customer-oriented. Digital transformation can contribute to sustainable development across various industries, ranging from industrial manufacturing to agriculture, energy, and urban development, all of which have seen practical outcomes. In the industrial manufacturing sector, digital transformation can enhance production efficiency, reduce energy consumption, and minimize waste emissions. In agriculture, it can enable precision farming and smart agriculture, thereby improving agricultural productivity and sustainability. In the energy sector, digital transformation can achieve clean, efficient, and renewable energy production. In urban development, it can facilitate the construction of smart and sustainable cities, improving urban environmental quality and residents' quality of life. Government, businesses, and society all play crucial roles in driving digital transformation forward.

Keywords: digital transformation; industry development; manufacturing development; agriculture development; energy development; urban development

1. Introduction

Digital transformation and sustainable development are two highly discussed topics in today's society. Digital transformation refers to the process of deeply restructuring and innovating traditional business models, workflows, and value chains through the use of digital technology and information means. We have made it clear that this process has profoundly affected every aspect of our lives, from the daily way of life to the macro model of the economy, to the complex form of social organization. Digital transformation is not just about simply migrating existing businesses to digital platforms but also involves redesigning business processes, integrating data and technology, and reshaping and innovating business models [1]. The main characteristics of digital transformation include being data-driven, real-time interconnected, automated and intelligent, and customer-oriented. The development of digital technology is evolving rapidly, covering multiple fields such as information technology, communication technology, artificial intelligence, big data, the Internet of Things (IoT), and blockchain, with technologies like cloud computing, big data, artificial intelligence, and IoT being particularly prominent.

Sustainable development, on the other hand, refers to the ability of future generations to meet their own needs while meeting current needs. Around the world, climate change, resource shortage, environmental pollution and other problems are becoming increasingly serious, and the attention and call for sustainable development

are growing. How to combine it with sustainable development and give full play to the huge potential of digital transformation in promoting the sustainable development of economy, society and environment is still an important topic that needs to be further explored and solved.

After extensive and in-depth research on digital transformation and sustainable development, the empirical research results by Zhang and Jin show that digital transformation can significantly promote the sustainable development of enterprises [2]. Lu et al. found that digital transformation is the promoter of enterprise sustainable innovation and performance based on the dual perspective of information processing and innovation [3]. Qing and Jin have confirmed the positive impact of digital transformation on the sustainable development of enterprises [4]. Zhang et al. found that digital transformation has a significant positive impact on the sustainable development of enterprises [5]. Li and Xu proposed that the digital transformation of enterprises is the key driving force for the sustainable development of urban economy [6]. In the past research, experts and scholars mostly put the impact of digital transformation on sustainable development in the enterprise perspective, but lack of macro related research. Different from previous studies, this paper focuses on the sustainable development of digital transformation in many different fields, and expounds the important role of digital transformation on the sustainable development of industrial manufacturing, agriculture, energy and urban development.

This study aims to provide theoretical support and practical guidance for the global promotion of sustainable development through digital transformation. In this paper, through the use of multidimensional, systematic analysis method, reveals the close connection between the digital transformation and sustainable development, analyze the digital transformation in promoting the development of all walks of life can hold positive effect and mechanism, and put forward to enhance the synergistic effect between the digital and sustainable development of targeted Suggestions. This study has certain theoretical significance and practical value. From the theoretical perspective, it is helpful to further enrich and improve the relevant theoretical system of digital transformation and sustainable development, provide a more solid foundation and a broader vision for the in-depth research of academic circles in this field, and promote the continuous innovation and development of related theories. From a practical perspective, this study can provide targeted and operational guidance and suggestions for enterprises in developing digital transformation strategies and fulfilling social responsibilities. At the same time, it provides a scientific basis for the government to formulate relevant policies and regulations, guides the rational allocation of social resources, and promotes the coordinated development of the economy, society and the environment.

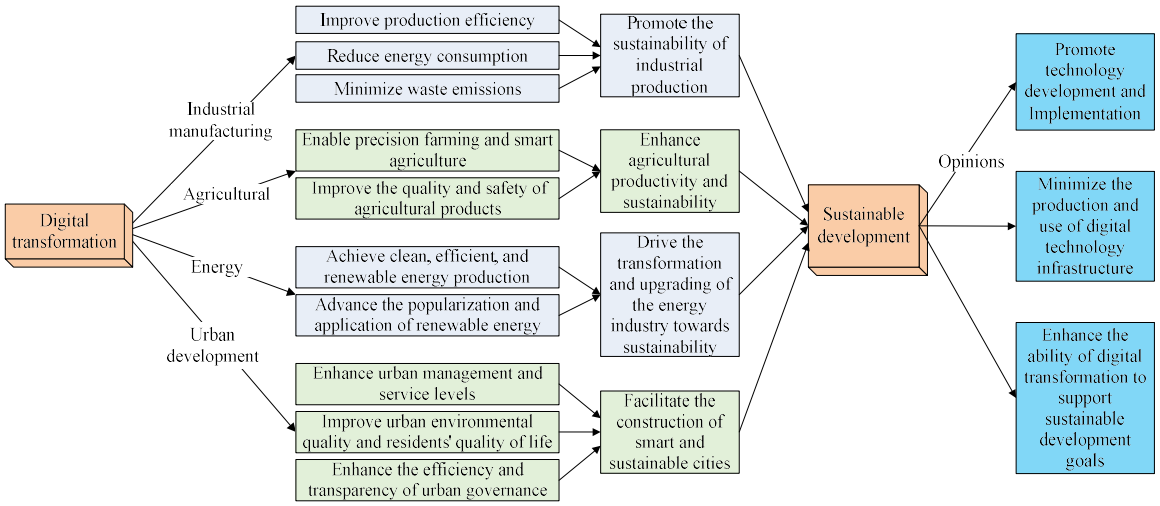

Figure 1. Research framework of digital transformation for sustainable development.

2. Industries of digital transformation for sustainable development

Digital transformation can contribute to sustainable development across various industries, from industrial manufacturing to agriculture, energy, and urban development, all of which have seen practical implementations and outcomes [7]. **Figure 1** illustrates the research framework for digital transformation for sustainable development.

(a) In the industrial manufacturing sector, digital transformation can significantly improve production efficiency, reduce energy consumption, and minimize waste emissions, thereby promoting the sustainability of industrial production. Through technologies like smart manufacturing and industrial Internet, companies can achieve intelligent monitoring and optimization of production processes, reduce energy waste and production costs, and improve product quality and efficiency. For example, big data analytics can help enterprises achieve intelligent production planning and inventory management, thereby shortening production cycles and reducing operating costs. Additionally, the application of artificial intelligence and machine learning can automate repetitive tasks in the production process, improving work efficiency and reducing the need for personnel [8]. Enterprises can adopt clean energy supplies, implement circular economy models, and pay attention to the entire product lifecycle, including design, production, use, and disposal. Businesses can better coordinate suppliers, production, and logistics to respond to market changes. Moreover, new production models such as Rapid Manufacturing (RM) and Custom Manufacturing are continuously evolving to meet the personalized and diverse needs of consumers [9].

(b) In the agricultural sector, digital transformation can enable precision farming and smart agriculture, enhancing agricultural productivity and sustainability. With technologies like IoT, big data, and artificial intelligence, farmers can achieve real-time monitoring and management of farmland, optimize agricultural production schemes, reduce the use of pesticides and fertilizers, and decrease environmental pollution and resource wastage [10]. Furthermore, digital technology can also improve the quality and safety of agricultural products, safeguard farmers' income and living standards, and promote sustainable agricultural development and rural revitalization.

(c) In the energy sector, digital transformation can achieve clean, efficient, and

renewable energy production, driving the transformation and upgrading of the energy industry towards sustainability. Through smart grids and intelligent energy management systems, real-time monitoring and scheduling of energy can be achieved, improving energy utilization efficiency and supply reliability while reducing energy consumption and carbon emissions [11]. Moreover, digital technology can promote the development and utilization of clean energy, advance the popularization and application of renewable energy, reduce reliance on traditional fossil fuels, and decrease environmental pollution and the risks of climate change [12].

(d) In the field of urban development, digital transformation can facilitate the construction of smart and sustainable cities, enhancing urban management and service levels, and improving urban environmental quality and residents' quality of life. By building and applying systems like smart transportation, smart energy, and smart environmental protection, urban traffic flow can be optimized, energy resources can be saved, and environmental quality can be improved [13]. Additionally, digital technology can enhance the efficiency and transparency of urban governance, promote the scientific and sustainable planning and development of cities, and drive the green development of urban economies and social harmony and stability.

3. Opinions of digital transformation for sustainable development

To enhance the synergy between digitalization and sustainable development, diverse entities such as governments and enterprises are implementing special policies to elevate the overall digitalization level of the economy and environmental efficiency, thereby improving sustainability.

(1) Digital system innovation requires the development and implementation of various technologies. These technologies must be synchronized with social innovation as well as institutional and behavioral changes. The use of digital technologies must be guided by a comprehensive efficiency strategy, adhering to the principles of purposefulness and minimization. Digitalization efforts should enhance rather than hinder citizens' sovereignty, expanding users' freedom of choice to competently and responsibly use digital media and services. Incentives should promote the use of digital technologies in decentralized business models, reducing dependency on oligopolistic companies for public and private services. Economic and social opportunities in the digital economy must be fair, including providing education opportunities for all to acquire the necessary skills for a digital society and more equitably distributing capital-based income across the population.

(2) The growth in the number of digital devices and services stimulates energy and resource consumption, and their application leads to additional consumption in other industries through various rebound effects. For instance, to meet the energy transition's demand for green technologies, the extraction of minerals like graphite, lithium, and cobalt could increase by 500% by 2050. Each stage of extraction, processing, and disposal of these mineral resources generates waste, significantly impacting land, water, air, and biodiversity. Additionally, the production and operation of digital technologies demand substantial energy and resources, leading to related environmental impacts. Therefore, the environmental footprint of producing and using digital technology infrastructure must be minimized. On one hand, the digital industry

needs to continually leverage new technologies to advance its own energy-saving and low-carbon development. On the other hand, digital innovation needs to systematically and extensively focus on efficiency improvements. Developers should adhere to sustainable software design principles to minimize electricity and resource consumption. For example, Germany's "Blue Angel" label has been incorporated into the evaluation system for energy-efficient data centers.

(3) The support capability of digital transformation for sustainability goals should be enhanced in every aspect. The sustainable digital ecosystem involves supporting environmental change responses through an effectively managed and inclusive data architecture and global digital ecosystem. By utilizing digital tools and non-traditional data sources, including sensors, and artificial intelligence, forming datasets for the public and private sectors can help automatically monitor global, national, and local progress in achieving Sustainable Development Goals and multilateral environmental agreements' key climate, biodiversity, and pollution indicators. Co-building digital transformation partnerships incentives and consumer behavior, using financial technology, e-commerce, social media platforms, and their underlying algorithms and filters to accelerate deep structural changes in markets, value chains, and consumer behavior, thereby steering incentives towards sustainable development. Through various digital innovation-focused hackathons, innovation labs, and similar initiatives, citizen science and open innovation should be encouraged and promoted, particularly supporting the active participation of SMEs, social entrepreneurs, women, and youth.

While digital transformation plays a crucial role in supporting sustainable development, it is a double-edged sword. The novelty, convenience, and functionality of digital technology innovation can provide opportunities for sustainable development. However, we must also be wary of the risks of digitalization being misused and its potential negative social consequences. Therefore, digital transformation must advance in parallel with sustainable development, promoting sustainable development through digital transformation while ensuring the sustainability of digital transformation itself.

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Review

Application of 3D printing across various fields to enhance sustainable manufacturing

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Abstract: 3D printing has fundamentally transformed traditional manufacturing practices by enabling decentralized production, customization, and significant reductions in waste and energy consumption. This paper provides a thorough examination of the advancements, applications, challenges, and future prospects of 3D printing in fostering sustainable manufacturing practices across diverse industries. Key additive manufacturing technologies such as Fused Deposition Modeling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), and Direct Metal Laser Sintering (DMLS) are discussed in relation to their role in achieving sustainability goals. The versatility of 3D printing materials, including biodegradable polymers, recycled metals, and eco-friendly composites, is highlighted alongside their environmental benefits and functional advantages in sectors such as automotive, healthcare, construction, consumer products, electronics, aerospace, and defense. Despite the transformative potential of 3D printing, challenges such as material limitations, energy consumption, regulatory compliance, and initial costs persist, requiring collaborative efforts to overcome. Looking ahead, ongoing research and development efforts in materials science, process optimization, and Industry 4.0 integration are poised to further enhance the sustainability and scalability of 3D printing technologies, thereby paving the way for a more environmentally conscious and economically viable manufacturing future.

Keywords: 3D printing; additive manufacturing; sustainable manufacturing; automotive; healthcare, construction; consumer products; electronics; aerospace; defense

1. Introduction

Sustainable manufacturing represents a critical paradigm shift in industrial practices, characterized by its focus on minimizing environmental impact, optimizing resource utilization, and enhancing societal benefits. This transformative approach seeks to harmonize economic growth with environmental stewardship and social responsibility. At the forefront of this shift is the adoption of 3D printing technologies, which have emerged as a highly promising strategy for achieving these sustainability objectives. By facilitating decentralized production, 3D printing reduces the need for large-scale manufacturing facilities and long supply chains, thereby minimizing transportation-related emissions and resource consumption. Additionally, the technology allows for unprecedented design customization, which not only meets specific consumer needs but also reduces material waste through precise, layer-by-layer manufacturing processes. Furthermore, 3D printing contributes to significant energy efficiency improvements by optimizing production

workflows and lowering energy demands compared to traditional manufacturing methods [1].

This paper aims to provide a thorough and detailed overview of how 3D printing is fundamentally transforming manufacturing practices across various sectors the overview given in **Table 1**. It explores the diverse applications and benefits of this technology, demonstrating its substantial contributions to global sustainability goals. By examining case studies and industry-specific examples, this paper highlights the ways in which 3D printing is driving progress towards more sustainable manufacturing practices and underscores the technology's potential to address some of the most pressing environmental and resource challenges of our time.

Table 1. Review overview.

Review Steps	Description	Review Outcome
1. Preliminary Reading	Read the abstract, introduction, and conclusion to understand the paper's scope and key arguments.	Initial understanding of the paper's main objectives and relevance.
2. Detailed Analysis	Review each section in detail, focusing on methodologies, technologies, applications, and case studies.	Comprehensive grasp of the paper's structure and detailed content analysis.
3. Evaluation of Technologies	Assess the discussion of 3D printing technologies (FDM, SLA, SLS, DMLS) and their environmental impact.	Evaluation of how well the paper covers the technologies and their sustainability aspects.
4. Industry Applications	Evaluate the applications of 3D printing across various industries and review key examples provided.	Understanding of the practical implementations and relevance to different sectors.
5. Challenges and Solutions	Review the challenges mentioned and the proposed solutions for sustainable manufacturing.	Insight into the obstacles faced and the effectiveness of suggested solutions.
6. Technological Advancements	Examine innovations in 3D printing technologies, materials, and digital tool integration.	Assessment of the advancements covered and their implications for sustainability.
7. Sustainability Assessment	Assess how the paper addresses sustainability through material efficiency, energy savings, and localized production.	Understanding of how well the paper integrates sustainability into the discussion of 3D printing.
8. Future Prospects	Review the proposed future developments in 3D printing and their potential impact on sustainable manufacturing.	Insight into the future trends and their potential effects on the industry.
9. Conclusion and Recommendations	Summarize the findings and provide recommendations for further research or practical applications.	Final overview of the paper's conclusions and actionable recommendations.

2. 3D printing technologies and materials

A fundamental aspect of 3D printing's versatility lies in its diverse range of technologies and compatible materials. Key additive manufacturing technologies include Fused Deposition Modeling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), and Direct Metal Laser Sintering (DMLS), each offering unique capabilities suited to different industrial applications [2]. The choice of materials plays a crucial role in determining the environmental footprint and functional properties of 3D printed products. Materials such as thermoplastics, metals, ceramics, and biocompatible polymers are commonly used, with ongoing advancements focusing sustainable alternatives like recycled filaments and bio-based resins [3].

Environmental sustainability assessments indicate that 3D printing processes can significantly reduce material waste compared to traditional subtractive manufacturing methods. Life cycle assessments (LCAs) have demonstrated

favorable environmental profiles for additive manufacturing, highlighting reductions in energy consumption, emissions, and raw material usage [4]. However, challenges such as energy-intensive post-processing steps and the environmental impact of material sourcing require ongoing research and innovation to enhance the sustainability credentials of 3D printing technologies [5].

3. Applications in different industries

Different applications of 3D printing, its future scope is explained below and summary is given in **Table 2**.

Table 2. Applications of 3D printing.

Industry	Current Applications of 3D Printing	Future Scope
Automotive Industry	Rapid prototyping of vehicle components	Direct printing of production parts
	Customized tooling and jigs	Integration of 3D printed electronics
	Lightweight and complex geometries for structural parts	Use of advanced materials like carbon fiber composites
	Production of electric vehicle components	Scalable production lines for additive manufacturing
Healthcare Sector	Patient-specific surgical guides and implants	Bioprinting of organs and tissues
	Prosthetics and orthotics	Development of personalized medicine
	Customized dental aligners and implants	Regulatory approval for mass customization in medical devices
	Bioprinting for tissue engineering	Telemedicine applications using 3D printed devices
Construction and architecture	3D printed concrete structures and prefabricated modules	Integration of robotics for large-scale construction projects
	Architectural elements with intricate designs	Sustainable building materials and recycling processes
	Disaster relief shelters and temporary housing	3D printed infrastructure in space exploration
Consumer Products and Electronics	Customized fashion accessories and jewelry	Personalized consumer products with embedded electronics
	Personalized consumer electronics	Customized food printing for nutrition and dietary needs
	Eco-friendly and sustainable product designs	Enhanced retail experiences through on-demand manufacturing
	On-demand production of spare parts	Integration with IoT for smart home applications
Aerospace and defense	Lightweight, high-strength components for aircraft	Production of aerospace-grade metals and alloys
	Complex geometries and integrated systems	On-site repair and maintenance using 3D printing
	Prototyping and small-batch production	3D printed satellites and space habitats

A. Automotive Industry.

In the automotive sector, 3D printing is revolutionizing manufacturing processes by enabling the production of lightweight, complex geometries with enhanced mechanical properties. Additive manufacturing techniques facilitate rapid prototyping, tooling production, and customization of vehicle components, leading to reduced lead times and production costs [6]. Applications range from interior trim components and structural elements to engine parts and vehicle prototypes [7]. Case studies from automotive giants like BMW, Ford, and Volkswagen highlight the integration of 3D printing for achieving sustainability goals through material efficiency and design optimization [8].

B. Healthcare Sector.

The healthcare industry has embraced 3D printing for personalized medicine, medical device manufacturing, and surgical planning. Additive manufacturing enables the production of patient-specific implants, prosthetics, and surgical guides tailored to individual anatomical variations [9].

Customization not only enhances patient outcomes but also reduces surgical risks and recovery times. Biocompatible materials such as titanium alloys and medical-grade polymers are commonly used in medical 3D printing applications, with stringent regulatory frameworks ensuring product safety and efficacy [10]. Challenges include scalability, regulatory compliance, and the need for standardized quality control measures to ensure reproducibility and reliability across medical 3D printing processes [11].3D Printed Wearables: In the healthcare sector, 3D printed wearables are significantly advancing patient care and medical monitoring. These wearables offer customization to fit individual anatomical and functional needs, enabling highly personalized solutions that traditional manufacturing methods cannot match. For instance, 3D printed orthotics and prosthetics can be designed for enhanced comfort and functionality, while wearable sensors made through 3D printing can continuously monitor vital signs and manage chronic conditions. The use of flexible polymers and biocompatible materials enhances the integration of these devices with the human body. The rapid prototyping and iterative design capabilities of 3D printing are crucial for developing effective and user-friendly medical wearables (43).

C. Construction and Architecture.

In the construction industry, 3D printing offers innovative solutions for sustainable building practices and infrastructure development. Large-scale 3D printers can fabricate concrete structures, prefabricated modules, and architectural components with intricate designs and geometries that are difficult to achieve using traditional construction methods [12]. The use of sustainable materials such as recycled aggregates, geopolymer concrete, and biodegradable polymers further enhances the environmental sustainability of 3D printed structures [13]. Applications range from residential housing and commercial buildings to disaster relief shelters and sustainable urban infrastructure projects [14]. Advancements in robotic construction systems and digital fabrication technologies are expanding the feasibility and scalability of 3D printing in construction, revolutionize the cost-effective, energy-efficient building solutions [15].

D. Consumer Products and Electronics.

Additive manufacturing is transforming the consumer products and electronics industries by enabling on-demand manufacturing, product customization, and sustainability-driven design innovations. Companies are leveraging 3D printing to produce lightweight, durable consumer goods, wearables, and electronics components using advanced materials and manufacturing techniques [16]. The integration of recycled plastics, biocompatible polymers, and eco-friendly materials in 3D printed products aligns with consumer preferences for sustainable and environmentally responsible manufacturing practices [17]. Case studies from leading brands demonstrate the commercial viability of additive manufacturing for creating high-performance, aesthetically appealing consumer products while minimizing

material waste and production costs [18].3D Printed Electronics: The use of 3D printing in electronics fabrication is transforming how electronic components are produced. This technology allows for the creation of complex circuits and components within a single 3D printed structure by integrating conductive materials directly into the print. This approach facilitates the development of custom electronic devices with embedded circuits and sensors, leading to innovative consumer products. Examples include personalized gadgets, wearable technology, and smart packaging. The reduction in material waste and assembly needs through 3D printed electronics supports more sustainable manufacturing practices.

E. Aerospace and Defense.

In the aerospace and defense sectors, 3D printing has emerged as a disruptive technology for manufacturing lightweight, complex components with superior strength-to-weight ratios and performance characteristics. Additive manufacturing enables design optimization, part consolidation, and rapid prototyping of aerospace components, reducing material waste and production lead times [19]. Applications include aircraft interiors, engine parts, satellite components, and defense equipment, where stringent quality standards and regulatory compliance are paramount [20]. Challenges such as material qualification, process repeatability, and supply chain integration require collaborative efforts between industry stakeholders, researchers, and regulatory bodies to accelerate the adoption of 3D printing in aerospace and defense manufacturing [21]. Hybrid 3D Printing Technologies: In aerospace and defense, hybrid 3D printing technologies are utilized to produce lightweight, multifunctional components. These technologies combine additive manufacturing with traditional manufacturing processes to create parts with complex geometries and superior performance. For example, hybrid 3D printing allows for the integration of metal and polymer layers in a single part, achieving strength and reduced weight, which is critical for aerospace applications. Additionally, such technologies enable the production of parts with integrated functionalities like thermal or electrical conductivity, essential for advanced aerospace and defense systems.

4. Cross-industry implications and challenges

The widespread adoption of 3D printing across industries necessitates addressing interdisciplinary challenges and considerations to maximize its potential for sustainable manufacturing. Economic feasibility remains a critical factor influencing the scalability and commercialization of additive manufacturing technologies [22]. While initial costs for 3D printers and materials may be higher than traditional manufacturing methods, cost savings from reduced material waste, design flexibility, and decentralized production models contribute to long-term economic benefits [23].

Ethical considerations encompass intellectual property rights, data security, and workforce implications associated with the digitalization and automation of manufacturing processes [24]. Regulatory frameworks governing product safety, quality assurance, and environmental standards vary across regions and industries, posing challenges for global adoption and standardization of 3D printing technologies [25]. Collaborative efforts between academia, industry, and regulatory

bodies are essential to develop robust certification protocols, industry standards, and best practices for ensuring the reliability, safety, and sustainability of 3D printed products [26].

5. Technological advancements

3D printing, also known as additive manufacturing, has undergone significant advancements that have revolutionized manufacturing processes across various industries. These advancements have not only expanded the capabilities of 3D printing but also enhanced its potential to support sustainable manufacturing practices.

a. Improved Printers and Materials: The evolution of 3D printer technology has led to significant improvements in precision, speed, and scalability. Modern printers now offer larger build volumes and increased resolution, allowing for the production of complex geometries with high accuracy [27]. Moreover, advancements in multi-material printing capabilities have enabled the creation of hybrid structures that combine different materials to optimize performance and durability [28].
b. New Materials Development: One of the most profound impacts of 3D printing on sustainable manufacturing is its ability to utilize a diverse range of materials, including biodegradable polymers, recycled plastics, and sustainable composites. These materials not only reduce environmental impact but also offer enhanced mechanical properties suitable for a wide range of applications, from consumer goods to aerospace components [29].
c. Process Optimization: Continuous research and development efforts have focused on optimizing 3D printing processes to improve efficiency and reduce production costs. For instance, innovations in printing techniques such as Selective Laser Sintering (SLS) and Stereolithography (SLA) have minimized material wastage and energy consumption compared to traditional manufacturing methods [30]. This efficiency not only lowers operational costs but also contributes to sustainability by conserving resources.
d. Integration with Digital Technologies: The integration of 3D printing with digital design tools, such as Computer-Aided Design (CAD) software and Artificial Intelligence (AI), has streamlined the product development cycle. Design iterations can be rapidly prototyped and tested, facilitating faster time-to-market and reducing overall development costs [31]. AI algorithms are also being employed to optimize printing parameters, enhance part quality, and predict material behavior, further enhancing the reliability and scalability of additive manufacturing processes [32].

6. Means to enhance sustainable manufacturing

The versatility of 3D printing technology offers numerous applications that enhance sustainable manufacturing practices across various sectors which is explained below and given in **Figure 1**.

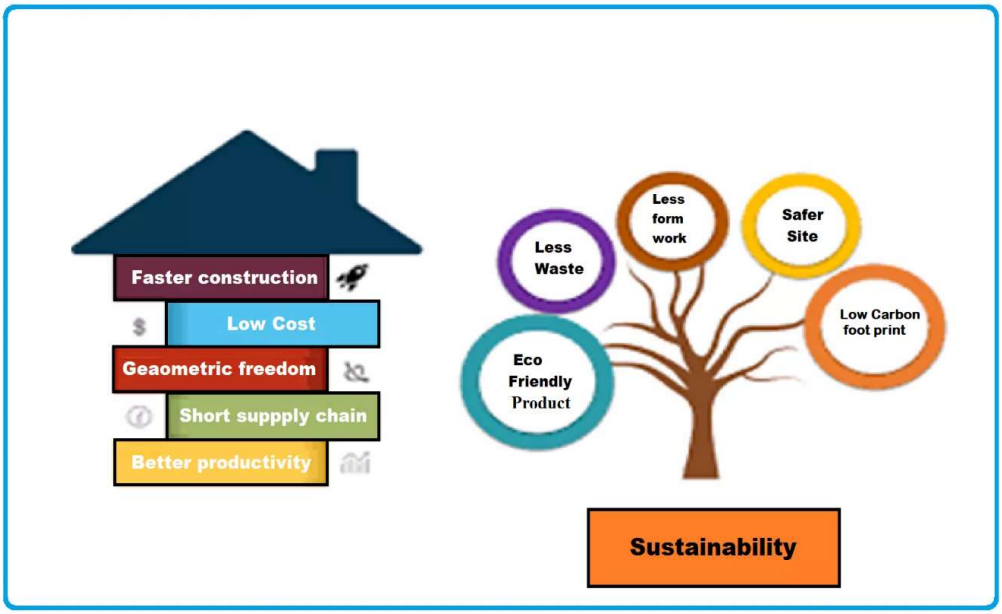

Figure 1. Different sustainable benefits of 3D printing.

a. Material Efficiency: Additive manufacturing minimizes material waste by utilizing only the necessary amount of material for each printed component. Unlike traditional subtractive manufacturing processes that generate significant waste from cutting or milling operations, 3D printing builds objects layer by layer, optimizing material usage and reducing environmental footprint [33].
b. Energy Savings: Certain 3D printing techniques require lower energy consumption compared to conventional manufacturing methods. For instance, processes like Powder Bed Fusion (PBF) and Digital Light Processing (DLP) use localized energy sources, such as lasers or light, to selectively solidify materials, minimizing energy-intensive heating and cooling cycles associated with traditional casting or machining processes [34].
c. Sustainable Materials: The adoption of recycled materials and bio-based polymers in additive manufacturing contributes to sustainable resource management. By repurposing waste materials or utilizing renewable resources, manufacturers can reduce reliance on virgin materials and mitigate the environmental impact of production processes [35]. Moreover, advancements in material science continue to expand the availability and performance of sustainable alternatives, enabling broader adoption in critical industries like healthcare and automotive manufacturing.
d. Localized Production: The on-demand and decentralized nature of 3D printing enables localized production of customized or spare parts, reducing the need for extensive transportation networks and warehouse storage. This localization not only minimizes carbon emissions associated with logistics but also enhances supply chain resilience by reducing lead times and minimizing inventory overheads [36].

6.1. Fused deposition modeling (FDM)

Material Cost:

- Low Cost: FDM uses thermoplastic filaments, such as PLA, ABS, or PETG, which are generally inexpensive and widely available. PLA is particularly noted for its lower cost and use of biodegradable materials.

Energy Consumption:

- Moderate to High: FDM printers require significant energy to heat the extrusion head and build platform, which can lead to relatively high energy consumption, especially for larger prints or extended operations.

Emissions:

- Low to Moderate: PLA, being a bio-based plastic, has a lower environmental impact compared to petroleum-based plastics like ABS. However, the heating process can still emit fumes, including volatile organic compounds (VOCs). Using enclosures and proper ventilation can help mitigate these emissions.

Lifecycle Impact:

- Waste Generation: FDM produces waste in the form of support structures and failed prints. However, many FDM materials can be recycled or repurposed, reducing overall waste.

6.2. Stereolithography (SLA)

Material Cost:

- High Cost: SLA uses photopolymer resins, which are more expensive than FDM filaments. The cost of resins can vary depending on their properties and intended use.

Energy Consumption:

- Moderate: SLA printers use UV light to cure resin layer by layer, which is less energy-intensive compared to the heating processes in FDM. However, the post-processing steps, including washing and curing, can be energy-consuming.

Emissions:

- Low to Moderate: SLA resins may release VOCs during curing. Proper handling and disposal are essential to minimize environmental impact. Many resins are now available with lower emissions profiles.

Lifecycle Impact:

- Waste and End-of-Life: SLA produces resin waste that can be hazardous. Proper disposal and recycling programs for resin containers and excess material are important to mitigate environmental impacts.

6.3. Selective laser sintering (SLS)

Material Cost:

- Moderate to High: SLS uses powdered materials, such as nylon or polymer blends, which tend to be more expensive than FDM filaments but can be more durable and functional.

Energy Consumption:

- High: SLS printers operate at high temperatures to sinter powders, requiring significant energy. The process involves heating the entire build chamber, which is energy-intensive.

Emissions:

- Moderate: SLS can produce emissions from the sintering process, particularly when using certain polymers. Advanced filtration systems can help reduce airborne particulate matter and VOCs.

Lifecycle Impact:

- Material Efficiency: SLS is known for its minimal waste generation as unused powder can be reused in subsequent prints. However, the end-of-life disposal of SLS parts can be challenging, particularly for composite materials.

6.4. Direct metal laser sintering (DMLS)

Material Cost:

- Very High: DMLS uses metal powders, which are significantly more expensive than polymers used in other 3D printing methods. This high material cost reflects the high-value applications of DMLS, such as aerospace and medical implants.

Energy Consumption**:**

- Very High: DMLS involves laser melting metal powders, requiring extremely high temperatures and significant energy consumption. The process is energy-intensive due to both the metal melting and the need for high-precision lasers.

Emissions:

- Moderate to High: The metal melting process can produce fumes and particulates, which need to be managed with effective filtration systems to minimize environmental impact.

Lifecycle Impact:

- Waste Generation: DMLS generates minimal waste as excess powder can often be reused. However, the disposal of metal powders and parts at the end of their life requires specialized recycling and recovery processes to manage the environmental impact effectively.

Fused Deposition Modeling (FDM) is generally more sustainable in terms of material cost and emissions when using biodegradable materials like PLA. Stereolithography (SLA) has higher material costs and requires careful management of resin waste but has lower energy consumption compared to other methods. Selective Laser Sintering (SLS) and Direct Metal Laser Sintering (DMLS) offer high material efficiency and minimal waste but are more energy-intensive and have higher material costs. Each technology has its advantages and limitations in sustainability, and the choice of technology should be aligned with specific application requirements and sustainability goals.

7. Future prospects

Looking ahead, the future of 3D printing in sustainable manufacturing holds promising prospects for innovation and growth:

1) Advancements in Materials Science: Ongoing research and development efforts are focused on expanding the range of sustainable materials available for additive manufacturing. Innovations in bio-based resins, recycled metals, and biodegradable composites will unlock new possibilities for environmentally friendly product design and manufacturing [37].

2) Industry 4.0 Integration: Industry 4.0 is the Fourth Industrial Revolution characterized by the integration of advanced technologies like IoT, AI, and robotics into manufacturing processes to create smart, interconnected systems that enhance efficiency, flexibility, and data-driven decision-making.The convergence of 3D printing with Industry 4.0 technologies, such as Internet of Things (IoT) and blockchain, will enable enhanced connectivity, real-time monitoring, and data-driven insights into manufacturing processes. This integration supports predictive maintenance, quality control, and supply chain transparency, paving the way for smart factories of the future [38].
3) Scaling Production: Advances in additive manufacturing techniques, including large-scale 3D printing and robotic automation, will enable the mass production of end-use parts across diverse industries. By optimizing production workflows and increasing throughput rates, manufacturers can achieve economies of scale and meet growing demand for sustainable products with enhanced cost-efficiency [39].

8. Challenges and possible solutions

Despite its potential benefits, integrating 3D printing into sustainable manufacturing practices presents several challenges that need to be addressed:

a. Material Limitations: While advancements have been made in developing sustainable materials for 3D printing, challenges remain in scaling up production and ensuring consistent material quality. Researchers and manufacturers need to collaborate to innovate new materials with improved mechanical properties and environmental credentials [40]. Solution: Invest in research and development to expand the range of sustainable materials available for additive manufacturing. Foster partnerships between academia, industry, and government agencies to accelerate material innovation and certification processes.
b. Energy Consumption: Although certain 3D printing processes are energy-efficient, others can still be energy-intensive, especially for large-scale production. Balancing energy efficiency with production speed and part quality remains a challenge for widespread adoption in energy-conscious industries [41]. Solution: Optimize printing parameters and invest in energy-efficient technologies such as hybrid heating systems and renewable energy sources to reduce the environmental impact of additive manufacturing processes.
c. Cost and Scalability: Initial costs associated with 3D printing equipment, materials, and training can be prohibitive for small and medium-sized enterprises (SMEs). Additionally, scaling up production while maintaining cost-effectiveness and quality control remains a challenge for large-scale adoption [42]. Solution: Implement cost-sharing initiatives, such as government grants or industry consortia, to reduce the financial burden on SMEs interested in adopting 3D printing technologies. Invest in workforce training programs to build capacity and expertise in additive manufacturing across diverse industrial sectors.

d. Adopting 3D printing within Industry 4.0 It presents several challenges. First, material limitations pose significant hurdles, as developing and qualifying new materials that meet industrial standards for strength and performance is complex. Cost and scalability issues also persist, with high initial investments in advanced 3D printing technology and difficulties in scaling up production affecting widespread adoption. Integration with existing manufacturing systems requires substantial adjustments to workflows and infrastructure, complicating the transition to additive manufacturing. Furthermore, quality control and consistency are critical concerns, especially for applications demanding high precision and reliability. Finally, navigating regulatory compliance is challenging due to diverse and evolving standards across industries and regions, which can impede the adoption and standardization of 3D printing technologies.
e. Ethical and regulatory challenges. However, the widespread adoption of these technologies also introduces potential regulatory and ethical challenges. Regulatory frameworks for 3D printing are still evolving, and ensuring that these frameworks adequately address issues related to safety, quality, and environmental impact is critical. Compliance with varying international standards can be complex and may hinder global integration. Furthermore, the ethical implications of advanced manufacturing technologies, such as data privacy, intellectual property rights, and the potential for job displacement, must be carefully considered. Addressing these concerns requires collaborative efforts between industry stakeholders, policymakers, and regulatory bodies to develop robust guidelines and best practices that ensure the responsible and equitable use of 3D printing and associated technologies.

9. Conclusion

3D printing stands as a transformative technology poised to significantly advance sustainable manufacturing practices across a wide range of industries. This paper has explored how additive manufacturing not only enhances production efficiency and customization but also contributes to environmental sustainability through reduced material waste and energy consumption. The versatility of 3D printing technologies, including Fused Deposition Modeling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), and Direct Metal Laser Sintering (DMLS), underscores their potential to revolutionize sectors such as automotive, healthcare, construction, consumer products, and aerospace.

Despite its considerable advantages, the adoption of 3D printing presents challenges that must be addressed. These include material limitations, energy consumption, cost scalability, and regulatory compliance. As 3D printing technologies continue to evolve, integrating advancements in material science, process optimization, and Industry 4.0 technologies will be crucial. The convergence with digital tools like IoT and AI promises to further enhance manufacturing capabilities, though it also necessitates careful consideration of regulatory and ethical issues.

The future of 3D printing in sustainable manufacturing is marked by its potential to drive innovation and efficiency, making it a cornerstone technology for a

more resilient and environmentally responsible production ecosystem. Continued research and development, alongside collaborative efforts from industry, academia, and regulatory bodies, will be essential to overcoming current challenges and fully realizing the benefits of 3D printing. As we advance, it is imperative to focus on sustainable practices and ethical considerations to ensure that the evolution of manufacturing technologies aligns with broader societal and environmental goals.

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