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REVIEW ARTICLE

A review of the industrial use and global sustainability of *Cannabis sativa*

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Abstract
The Cannabis plant (*Cannabis sativa* L.), also known as hemp, is a sustainable and multipurpose plant that may be used for a wide range of purposes, from the fiber in its stalks to the food in its seeds to the oil in its flowers and seeds. Since the Cannabis plant has been recognized to be an outstanding carbon trap and environmentally friendly biofuel that supports all three aspects of sustainability—the economy, the environment, and society—it may provide a solution to the climate change dilemma. The cultivation of the Cannabis plant has been practiced as a dietary staple in numerous places across the globe for an extended period. However, its production has been prohibited in several countries mostly owing to its relationship with illicit drug consumption. The illegality of the plant has impeded research efforts for an extended period of time on a global scale. As a result, people's ability to assess the whole range of beneficial effects and dangers shrank. However, the global trend toward Cannabis legalization and decriminalization has accelerated in recent years. This has stimulated more investigation into the botanical, ecological, and practical aspects of the plant. This study reviewed the available literature to understand more about the Cannabis plant's global sustainability. The results demonstrated the potential of Cannabis plants to affect product sustainability and the use of hemp as a renewable raw material. Furthermore, this review outlines the connections between the Cannabis plant and the Sustainable Development Goals (SDGs) of the United Nations. This research fills a gap in our understanding of the Cannabis plant's sustainability as a highly promising multi-purpose crop for the future.

Keywords: Cannabis; Hemp; Fiber; Industry; Environment; Sustainability

Introduction

Global environmental issues are being exacerbated by the current climate changes on the planet, which are mostly the result of human activity (Raihan et al., 2022a; Abbas et al., 2023). Some of the results of these issues are overpopulation, climate change, and the loss of biodiversity. The literature confirms that these phenomena arise from the irresponsible consumption of natural resources (Jaafar et al., 2020; Begum et al., 2020; Voumik et al., 2022; Raihan, 2023a). Ecological, economic, and agricultural sustainability are interdependent and necessary for environmental protection (Agrawal et al., 2022; Ibarra et al., 2023; Raihan, 2023b). Sustainable farming options have recently garnered a lot of attention from farmers all around the world (Raihan et al., 2023a; Sharma et al., 2023). Hemp, often known as the Cannabis plant, is attracting interest as a sustainable crop with great potential (Rivas-Aybar et al., 2023). Cannabis is thought to have originated in East and Central Asia before spreading throughout the rest of Asia and, eventually, to Europe (Wani et al., 2023). Industrial hemp, also known as *Cannabis sativa* L., is cultivated for its fiber, oilseed, medicinal, and recreational uses (Visković et al., 2023).

The Cannabis plant is an annual herb that can reach heights of 1 to 6 meters and is dioecious in nature (Agate et al., 2020). Hemp, one of the world's fastest-growing plants, is an annual with a complex leaf structure (Kaur & Kander, 2023). Besides improving air quality, thermal balance, and environmental impact, Cannabis plants can remove up to 10 metric tons of carbon dioxide from the air in a single vegetation cycle (Zimniewska, 2022).
The Cannabis plant has a high yield when it comes to fiber production; on the same amount of land, it may generate 250% more fiber than cotton and 600% more fiber than flax (Rupasinghe et al., 2020). Figure 1 presents the benefits of the hemp apparel industry. Cannabis plants can be produced without the use of herbicides because their dense canopies shade out weeds and reduce the number of soil-dwelling fungi and nematodes (Adesina et al., 2020). Because of how firmly it anchors its roots in the ground, the Cannabis plant helps preserve soil quality by preventing erosion and nutrient leaching. It also aids in phytoremediation by removing pollutants such as heavy metals from the soil and preserving them inside the plant (Cleophas et al., 2022). Throughout the growing season, leaves fall to the ground, providing a steady supply of wet organic matter (Rupasinghe et al., 2020). The Cannabis plant is an excellent option for use in crop rotation plans to enhance the production of the primary crop because of its role in enhancing the soil quality. If Cannabis cultivation is handled correctly, the plant is predicted to be a sustainable and environmentally benign crop (Adesina et al., 2020). Farmers who cultivate the Cannabis plant have the option of using fewer herbicides, rotating crops, and eventually becoming certified as organic (Visković et al., 2023). The agricultural sector is interested in cultivating Cannabis due to its environmental benefits and the expanding market for hemp products (Quaicoe et al., 2023). Growing, processing, using, recycling, reusing, bio-refining, and waste management—the entire value chain of the Cannabis plant—satisfies the principles of sustainability tactics and can aid in combating climate change (Kaur & Kander, 2023).

Figure 1. The benefits of the hemp apparel industry.

Many different plants, notably hemp and marijuana, are produced by the Cannabis genus. Cannabinoids, which are found in high concentrations in Cannabis, each have their own unique physiological effects in humans, numbering over a hundred (Simiyu et al., 2022). The two most studied cannabinoids are tetrahydrocannabinol (THC), the psychoactive component responsible for the "high" associated with Cannabis, and cannabidiol (CBD), a safe, non-addictive, and non-hallucinogenic substance known for its medicinal properties. profile (Johnson, 2019). Bud, oil, and tinctures containing CBD are on the market for the purpose of reducing inflammation and stress (Iseger & Bossong, 2015; Hameed et al., 2023). Because of its intoxicating effects, THC is prohibited in many countries despite its widespread medical and recreational usage (Bridgeman & Abazia, 2017). Hence, it is imperative to differentiate between the several classifications of *Cannabis sativa* L., namely marijuana and industrial hemp, in order to engage in lawful cultivation practices. The determination of the THC concentration threshold on a dry weight basis is commonly employed as the primary criterion for distinguishing between the two unique types. On a dry weight basis, THC concentrations in industrial hemp are typically below 1%, but in marijuana can range from 3% to 15% (Rupasinghe et al., 2020). Industrial hemp's validity varies across different locations and countries. Producing hemp with high concentrations of psychoactive cannabinoids is illegal in most countries, including the European Union (EU), in order to deter its usage for recreational purposes (Sgrò et al., 2021). The EU regulations impose the most stringent limitation on THC concentration, capping it at 0.2%. In comparison, Mexico allows up to 1.0% THC, Malaysia permits 0.5% THC, and the majority of countries, including America, Canada, China, and East Asian countries, set the maximum at 0.3% THC (Zhao et al., 2021). Research into Cannabis has been hampered for decades by the plant's widespread prohibition, slowing the development of policies and agricultural extension guidelines needed to minimize adverse environmental outcomes (Wartenberg et al., 2021; Clarke & Fitzcharles, 2023). As a result, people's ability to assess the whole range of beneficial effects and dangers shrank. However, the global trend toward legalizing and decriminalizing *Cannabis sativa* has accelerated in recent years (Yousufzai et al., 2023). Because of this, researchers have begun to focus more on the plant and its many potential applications (Simiyu et al., 2022). Governments, individual researchers, and corporations from all around the world have recently expressed an intense curiosity about industrial hemp (Kaur & Kander, 2023). Proponents of Cannabis legalization point to the plant's environmental benefits, adaptability to different agronomic circumstances, and myriad uses to argue that it should be legalized as a cash crop for farmers (Taylor et al., 2023). It has been suggested in research that the cultivation of the Cannabis plant could be financially rewarding if treated like any other commercial agricultural entrepreneurship (Kaur & Kander, 2023). However, due to global limitations and restrictions on industrial hemp production, much of the existing research on the sustainability potential of the Cannabis plant is based on notions that have not been validated or are already out of date (Visković et al., 2023). Therefore, this study seeks to fill these gaps by reviewing the existing literature on industrial uses of the Cannabis plant and its sustainability from multiple points of view of economic, environmental, and social sustainability. In addition, this study portrays how the Cannabis plant contributes to achieving the United Nations' Sustainable Development Goals (SDGs). This research has the potential to contribute to the development and implementation of appropriate policies aimed at the global legalization of the Cannabis plant, as well as the promotion of industrial hemp, with the ultimate aim of accomplishing the SDGs.

Methodology

The present study employed the systematic literature review methodology as suggested by Tawfik et al. (2019). According to Benita (2021) and Raihan (2023c), the systematic literature review framework is considered to be a reliable approach. A preliminary review of the literature was conducted to identify pertinent articles, validate the proposed idea, avoid redundancy with previously covered issues, and ensure the availability of sufficient articles for conducting a comprehensive analysis of the subject matter. Both scholarly and gray literature were identified and sourced using a global Google Scholar search of the literature on industrial hemp, its applications, and its sustainability. The industrial application and long-term viability of the Cannabis plant are examined by reviewing a variety of publications covering the time span from 2000 to 2023. "Cannabis sativa," "industrial hemp," "parts of the hemp plant," "hemp fiber," "hemp seed," "hemp oil," "uses of industrial hemp," "hemp global production," "pillars of sustainability," and "hemp and sustainability" are only some of the search keywords used in this literature study. The Google Scholar search returned almost a thousand results. Peer-reviewed publications, book chapters, and government and international agency reports were filtered into a second search. The study then analyzed the titles, keywords, and abstracts of the search results to determine how relevant they were. For instance, documents were omitted if they failed to address the present applications of industrial hemp or the sustainability of hemp. Figure 2 illustrates the development of review criteria employed for the selection of suitable documents for review analysis.

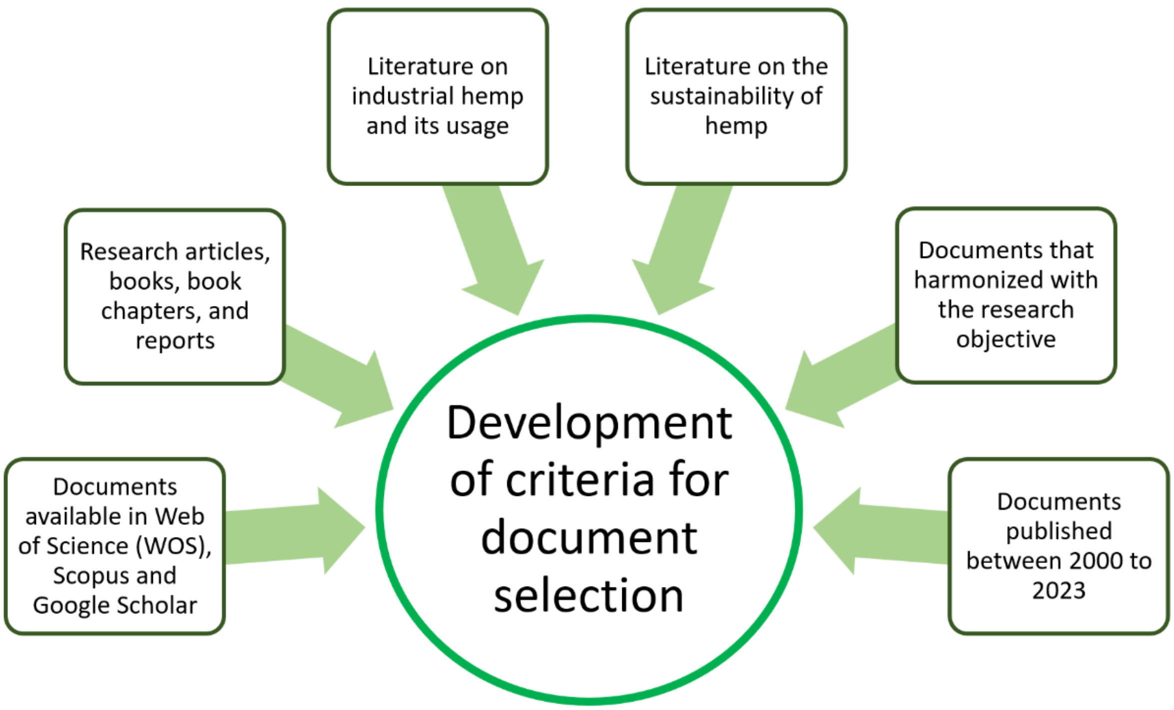

Figure 2. The development of criteria for the selection of documents.

The comprehensive literature review encompassed a total of 86 distinct scholarly documents. The present study implemented a data verification process, wherein each included article was cross-checked with its corresponding entry in an extract sheet using visual evidence. It is noteworthy to mention that of the 86 documents subjected to qualitative synthesis, only those publications containing relevant material were cited in the reference list contained in the manuscript. This implies that certain articles were not included in the reference list. Figure 3 illustrates the systematic review procedure utilized in the current study. After the research topic was chosen, this study conducted a systematic search for relevant publications, analyzed and synthesized information from diverse literature sources, and prepared written materials for article review. The synthesis phase encompassed the collection of a wide range of publications, which were subsequently amalgamated into conceptual or empirical analyses that were relevant to the finalized research.

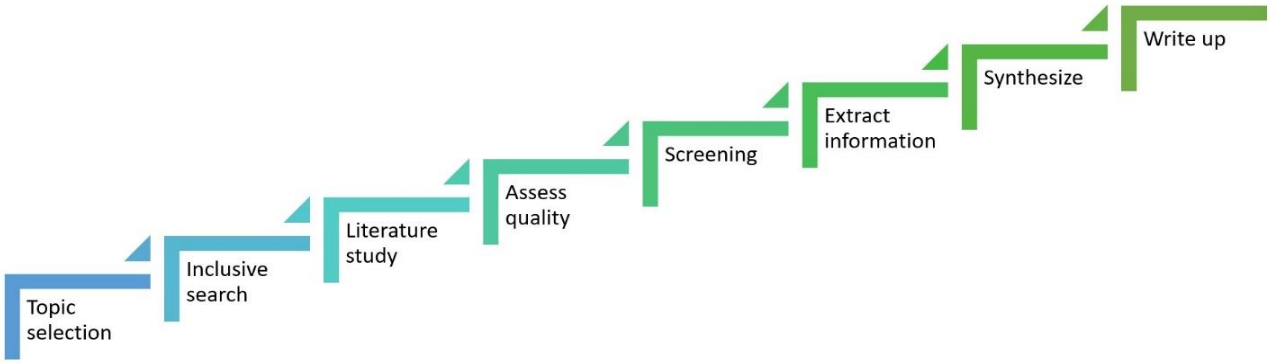

Figure 3. The procedure of systematic review conducted by the study.

Usage of Cannabis plant

Seeds, stems, flowers, leaves, and roots are all components of the Cannabis plant. Figure 4 depicts various components of the Cannabis plant. Hemp fiber is the stem and stalk of the industrial hemp plant. Hemp fiber production requires preventing the plant from spreading out and flowering. Plants are spaced at a density of 35-50 per square foot. Ten to fifteen feet is the optimal height at which to harvest Cannabis plants for fiber (Johnson, 2019). The outside layer of a hemp stem is made up of bast fiber bundles, which are more valued than the inner layer, which is made up of hurd or shive fiber bundles, which are less expensive woody components (John, 2019; Kaur & Kander, 2023). Figure 5 shows the hemp stem separated into fiber and hurd.

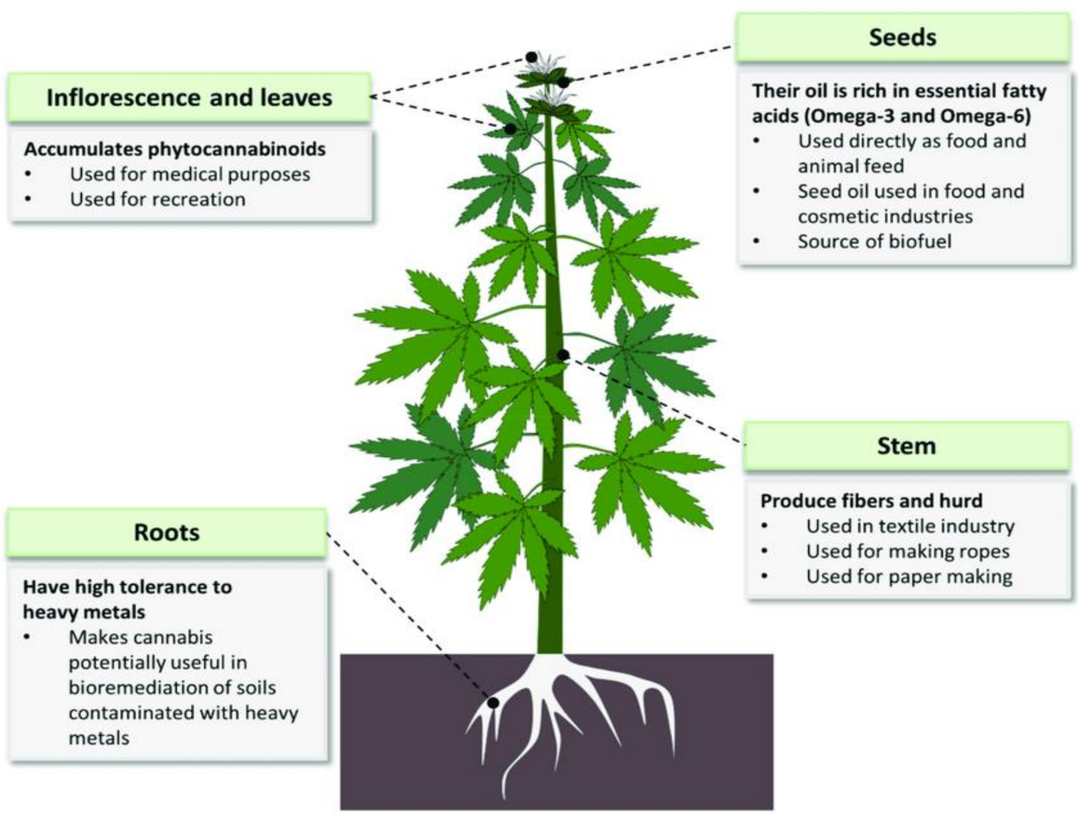

Figure 4. Various components of the Cannabis plant (Simiyu et al., 2022).

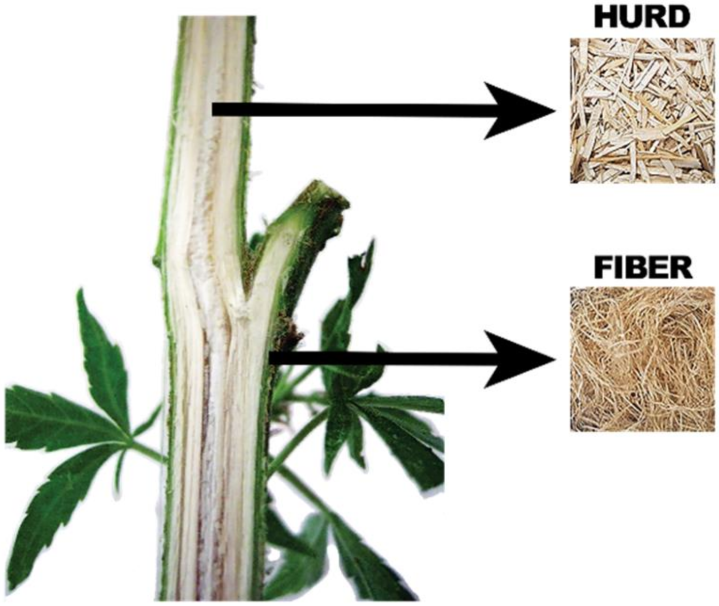

Figure 5. The stem fibers and hurd derived from the Cannabis plant (Kaur & Kander, 2023).

The hurd of a hemp stem accounts for 85% of its biomass (Li et al., 2018), while the bast fiber only accounts for 15%. Using a decorticator, retting, or both, the core fibers are mechanically removed from the bark to create fiber. After being cleaned, dried, and bale, hemp fibers can undergo further mechanical separation to undergo processes including cottonizing, shredding, and spinning into yarn. Oilseeds are obtained from the seeds of industrial hemp plants (Kaur & Kander, 2023). Growing hemp plants for their seeds is quite similar to growing hemp plants for their fiber. Seeds and grains from Cannabis plants can be harvested when they reach a height of 6 to 9 feet (Johnson, 2019). Hemp seeds range in size from about 1/8 to 1/4 inch and have a smooth exterior. Figure 6 is a cross-sectional view of a hemp seed from the side. During seed processing, the seed kernels are separated from their hulls (Kaur & Kander, 2023).

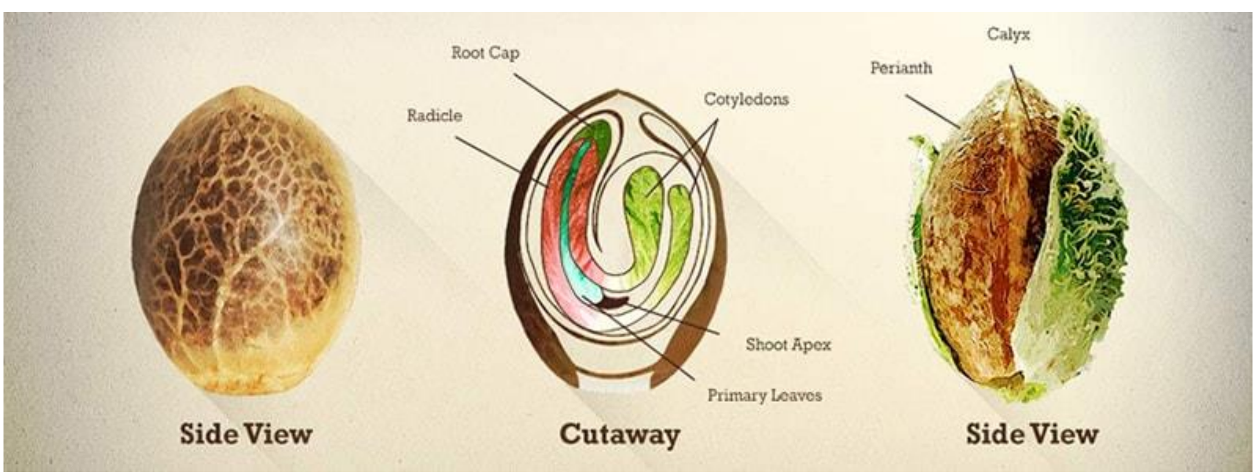

Figure 6. A side view and cross-section of a hemp kernel.

Flower buds and other floral components on Cannabis plants are collected for extraction of CBD and other oils. Flower buds and other floral materials can be cultivated by encouraging the development of wider branches and leaves. Hemp is spaced out more, typically between three and five feet, so that the plant has room to spread its roots and shoots (Johnson, 2019). Flowers on industrial hemp plants can be harvested when they are between four and eight feet tall. Lipid infusion, carbon dioxide extraction process, and solvent-free extraction are all necessary for oil production (Johnson, 2019). While hemp produced for seeds and grain produces 800 to 1000 pounds per acre, hemp farmed for fiber produces 2,000 to 11,400 pounds of entire dry stems per acre. According to Kaur and Kander (2023), each hemp plant may produce roughly one pound of dry flower buds.

Cannabis is a versatile plant in that nearly every part of it can be utilized (Simiyu et al., 2022). Hemp is one of the most rapidly reproducing plant species, and its fiber, seeds, and oil can be used in a variety of ways (Kaur & Kander, 2023). Multiple commercial applications for the Cannabis plant are shown in Figure 7. The dehulled or unhulled seeds can be used in cooking, as animal feed, in cosmetics, or pressed into oil using a cold process (Montero et al., 2023). The stem can be harvested for its shives (hurd), which can be used as animal bedding, as well as its fiber, which can be made into paper or textiles (Naeem et al., 2023). Essential oils, among other things, can be extracted from the hemp flower for application in cosmetics and medicines (Farinon et al., 2020; Arif et al., 2023). More than 25,000 products are made from industrial hemp around the world in various industries such as paper, fabrics and textiles, construction and insulation materials, home furnishings, yarns and spun fibers, carpeting, and bio-composites owing to the expanding global industrial hemp market (Kaur & Kander, 2023).

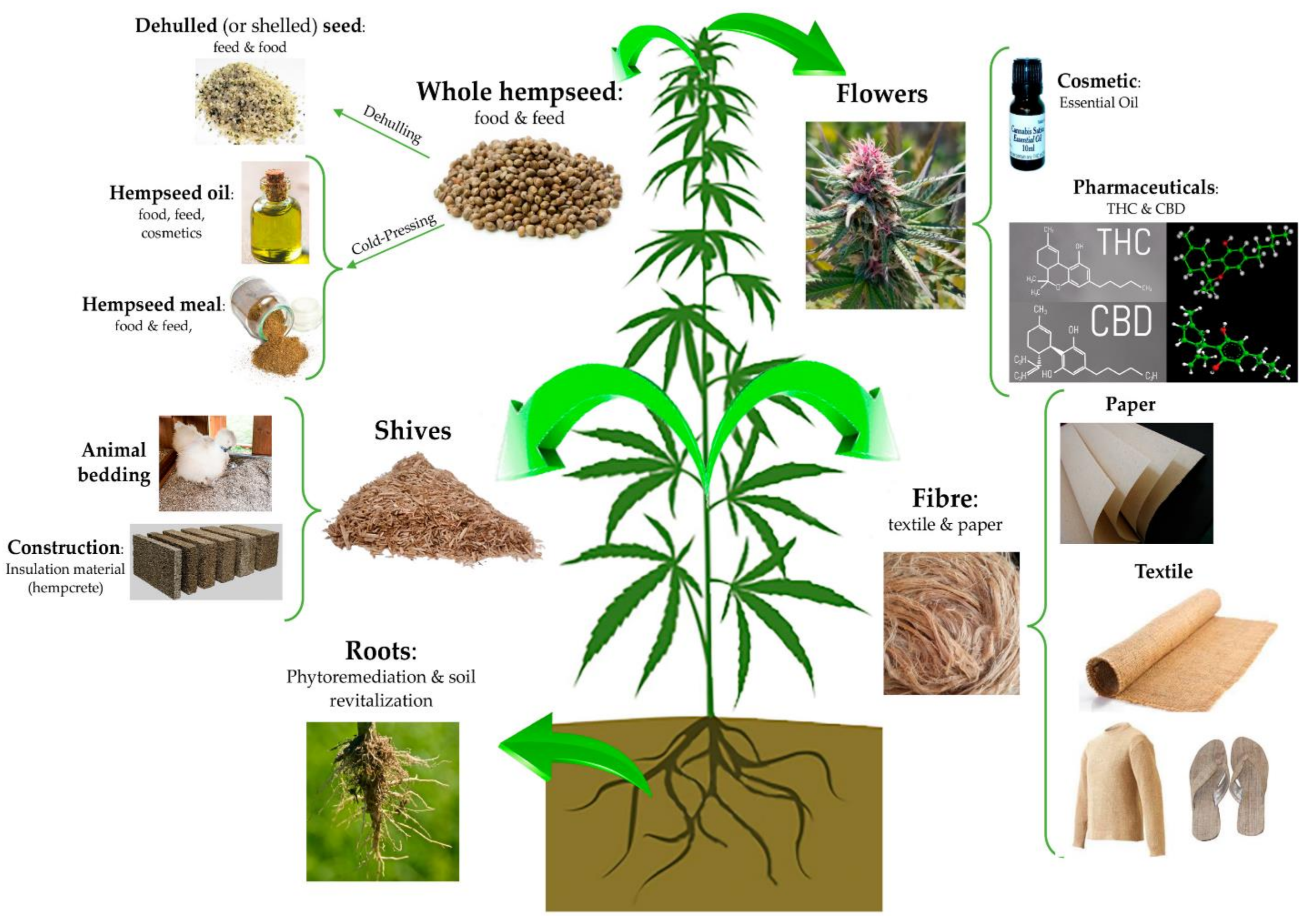

Figure 7. Various industrial applications of the Cannabis plant (Kaur & Kander, 2023).

It's possible to extract useful components from the Cannabis plant, which could be employed in a variety of applications (Martinez et al., 2023). Figure 8 is a schematic illustration of the many possible applications of the Cannabis plant. Hemp fiber is a renewable source of bast fiber and is used in a wide variety of industrial applications (Chaowana et al., 2024). Hemp fibers have been used for a variety of uses, including the production of paper, rope, and textiles (Naeem et al., 2023) due to their strength, resilience, and length (fiber bundles can reach 1-5 m). High-quality fabrics used in the global apparel industry can be woven from the hemp plant's fibers (Kozlowski & Muzyczek, 2023). Hemp fiber production is more sustainable and uses less water than conventional cotton farming (Yano & Fu, 2023). As an alternative to artificial, flammable synthetics, hemp is utilized to reinforce carpets that are resistant to rotting and fire (Filer, 2022). The market share for textiles, fabrics, and garments made from hemp fiber has expanded due to a growing worldwide preference for eco-friendly products from nature and sustainable systems (Gedik & Avinc, 2020; Raihan et al., 2022b).

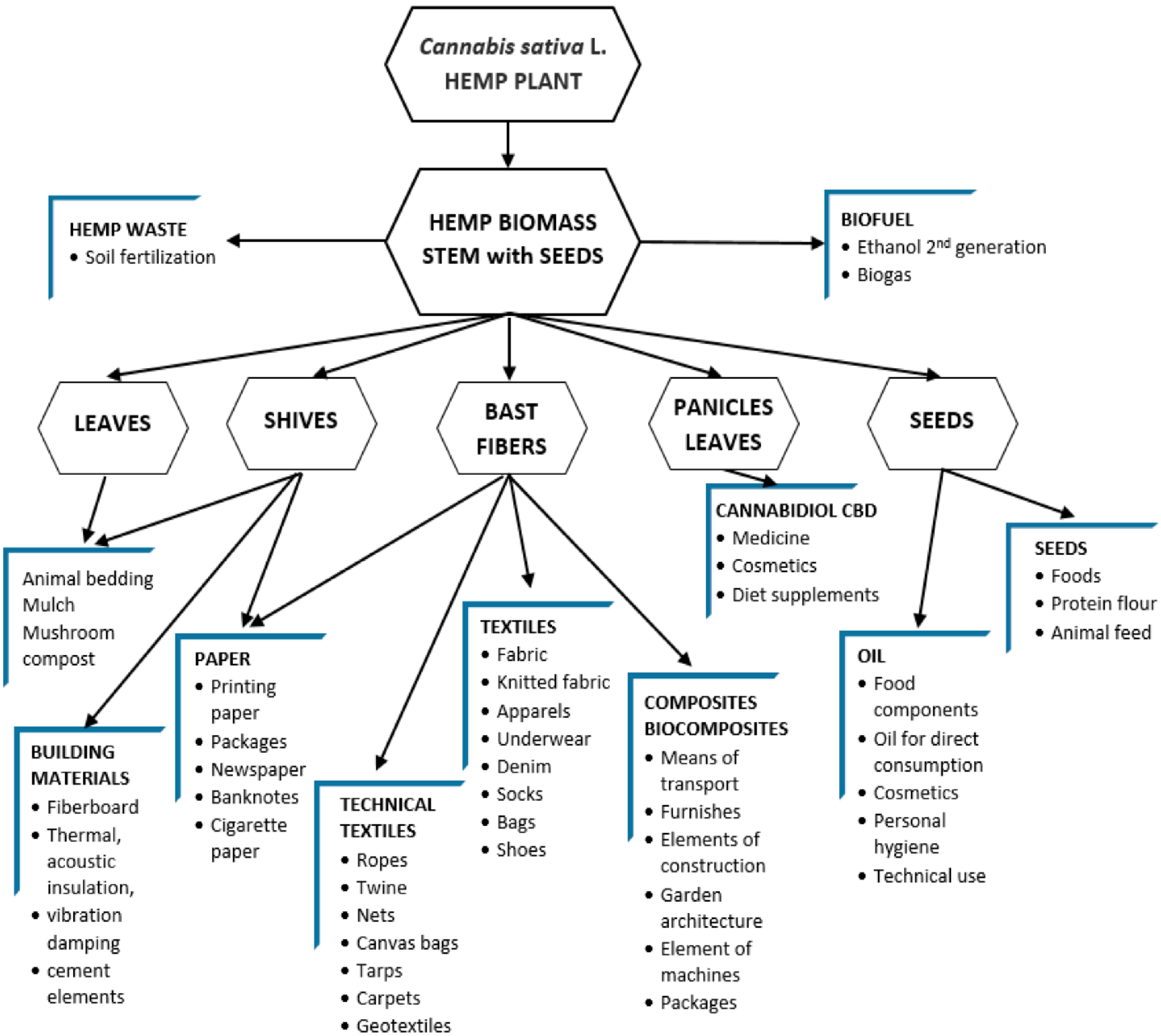

Figure 8. The diverse potential applications of the Cannabis plant as a raw material (Zimniewska, 2022).

The pulp and paper business has long faced formidable competition from the Cannabis plant. Hemp fiber, which makes up about 20%-30% of hemp stalks, is used to make eco-friendly paper (Tutek & Masek, 2022). In the car business, hemp fiber is utilized to manufacture dashboards, seats, and other interior components. However, the extracted hemp oil is an eco-friendly additive to paints and varnishes (Nachippan et al., 2021; Visković et al., 2023). A wide variety of goods, including horticultural planting materials, biodegradable mulching material, building-construction components, insulating materials, hurd-produced animal bedding, plastic bio-composites, and compressed cellulose polymers, are made from hemp fiber (Kaur & Kander, 2023) for a variety of uses. In agriculture, hemp straw is utilized as fodder because of the high nutritional value it provides for livestock, especially cattle (Wang et al., 2023). Industrial hemp is of interest to a variety of businesses due to the vast ecological potential associated with the Cannabis plant and the variety of raw materials it can offer (Malabadi et al., 2023). Figure 9 exhibits some of the possible applications of the Cannabis plant.

Figure 9. Potential industries that could use the Cannabis plant as their main raw material (Tutek & Masek, 2022).

For a long time, hemp seed was a crucial staple crop (Crescente et al., 2018; Visković et al., 2023). In addition to the many critical nutrients, antioxidants, and vitamins suggested for human beings (Jeliazkov et al., 2019; Burton et al., 2022; Strzelczyk et al., 2023), it also contains 35% edible oil (Hidayet & Tolu, 2023). Whole and dehulled hemp seeds, hemp flour, hemp oil, hemp seed cake (the residue of mechanical oil extraction), hemp seed meal, hemp hulls, and hemp protein extracts and concentrates are all products derived from hemp seeds (Burton et al., 2022; Frankowski et al., 2023). Oil extracted from hemp seeds is used to make salad dressing, and the oil and the seeds themselves are both high in healthy omega-3 fats and protein (Strzelczyk et al., 2023). Figure 10 shows the methods used to make the most common varieties of hemp seed-based ingredients for food. However, CBD oil is a non-psychoactive cannabinoid chemical derived from industrial hemp, and it does not have the same addictive properties as THC (Sun, 2023). Several nations have recently legalized CBD oil due to its potential health advantages and lack of addictive properties (Fauziah & Runturambi, 2023). CBD is utilized in a wide variety of items, including carbonated water, lotions, and pharmaceutical compounds, despite claims that it has beneficial health effects (Kaur & Kander, 2023). Research potential in these subfields is promising (Jeliazkov et al., 2019).

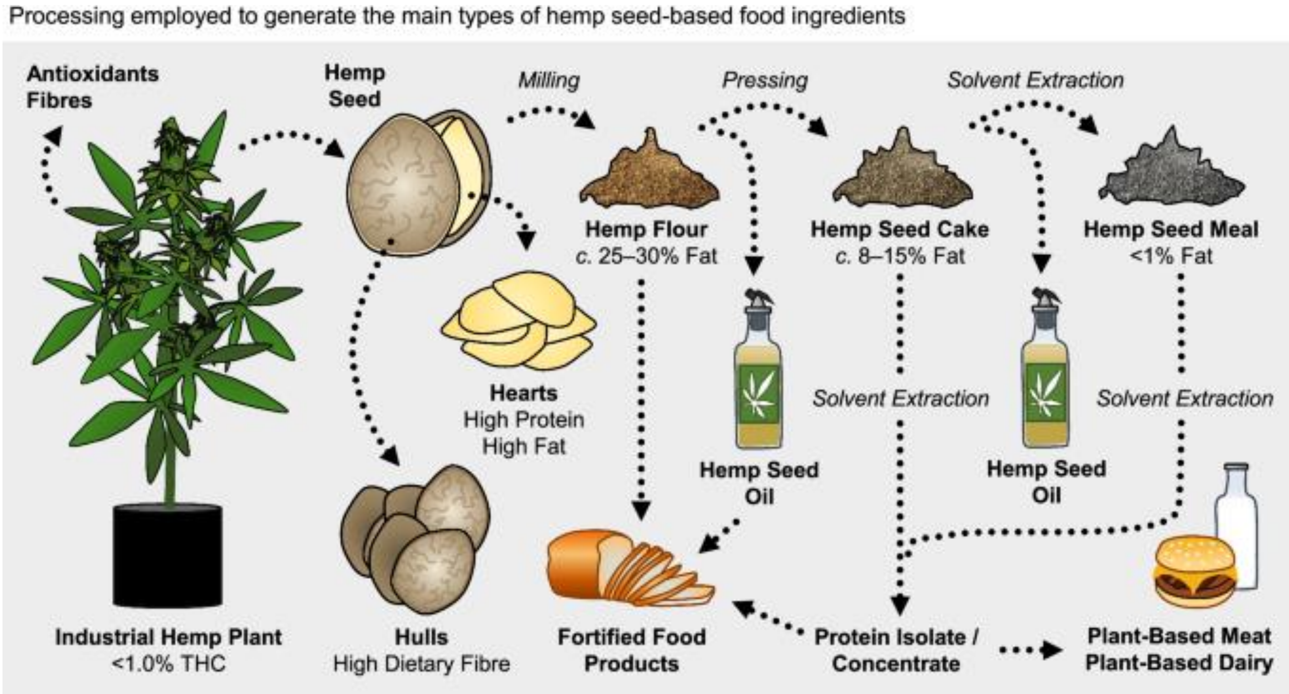

Figure 10. Processing employed to produce the most common forms of food ingredients derived from hemp seed (Burton et al., 2022).

The entire food sector, notably organic food, presents a strong rivalry for hemp-based food products. Incorporating hemp-based foods into diet is good for health (Malabadi et al., 2023). They influence cell regeneration, aging processes, cancer cell development inhibition, and immunity significantly (Fike, 2016; Sheik et al., 2023). According to research by Kaniewski et al. (2017), hemp seeds are loaded with antioxidant-rich nutrients like iron, calcium, zinc, phosphorus, magnesium, and vitamin E as well as micro and macro elements like edestin, choline, phytic acid, trigonelline, chlorophyll, lecithin, and vitamin K. Furthermore, it has a beneficial impact on the circulatory system by increasing blood vessel elasticity, enhancing blood flow, and decreasing the risk of ischemic heart disease and atherosclerosis (Tutek & Masek, 2022). Heart disease is a major problem in the developed world in the 21st century, however eating hemp cuisine can help reduce the risk of heart attack and improve the digestion process (Apostol, 2017).

Hemp seed oil has several uses in the cosmetics industry (Jeliazkov et al., 2019; Sarkar & Sadhukhan, 2023). Recently, a popular trend in the cosmetics business has been the use of hemp-derived ingredients (Naeem et al., 2023). Hemp-based cosmetics make use of hemp oil and extracts that contain regenerative, anti-aging, and anti-inflammatory ingredients. Hemp oil is classified as a "dry oil" due to its rapid absorption and lack of residual greasiness. Many companies now make cosmetics like lotions, oils, soaps, shampoos, and conditioners that contain hemp oil (Sarkar & Sadhukhan, 2023). The CBD and resin portions of hemp extract are responsible for the sedative and relaxing effects (Malabadi et al., 2023). Hemp compounds are gaining popularity in the pharmaceutical and medical industries as well. Nutritional issues, as well as post-traumatic stress disorder (PTSD), melancholy, anxiety, sleep disturbances, constipation, convulsions, and degenerative diseases like Alzheimer's, are the subjects of recent research (Pintori et al., 2023). CBD has also been studied for its potential to treat cancers in the brain, breast, prostate, skin, pancreatic, and colon (Afrin et al., 2020; Rupasinghe et al., 2020; Almeida et al., 2021; Pugazhendhi et al., 2021; Hasan et al., 2022; Nahler, 2022; O'Brien, 2022; Pennant & Hinton, 2023; Praphasawat et al., 2023; Kaur et al., 2023; Sheik et al., 2023).

Sustainability of Cannabis plant

The economy, the environment, and society are the traditional cornerstones of sustainability (Raihan et al., 2022c; Raihan, 2023d). As a renewable resource, hemp is consistent with all three tenets (Kaur & Kander, 2023) of sustainability.

Economic sustainability of hemp

Sustainability in business is essential for ensuring economic sustainability, which is defined as the preservation of capital (Huang et al., 2022; Raihan & Tuspekova, 2022a; Raihan, 2023e). The economics of hemp are intricate, as they are with many other kinds of industrial plants (Kaur & Kander, 2023). Although hemp has been traded for millennia, the hemp business and its supply chain actors such as hemp producers, manufacturers, processors, input suppliers, retailers, and consumers are today experiencing significant economic difficulties (Mark et al., 2020). Three things about the Cannabis industry's finances are stable despite the industry's dynamic nature. To begin, the Cannabis plant has several potential uses and applications (Visković et al., 2023). Second, although only a fraction of the total market for these goods, sales of hemp food, clothing, toiletries, medicines, and nutritional supplements are on the rise (Kaur & Kander, 2023). Finally, corporate and policy shifts, infrastructure investment, and enhanced production methods have contributed to a resurgence in the cultivation of hemp throughout the past decade (Mark & Will, 2019), despite its dropping production worldwide due to its link with marijuana since the 1950s.

The Cannabis plant has enormous untapped potential in a wide variety of contexts. The Cannabis plant is one of the most essential plants within the bioeconomy, as seen from the agriculture sector, consumers, industry, the circular economy, and the environmental standpoint (Kaur & Kander, 2023). It is anticipated that the value of the hemp market worldwide will increase fourfold in the next years, from $4.7 billion in 2020 to $18.6 billion by 2027 (Zimniewska, 2022). Over the projection period, annual growth is anticipated to average 15.8%. Hemp-based products, for instance, seeds for oil, food, and beverages, and fibers used for technical applications, such as a composite used primarily for automotive and construction projects, but also in the textile industry, have become increasingly popular, especially in developing regions like the Asia Pacific (Crini et al., 2020). Even though the full potential of the Cannabis plant has not been tapped, the hemp business in Europe is expanding rapidly (Kaur & Kander, 2023). From 2015 to 2022, hemp production in Europe saw a 60% growth in acreage (Visković et al., 2023). Currently, it is estimated that Europe cultivates up to 25% of the world's hemp. France is the third biggest producer of industrial hemp worldwide (Kaur & Kander, 2023). France produces 60% of all EU output, next to Germany (17%) and the Netherlands (5%). Figure 11 displays the annual trend of agricultural land for hemp cultivation in the EU compared to Canada and China.

Positive economic and ecological effects on agricultural systems (Raihan et al., 2023b) are realized through the integration of agriculture and energy in "agrivoltaics," where solar modules are placed above hemp crops (Panchenko et al., 2021). The growth of the hemp food components market is being fueled, in part, by the increasing acceptance of hemp seed in the food supply (Tripathi et al., 2023). Estimates for the size of the global market for industrial hemp in 2025 range from USD 5.6 billion to USD 26.6 billion (Burton et al., 2022). The market is being pushed forward by rising textile sector demand and supportive government initiatives. In response to rising worldwide demand and decreased production costs, hemp cultivation has exploded across the Asia–Pacific area. Growth in the area is anticipated to persist through 2028 (Kaur & Kander, 2023). As a result of its growth, businesses and academic institutions are devoting more resources to creating cutting-edge goods. The possible cure for chronic diseases like diabetes is one important field of study, as is the development of biofuel and bioplastics. According to Naeem et al. (2023), the expansion of the hemp market is anticipated to be spurred by the variety of potential applications for the plant.

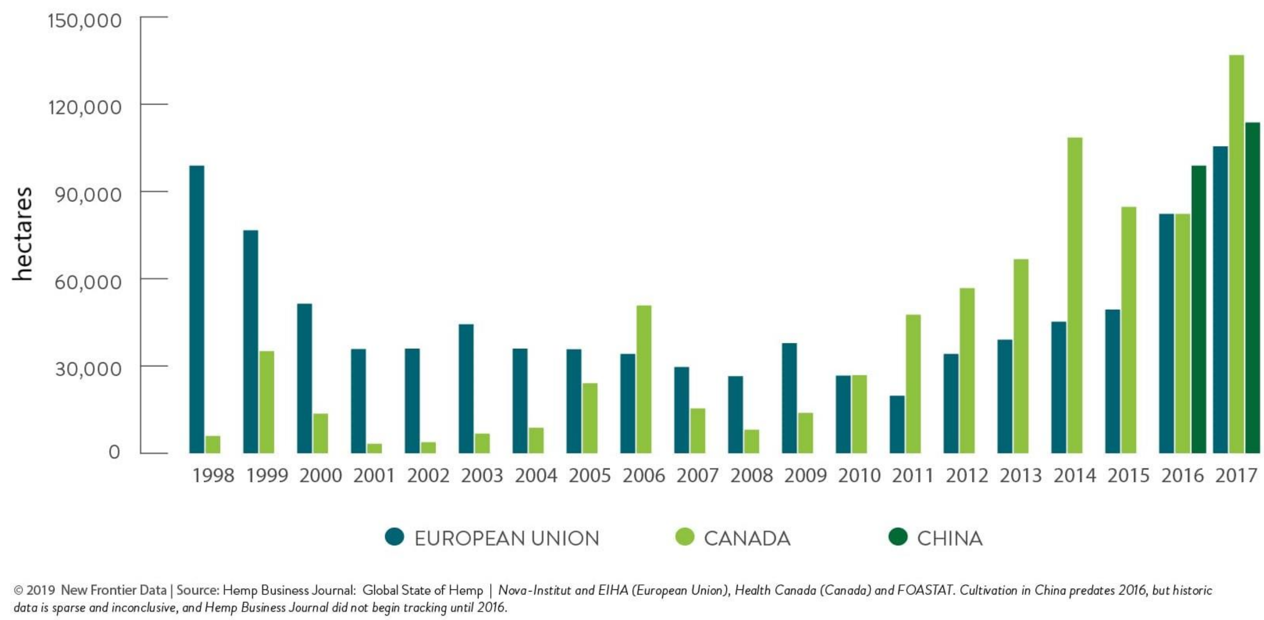

Figure 11. Agricultural land for hemp cultivation in the EU compared to Canada and China.

About 30 nations across Europe, Asia, North America, and South America have legislated the cultivation of the Cannabis plant (Kaur and Kander, 2023). Canada dominates the global market for hemp-based goods such as hemp oil, hemp seeds, and hemp protein powder (Crini et al., 2020). Moreover, China produces about half of the world's supply of hemp fiber (Mcgrath, 2019; Sun, 2023). Seventy percent of China's hemp output is textiles, while the other thirty percent is CBD products, cosmetics, food, and vitamins (Sun, 2023). When it comes to both industrial hemp and consumer textiles, China is often regarded as an industry leader (Horner et al., 2019; Sun, 2023). Hemp has been farmed for thousands of years in China, however from 1985 to 2010 it was illegal to cultivate either the fiber or the seed. Its output has been rising quickly in recent years, and this trend is anticipated to continue (Mcgrath, 2019; Kaur & Kander, 2023). In addition, hemp is grown in many European countries, with production rising sharply in recent years (Chaowana et al., 2024). Among the many uses for hemp, hurds, organic seeds for food, hemp fiber for vehicle composites, pharmaceuticals, and the increasingly popular cannabidiol (CBD) are among the most common in the European Union (Mark & Will, 2019; Kaur & Kander, 2023). Hemp businesses can turn a profit if their hemp oils, fibers, therapeutic ingredients, and health supplements are competitive with the prices of similar products (Naeem et al., 2023). Hemp growers need to weigh the crop's profitability against that of competing crops and foreign hemp imports (Kaur & Kander, 2023).

As legal markets for cannabis develop and illegal markets continue to thrive, policymakers are tasked with regulating cannabis cultivation, distribution, and consumption in new ways. The combined economic values of legal and illicit global cannabis markets have been estimated at $214−344 billion (Wartenberg et al., 2021). Legal markets are projected to grow significantly by 2025. Still, today's global markets remain dominated by illicit channels. While accurate estimates of cultivation area and production quantities are not feasible due to a lack of empirical data, the cultivation of the Cannabis plant has been reported in 151 countries for the period of 2010−2018, highlighting the broad geographical scope of production activities. Today, most cultivation appears to be outdoors; however, there have been indications of recent increases in indoor cultivation, particularly in the United States, Canada, Chile, Uruguay, Colombia, and Ecuador.

Environmental sustainability of hemp

The goal of environmental sustainability is the long-term conservation of natural resources for human use (Raihan & Tuspekova, 2022b; Raihan et al., 2023c). The Cannabis plant aids biodiversity, absorbs a lot of carbon, which helps slow down global warming (Raihan, 2023f), and doesn't need a lot of fertilizer or pesticides, so it's good for the environment (Dhondt et al., 2021). Hemp is either a carbon-neutral or a carbon-negative plant, based on the cultivation and processing techniques used. According to Adesina et al. (2020), Cannabis plants can take up roughly 22 tons of carbon dioxide per hectare. Through photosynthesis and subsequent bio-sequestration, high-biomass crops like hemp can store carbon in the plant's body and roots. Most of the plant's carbon is found in the stem, while only a small amount is kept in the roots and leaves (Raihan & Tuspekova, 2022c; Raihan, 2023g). A minimum of 13 tons of biochar may be produced from one acre of hemp every year (Adesina et al., 2020; Naeem et al., 2023). In addition, the extended shelf life of hemp products means that the carbon the plant stores is unlikely to be released back into the environment for quite some time (Parvez et al., 2021). Specifically, Bouloc et al. (2013) found that the lifespan of hempcrete is greater than 30 years. Moreover, plastics made from hemp could be a good way to keep polymers useful while minimizing our ecological footprint (Naeem et al., 2023). These bioplastics are low-cost biomaterials that could be used to replace petroleum products, and they are reinforced with natural fibers. The incorporation of fiber makes them more durable, recyclable, and environmentally friendly (Naeem et al., 2023).

The fibers from Cannabis plants may also be utilized for manufacturing eco-friendly paper. There is an urgent need for alternate sources because the paper industry's reliance on trees as a significant raw resource causes severe environmental degradation (Raihan & Tuspekova, 2022d; Raihan, 2023h). The paper made from the Cannabis plant is more eco-friendly and of higher quality than paper made from trees. Hemp paper is extremely eco-friendly, as it requires less water, land, pesticides, and fertilizers than conventional paper (Simiyu et al., 2022). Three to four times as many papers can be made from a single hectare of hemp as from the same acreage of forests, and the plant matures in a fraction of the time it takes trees to do so. Unlike its wood pulp counterpart, hemp paper production does not necessitate the felling of ancient trees that give off life-sustaining oxygen or the use of toxic chemical procedures. There are seven times as many opportunities to use recycled hemp paper as there are to use wood. Hemp paper made in this way doesn't need to go through a damaging bleaching procedure and the production process might utilize significantly less sulfur and acid chemicals (Tutek & Masek, 2022).

The Cannabis plant has numerous positive effects on the agriculture and environment as the plant can be used as a renewable industrial raw material (Gedik & Avinc, 2020; Tutek & Masek, 2022). The extensive root system of the Cannabis plant has been shown to have positive agronomic effects, including reduced fertilizer and pesticide consumption and increased soil oxygenation (Cherney & Small, 2016; Visković et al., 2023). It's great for using as a rotation crop as well (Barnes et al., 2023; Liu et al., 2023). The long taproot and extensive origin system of the Cannabis plant have been shown to prevent soil disintegration and improve topsoil quality when the plant is cultivated in a multi-crop system (Ranalli & Venturi, 2004; Kaur & Kander, 2023). The Cannabis plant can thrive with far less water and less chemicals than other natural fiber plants like cotton (Visković et al., 2023). Farmers who care about the environment should consider the environmental impacts of their farming practices at every stage, from planting to harvesting and processing (Raihan & Tuspekova, 2022e; Kaur & Kander, 2023). The Cannabis plant, in general, has a lower environmental impact than many other plant species, and this benefit will grow when new methods of harvesting are developed (Visković et al., 2023).

Moreover, recent research has found that hemp is exceptionally compatible with biodiversity (Kaur & Kander, 2023). The potential application of Cannabis plants in the restoration of mine shafts is intriguing and should be emphasized. The Cannabis plant is well suited for introduction as a pioneer organism in post-mining and damaged heap regions because of its excellent resilience to pests and diseases. With their ability to bind heavy metals in their system, contaminated soil can be cleansed quickly and ecologically, making way for the reintroduction of native plant and animal species (Crini et al., 2020; Visković et al., 2023). The Cannabis plant can be utilized to detoxify soil of toxic metals, such as lead, nickel, cadmium, and other harmful elements and substances as part of a bioremediation project. In addition, the Cannabis plant can produce eco-friendly materials such as carbon-sequestering polymers, heat-insulating materials, and concrete replacements that are both long-lasting and lightweight (Visković et al., 2023).

Hemp can be exploited as a feedstock for the production of heat, electricity, or fuel when the entire plant, including its low-grade fibers or hurds, is utilized (Visković et al., 2023). In order to provide heat, hemp biomass that has been compressed into pellets and then burned can be used in household wood stoves. Utilizing hemp as a crop for the purpose of producing electricity can be scaled up to produce "green" energy from generators if the biomass is converted into charcoal first. It is possible that this might be used to replace the combustion of coal in the cogeneration process, which now relies on residue from forestry and agriculture (Parvez et al., 2021; Raihan & Tuspekova, 2022f). Figure 12 below demonstrates how the Cannabis plant can be used as an amazingly effective biomass in the production of both thermal and electrical energy. Hemp-based biofuels have been recognized as one of the most effective tools for reducing dependency on imported oil while decreasing greenhouse gas emissions (Karche, 2019; Raihan & Tuspekova, 2023; Yano & Fu, 2023). This biofuel has the potential to lessen our dependence on fossil fuels and help maintain a healthy environment (Marrot et al., 2022; Raihan & Tuspekova, 2022g; Raihan et al., 2023d). Because of their large biomass and rapid growth, Cannabis plants are ideally suited to be utilized as a biofuel crop (Chaowana et al., 2023). Hemp is more effective in reducing greenhouse gas emissions than oil seed rape (OSR) and sugar beet, two crops utilized for bioenergy generation in Europe (Simiyu et al., 2022). Hemp's dual use as a biofuel does not pose an immediate threat to food security because it is not a staple food crop. Therefore, it has been determined that hemp is a superior fossil fuel alternative to OSR biodiesel and sugar beet bioethanol. Another study evaluating the bioenergy potential of several crops found that Cannabis generated more money per hectare than kenaf, switchgrass, and sorghum (Das et al., 2017). Carbon emissions and global warming may be reduced significantly if fossil fuels were replaced with biofuels (Raihan et al., 2023e) made from the Cannabis plant.

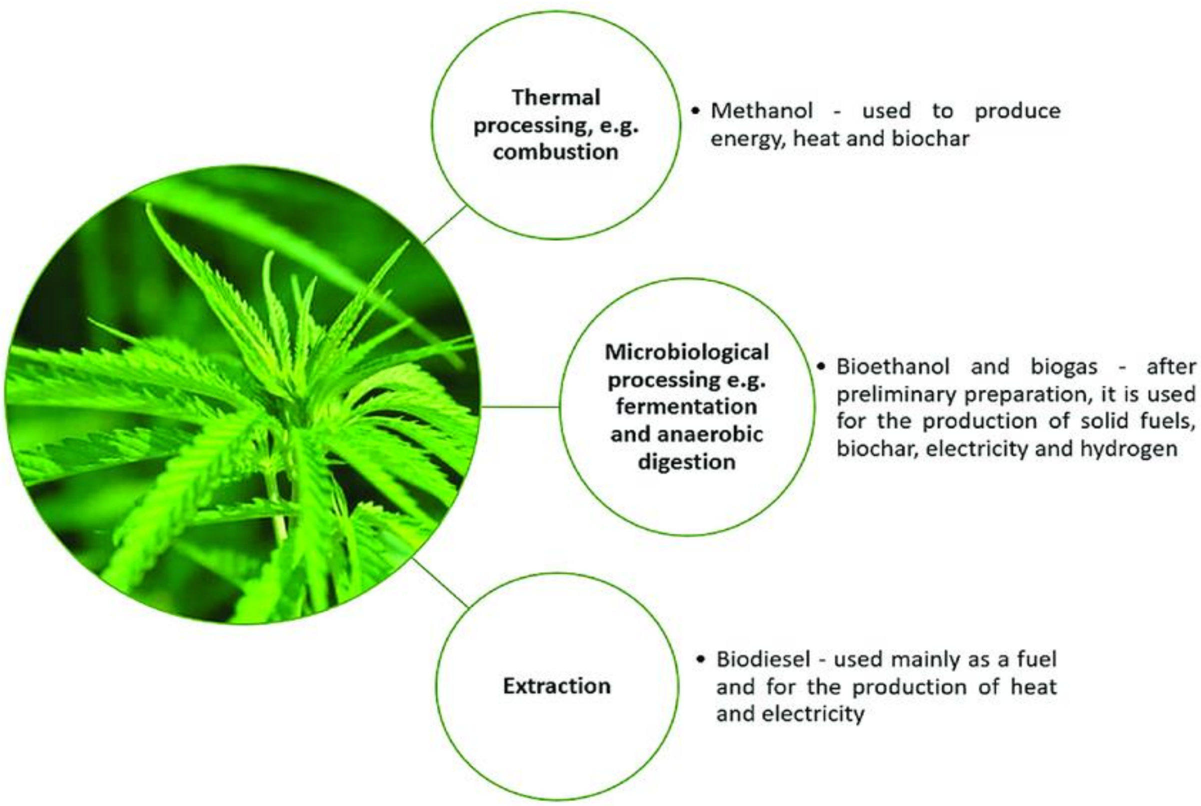

Figure 12. Processing Cannabis for energy purposes (Tutek & Masek, 2022).

Social sustainability of hemp

Investing in and providing for society's essential services and infrastructure are examples of social sustainability. It can be fostered within a society to improve communication, self-control, and morality (Kaur & Kander, 2023). Nurturing principles, interactions, and socialization are all aspects of human sustainability that are interconnected with social sustainability. The economic and ecological effects of the Cannabis plant provide evidence of its social sustainability. As a result of its many applications, it has gained widespread acceptance and contributed significantly to the economies of many nations.

The capability to establish regional and local supply chains is fundamental to the societal significance of industrial hemp as a raw material. There are two main drivers that promote regional distribution networks. First, because of their low density, bales of farmed hemp stalks are expensive to ship. Second, different climates and soil types produce different results when growing Cannabis. There is an incentive for processing and manufacturing hemp close to its source farms because of the economic benefits associated with doing so. The economic worth of regional produce increases as it is traded on an international or national level. When compared to shipping raw resources to distant sites for processing, producing higher-value goods and materials locally yields better economic benefits for the community's farmers and local manufacturers (Wagner et al., 2022). These motivators promote social sustainability by keeping money in the area.

Despite encouraging findings from preliminary research, determining the social sustainability of the Cannabis plant as a renewable industrial raw material is still in its beginning, and more study is needed to improve quantify, and evaluate the effects of cultivating and producing industrial hemp and processing hemp-based products.

Industrial hemp and sustainable development goals

The 17 sustainable development goals (SDGs) of the United Nations (UN) aim to end poverty, improve health and education, decrease inequalities, safeguard the environment, and boost economic growth by 2030 (Raihan et al., 2023f). All 193 member states agreed to the SDGs, which include 169 targets and global indicators to guide national, state, and municipal government priorities and collaborations. Sustainable growth balances current and future requirements (Raihan & Tuspekova, 2022h). Many SDG indicators recur across targets because complex challenges like health, equity, and climate change demand multidisciplinary solutions. In a contentious political atmosphere, the SDGs are popular worldwide and offer a template for galvanizing local assets to transform the globe (Raihan & Tuspekova, 2022i). Corporations, institutions, and non-governmental organizations are incorporating the SDGs into their business plans. Hemp industrialization is transforming healthcare, agriculture, energy, banking, technology, policymaking, and more. The growing industrial hemp and marijuana sector is improving epilepsy, multiple sclerosis, chronic pain, Post Traumatic Stress Disorder, and other treatments globally. As an alternative crop for paper, textiles, plastics, construction materials, and other green technologies that regenerate biodiversity, the Cannabis plant helps combat climate change. The global market potential for industrial hemp surpasses that of medical and recreational marijuana because of the wide range of applications associated with the Cannabis plant. The adaptability of the Cannabis plant is exemplified by its inclusion in the SDGs, which also contribute to dispelling misconceptions about the plant. The SDGs provide a framework for enhancing education, legislation, research, and partnerships to effectively promote hemp as a vital crop that offers multiple societal advantages. The manifold advantages of industrial hemp have led to the identification of 54 hemp-related SDG targets, aimed at enhancing multi-sectoral collaboration, research, and education on a global scale. The links of hemp across the SDGs are depicted in Figure 13.

Figure 13. The association of industrial hemp with the SDGs.

No poverty (SDG 1)

Hemp has been recognized for its agricultural and sustainable food/energy potential for thousands of years across several continents and continues to be accepted by contemporary societies worldwide. Wide-scale hemp growing, and related sectors may quickly eliminate large amounts of poverty at the national and local levels in three ways that support all other goals. First, dramatically reducing unsustainable energy and resource-based conflicts worldwide; second, increasing access to locally/regionally-grown healthy and nutritious foods for humans and livestock—hemp is naturally organic and superior to corn and soy; and third, creating a carbon-neutral farming, processing, manufacturing, and consumption infrastructure with huge economic and ecological benefits.

Cannabis plant cultivation worldwide could help resolve issues over fossil fuels. Afghanistan, called the "Graveyard of Empires" for its history of thwarting energy-dependent colonial empires, is one example. It is also one of the poorest nations worldwide. Cannabis plants could replace opium, lowering drug use. This market could also contribute to regional poverty since farmers make minimal revenues. Cannabis plant cultivation nationwide benefits the population economically and reduces the power of extreme Islamic organizations and invading empires. Afghan farmers' desire to grow hemp dates back at least ten years, when global demand for hemp began to rise before the 2018 Farm Bill in the US. The U.N. Office on Drugs and Crime reported a 63% increase in opium cultivation in Afghanistan in 2017, hitting a record 328,000 hectares. A large fiber and seed-hemp crop in Afghanistan would undoubtedly make the country more peaceful, productive, and rich. This would enable self-sufficiency through the consumption of nutritious hemp seed-derived food, relieving a large percentage of the people from conflict and scarcity. The same goes for impoverished Southern Asian and sub-Saharan African communities. Malawi, one of the poorest nations, is another example. The region can support hemp farming, new industries, and sustainable resource development. These nations might become major hemp producers with UN support. Cannabis plants could replace opium farms in Afghanistan, tobacco plantations in Kentucky, and the global demand for petroleum, valuable minerals, and petroleum-derived products. Hemp planting at the national and corporate levels in industrialized nations like the US could minimize the need for historical incursion into Afghanistan and other countries. Hemp was the world's largest industrial crop until the late 19th century and hemp production was reduced mostly due to government mismanagement. Over numerous decades, incorrect propaganda has shaped the current resource and energy environment, requiring significant efforts to repair the damage.

Zero hunger (SDG 2)

Hemp, as a sustainable and renewable resource, possesses the capacity to offer substantial quantities of nourishing and healthful food products. These include hemp seed protein, which exhibits variable potencies based on processing methods, as well as hemp seed milk, hemp seed oil, hemp hearts, and hemp seed flour. Using these ingredients, individuals can create or enhance a wide range of culinary dishes, including bread and butter. The diet exhibits a commendable balance of nutrients and is deemed suitable for both human and cattle consumption, hence enhancing the nutritional value of animal-derived goods such as eggs and milk. The production of this food has the potential to yield cost savings and enhance nutritional value, thereby offering a viable solution in the face of climate change-induced disruptions to existing food supplies. Hemp possesses the potential to significantly contribute to the mitigation of worldwide malnutrition and hunger rates. The plant exhibits a high degree of manageability and may be efficiently processed into food products with low reliance on external machinery, mostly decorticators.

Good health and well-being (SDG 3)

The consumption of healthier food, particularly plant-based protein as a substitute for animal protein, the adoption of sustainable homes, the integration of hemp fiber in the textile industry to promote green practices, the reduction of resource-driven conflicts, and the stimulation of economic activity collectively contribute to the enhancement of human and animal health as well as overall well-being. Every aspect of the Cannabis plant, including the stalk, flower, seed, root, and stem, contributes to the enhancement of human and animal health and well-being. These components are free from any adverse side effects, psychoactive properties, or detrimental environmental consequences typically associated with traditional resources or their absence. Hemp possesses unparalleled potential in reducing childhood death rates, surpassing any other available resource on the planet. Research has demonstrated that cannabis possesses a range of therapeutic advantages, encompassing the alleviation of pain, mitigation of anxiety, and enhancement of sleep quality. Consequently, the cannabis sector has the potential to

contribute to SDG 3 through the production of cannabis-derived goods that are of superior quality and safety, thus enhancing individuals' health and overall well-being.
Within the framework of SDG 3, four targets pertaining to hemp and marijuana have been delineated. These targets encompass the prevention and treatment of substance misuse, ensuring access to safe and cheap vital medications, promoting research and development in the field of medicinal applications, and augmenting the allocation of financial resources and recruitment efforts within the health workforce. SDG 3.5 aims to address the issue of substance misuse through prevention and treatment measures. This statement underscores the necessity for expanded study on marijuana and hemp, since cannabis has potential alternative applications in comparison to opioid medicines, alcohol, and other addictive substances, with reduced risks of overdose and addiction. According to the study conducted by Lucas et al. (2013), a significant proportion of participants, specifically 41%, reported using marijuana as a substitute for alcohol. Additionally, 36% of participants indicated that they used marijuana as a substitute for illicit substances, while a substantial majority of 67% reported using cannabis as a substitute for prescription medicines.

Quality education (SDG 4)

With regards to facilitating the provision of high-quality education to the global population, one significant advantage of hemp pertains to its ability to generate and allocate economic resources at the local, regional, and national scales. It is evident that subject to the discretion of nation-states and regional authorities, this economic development has the potential to enhance education on a broad scale.

Gender equality (SDG 5)

Hemp, particularly in the form of hempcrete, presents itself as a significantly lighter construction material compared to conventional options such as concrete or steel. When cultivating hemp, a significant amount of physical power is not necessary. When it comes to the processing of fiber and seed, it is necessary to employ machinery or rely on individuals with significant physical strength in places where mechanical assistance is limited. This is owing to the substantial muscular power and endurance demanded by such tasks. Subsequently, there exists a comparable level of opportunity in many sectors such as textiles, house and building construction, food production, and an array of industrial industries including a multitude of consumer goods. A similar argument may be made about the establishment of extraction centers aimed at supplying communities with hemp extracts and dietary supplements specifically designed for female populations. Hence, the hemp industry has the potential to promote gender equality through the creation of employment opportunities for individuals of men and women within the hemp sector.

Clean water and sanitation (SDG 6)

Certain varieties of Cannabis plants are selectively developed for the purpose of phytoremediation, a technique that involves employing plants to extract contaminants from soil, water, or air. In the pursuit of achieving SDG 6, the cultivation of hemp presents a promising solution. This versatile plant possesses the unique ability to effectively address environmental contamination by virtue of its extensive root system. Through this mechanism, the Cannabis plant is capable of absorbing and sequestering heavy metals such as nickel and lead from the soil. Consequently, it serves as a regenerative cleanup crop that can be cultivated in proximity to hazardous materials. Hemp and cotton exhibit comparable characteristics; however, hemp seeds are more cost-effective and demand less water, fertilizer, and pesticides. Consequently, this leads to a substantial reduction of 77% in agricultural production costs, promoting the achievement of SDG 6.3, which aims to reduce pollution, as well as SDG 6.4, which seeks to enhance water-use efficiency across various sectors. In addition, diets based on hemp seeds would reduce the environmental impact of human waste and animal dung on sewage systems.

Affordable and clean energy (SDG 7)

The primary benefit of industrial hemp resides in its capacity to generate carbon-neutral ethanol and biodiesel derived from hemp seeds. The application of hemp biofuel possesses the capacity to substantially diminish the carbon emissions linked to human endeavors (Raihan et al., 2022d), all the while offering accessible and environmentally friendly energy sources. Hence, the utilization of hemp biofuel holds significant promise in enhancing energy efficiency, mitigating energy crises, and addressing environmental pollution concerns by substituting fossil fuels and thereby reducing emissions.

Decent work and economic growth (SDG 8)

The hemp supply chain in the 21st century is extensive and has yet to be fully investigated. It encompasses various stages, including large-scale farming, initial retting, advanced processing, and manufacturing of numerous consumer-based products. Additionally, the Cannabis plant has the potential for food supply, energy production, and livestock feed, which could reduce the need to clear rainforests. Consequently, the cultivation and utilization of hemp have the potential to generate a substantial number of environmentally sustainable manufacturing employment across both developing and industrialized nations. The legalization of the Cannabis plant has the potential to enable governments to harness hemp as a means of generating a substantial number of employment opportunities, thus fostering the development of numerous sectors within the global economy. SDG 8 can be accomplished by establishing legal and controlled markets for cannabis, facilitating job creation, and tax generation, and fostering entrepreneurial prospects for small-scale enterprises. The legalization of hemp production in Thailand has engendered novel prospects for farmers, given the versatile applications of hemp in several industries, including health and wellness, textiles, paper, and construction materials. Through the cultivation of hemp, local farmers have the opportunity to enhance the diversity of their crop portfolio, augment their revenue, and make a valuable contribution to the overall economic growth of the nation.

Industries, innovation, and infrastructure (SDG 9)

Hemp possesses the potential to serve as a raw material for the production of more than 20,000 consumer goods. Moreover, the transition from traditional petroleum-derived commodities such as wood and plastic to hemp is poised to give rise to a profoundly transformative era. In the context of developing nations, the utilization of a highly adaptable multi-crop like the Cannabis plant holds the potential to yield a wide range of essential resources such as housing, clothing, medicine, and construction materials during the initial phases. Despite the federal legalization of industrial hemp in the United States, a significant number of prominent firms, banks, and credit unions are hesitant to involve themselves with this plant. This reluctance stems from the ambiguous banking regulations and potential tax consequences associated with engaging in activities related to industrial hemp. SDG 9.3, which pertains to the target of enhancing access to financial services, emphasizes the necessity of implementing appropriate measures to facilitate the establishment of the legal hemp business.
Furthermore, the hemp and cannabis sectors have the potential to contribute to SDG 9 by fostering advancements in various aspects including cannabis production, product innovation, applications of cannabis, and distribution. This phenomenon has the potential to propel technological progress and generate novel prospects for both enterprises and individuals. The cannabis sector in Thailand has garnered interest from international companies, leading to foreign investments in the nation. This influx of investments has not only generated employment possibilities but has also contributed to the overall economic growth and potential of the country. The projected

growth rate of Thailand's cannabis industry is estimated to be approximately 15% per year from 2023 to 2025. It is anticipated that the market value will potentially reach 1.17 billion USD by the year 2025.

Reduced inequalities (SDG 10)

Hemp, as a resource, confers empowerment upon individuals due to its environmentally friendly nature, cost-effectiveness, ease of utilization, and ability to offer equitable opportunities. SDG 10 provides a robust framework for effectively mobilizing resources and establishing the necessary infrastructure for the development of the hemp industry, thereby promoting and advancing equality. The two specific targets outlined under SDG 10 are as follows: Target 10.1 focuses on the objective of achieving income growth, while Target 10.2 aims to promote social, economic, and political inclusiveness. In section 10.3, the target is to abolish laws that promote discrimination. In section 10.4, the aim is to establish fiscal, wage, and social protection measures that can facilitate the utilization of hemp's potential to address inequality issues and include comprehensive solutions into policies, programs, and partnerships involving multiple sectors.

Sustainable cities and communities (SDG 11)

The utilization of hemp-based construction materials has the potential to contribute to the development of sustainable cities and communities. Hempcrete bricks are characterized by their reduced weight compared to conventional cinder blocks and their exceptional durability, enabling them to endure for extended periods of time. Without considering any other factors related to the adoption of hempcrete, it can be argued that its implementation alone has the potential to significantly enhance the health, cleanliness, and sustainability of cities and communities. In addition, the growth of the Cannabis plant has the capacity to sequester carbon, presenting the possibility of obtaining Carbon Credits. Furthermore, the establishment of legalized and well-regulated markets for cannabis has the potential to contribute to a decrease in crime rates and foster the creation of safer and more stable communities.

Responsible consumption and production (SDG 12)

The initiation of responsible consumption can be attributed to the utilization of the Cannabis plant. Hemp possesses the potential to significantly influence both the environment and human society due to its multifaceted applications as a food source, textile material, energy provider, construction resource, and constituent of biodegradable products. The broad adoption of major consumer and industrial markets has the potential to significantly mitigate economic, environmental, and social problems associated with hemp. The production of hemp products, encompassing various components such as seeds, stalks, and flower-based extracts, can be effectively achieved using carbon-neutral and environmentally sustainable methods. The implementation of this practice is currently underway on a limited scale globally. SDG 12 encompasses various targets, including the promotion of sustainable production techniques (SDG 12.1), which necessitates the adoption of corresponding policies by enterprises (SDG 12.6) and the reduction of waste (SDG 12.5). Hemp offers a viable means of fostering a more environmentally sustainable economy. Hence, it is imperative for governments, academia, and corporate partners to collaborate and engage in technological advancements to facilitate the industrialization of hemp.

Climate action (SDG 13)

The hemp industry has the potential to contribute to the achievement of SDG 13 by adopting sustainable and environmentally friendly practices in their production processes. This can be accomplished through the implementation of organic farming methods and the reduction of water and energy consumption, particularly when compared to the cultivation of alternative crops like cotton. Furthermore, it is imperative for the industry to actively support and invest in research and development endeavors aimed at the creation of novel technologies capable of effectively curbing carbon emissions and mitigating the adverse consequences of climate change (Raihan, 2023i). The Cannabis plant has been found to contribute to mitigating the adverse effects of global warming and climate change by engaging in carbon sequestration, mitigating desertification, substituting fossil fuels with biofuel derived from hemp, and curbing deforestation to accommodate the growing agricultural needs to meet societal demands for food, fiber, and other commodities.

Life below water (SDG 14)

The integration of the hemp supply chain has several beneficial outcomes, including reduced reliance on fish protein and fish oil aminos, coastal revitalization, diminished plastic pollution in oceans, and decreased petroleum use. The Cannabis plant has the potential to significantly mitigate the emission of anthropogenic carbon dioxide into the atmosphere, as well as lessen the discharge of detrimental pollutants into the ocean resulting from agricultural practices such as cotton cultivation, deforestation, topsoil degradation, livestock farming, and other agricultural activities. The utilization of hemp-based biodegradable products has the potential to mitigate marine pollution and safeguard underwater biodiversity through the substitution of plastic materials. Hemp has the potential to serve as a substitute for petroleum-based energy and its derivative products in the context of offshore drilling.

Life on land (SDG 15)

The hemp industry contributes to environmental conservation efforts. Cannabis plant, as a regenerative crop, possesses the capacity to rebuild soil organic matter and facilitate the restoration of deteriorated soil. This characteristic aligns with the targets outlined in SDG 15.3, which aims to rehabilitate soil and land that has undergone degradation. Certain varieties of Cannabis plants are selectively developed for the purpose of phytoremediation, a technique that involves employing plants to extract contaminants from soil, water, or air. Cannabis plant possesses extensive root systems that effectively infiltrate the soil, facilitating the absorption of heavy metals such as nickel and lead. Consequently, the Cannabis plant serves as a regenerative crop capable of remediating contaminated areas, even when cultivated in proximity to hazardous substances.

Furthermore, the Cannabis plant relies solely on wind for pollination and exhibits a notable capacity for generating a substantial quantity of pollen. This characteristic contributes to the establishment of an ecosystem that is very appealing to various bee species, which plays a vital role in promoting sustainable agricultural practices (O'Brien & Arathi, 2019). Although the Cannabis plant does not generate nectar, its blooms, which are abundant in pollen, contribute to the ecological significance of the Cannabis plant as a crop. Hemp, as a sustainable crop, exhibits the advantageous characteristic of necessitating minimum water usage, positioning it as an ecologically conscious substitute for conventional crops. Hemp has the capacity to yield three times more metric tons than cotton, aligning with the target of SDG 15.3, which aims to restore life on land (Schumacher et al., 2020). In addition, the cultivation of the Cannabis plant has the potential to contribute to the preservation of wildlife biodiversity through its ability to mitigate unlawful poaching and hunting. This is due to the economic incentives derived from hemp cultivation, which divert the attention of poachers and hunters away from capturing rare and endangered animals.

Peace, justice, and strong institutions (SDG 16)

The implementation of a program aimed at releasing individuals convicted of minor drug offenses from incarceration and integrating them into various sectors of the emerging hemp industry can perhaps contribute to the cessation of the worldwide campaign against illicit narcotics. These equity programs can be improved by integrating SDG targets 4.4: relevant skills for employment and entrepreneurship; SDG 4.5: decent work; SDG 8.3: job creation and entrepreneurship; SDG 11.a: strengthen national and regional development planning, and SDG 16.6: develop accountable and transparent institutions at all levels. The governments can also create hemp education programs for everyone, especially at-risk youth around how hemp can be used to day-by-day build a better future for all intelligent life on earth!
Furthermore, SDG 16.6 targets the development of accountable and transparent institutions at all levels. The hemp industry has the potential to contribute to the achievement of this objective by establishing diverse industries and organizations with several purposes, for example:

- Hemp agronomics and farming
- Hemp fiber applications in the automotive industry
- Hemp biofuel applications throughout human society
- Hemp business entrepreneurship
- Hemp medicine and cannabinoid-based science
- Hemp fiber applications in residential and commercial construction
- Hemp food, nutrition, and herbal supplementation
- Hemp bioplastic applications
- Hemp as part of societal digital transformation technologies
- Hemp musical instruments and spaceship components

Partnerships for the goals (SDG 17)

Various stakeholders, including farmers, entrepreneurs, startups, corporations, politicians, NGOs, and local businesses, derive advantages from the utilization of hemp. SDG 17 outlines a strategic framework for harnessing the untapped potential of hemp and sets specific objectives to be achieved. SDG 17.14 emphasizes the need to strengthen policy coherence, while SDG 17.16 highlights the importance of establishing multi-stakeholder partnerships. Additionally, SDG 17.17 underscores the significance of successful collaborations between the public sector, commercial sector, and civil society. These three targets provide valuable frameworks for exploring potential avenues to expand the industrialization of hemp. The integration of the 54 SDGs into the business plans of the industrial hemp and cannabis industry is recommended. This industry, being in its early stages, could actively participate in shaping collaborations across several sectors and contribute to the advancement of sustainability.

Conclusion

This review study delves into the exploration of the potential and historical magnitude of the Cannabis plant in human culture. Additionally, this study illustrates the associations of the Cannabis plant with the SDGs. Using the Cannabis plant as a renewable raw material, this study concluded that hemp has the potential to positively improve product sustainability, which has contributed to its rapid rise in popularity. Many people admire the Cannabis plant for its many benefits, including its compatibility with nature, its potential as an economic venture for local business owners, and its usefulness as a cover crop for small-scale farms. The majority of the study's findings on hemp's sustainability related to its ecological effects, followed by its economic impact. However, the social repercussions and social sustainability are poorly understood. This may be because research methods for assessing societal effects in terms of sustainability and life cycle assessment (LCA) are still developing. However, new research into circular economies is beginning to consider the societal effects of these systems alongside the environmental and financial ones. In addition, the future demand for the Cannabis plant will be determined by the pricing of hemp products, which in turn will be determined by customers' perceptions of the health and environmental benefits of using hemp products. Research potential exists in these areas because neither a worldwide organization nor the federal government currently gathers worldwide information on the cultivation of hemp or its impact. The Cannabis plant has a lot of potential in terms of sustainability, despite the current gaps, because it naturally fits into every aspect of sustainability and SDGs. As such, it satisfies the demand for a sustainable raw material alternative and provides a possible response to the critical climate problem. The full potential of this extremely promising multi-purpose crop cannot be realized without more investigation into appropriate agronomic production practices for greater productivity and sustainability.

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RESEARCH ARTICLE

Examining the Effect of Urban Household Food Insecurity on Fertility in Lideta Sub-City, Addis Ababa, Ethiopia

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Abstract

Despite investment and support for family planning in developing countries, some people living in poverty are hesitant to use modern birth control methods, and usage rates are insufficient. Improved reproductive health is directly related to enhanced nutrition, while optimal nutrition fosters superior reproductive health outcomes. This study aims to examine the relationship between household food insecurity and fertility in Lideta Sub-City, Addis Ababa, Ethiopia. A study was conducted on 649 reproductive-age women in three randomly selected Woredas (districts) from a sub-city from February to March 2023. Data was collected through a validated survey by trained individuals, and household income and expenditure were used to measure food insecurity access. Poisson regressions were used to examine the link between household food insecurity and fertility, considering other covariates. The result of the study shows that food insecurity status was a significant predictor of the number of children ever born. The number of children ever born for women within food-secure households is 0.655 times lower compared to women with food insecurity. Similarly, the age of the mother, marital status, contraceptive use, women's income, and childhood mortality were significant in predicting the effect of the number of children ever born at $P < 0.05$. Household food insecurity exhibits a positive relationship with the number of children ever born. Thus, it is imperative to recognize food insecurity as a barrier that must be addressed when developing family planning services.

Keywords: Fertility; Children ever born; Food insecurity; Lideta Sub-City; Addis Ababa; Ethiopia

Introduction

The world's population has experienced a remarkable increase, growing from 1 billion in 1800 to a staggering 8 billion today. The less developed countries of Africa, Asia, and Latin America now account for 85 percent of the world's population but account for 99 percent of global population growth (United Nations, 2022). The highest fertility rates and higher childhood mortality rates are found in the poorest and most food-insecure countries (Boliko, 2019; FAO, 2020). Surprisingly, the world is still home to over 800 million undernourished people, over 97% of whom live in developing countries. The rate of undernourishment worldwide is on the rise, affecting 9.9% of people globally (FAO, 2021).

Sub-Saharan Africa, with a population of 1.3 billion (17% of the world population), has by far the fastest-growing population of any major region in the world (United Nations, 2022). Despite significant advancements in reducing child mortality and enhancing life expectancy, reproductive health among women residing in developing nations, particularly in sub-Saharan Africa, remains insufficient, leading to persistently high birth rates. On average, women residing within the region have about 4.26 children (United Nations, 2022). The widespread adoption and utilization of family planning methods have become instrumental in mitigating the growth of the population as well as addressing the issues of hunger and malnutrition (Smith & Rhonda, 2015).

Ethiopia remains one of the world's most impoverished and food-insecure nations, with 30.8% of its population living below the poverty line for sustenance (Odekon, 2022). The majority of urban households in Ethiopia, comprising approximately 80%, exhibit food insufficiency and rely heavily on market mechanisms to procure their food requirements (WFP/UNICEF, 2019). Following the Interim Report on Poverty Analysis Study in Ethiopia (FDRE, 2017), there was an estimated 14.8% proportion of the population in urban areas categorized as being below the food poverty line. In Addis Ababa, the estimated proportion of individuals experiencing food insecurity, defined as those unable to purchase consumption items that yield a minimum of 2,200 kilocalories, is 19.1% (PDC, 2019). Similarly, the proportion of people suffering from food insecurity in the Lideta sub-city, which is considered to be one of the most deprived sub-cities in Addis Ababa, was estimated at around 29.3%. This means that about one-third of the population falls below the threshold of adequate food intake (MOFED, 2018). The share of total household income spent on food is around 42.2% (CSA, 2016b).

Urban food insecurity is mostly chronic, combined with higher urbanization rates, food price changes, and market instability (Boliko, 2019; Riley et al., 2019), and persists for long periods, if not lifetimes (FAO, 2020). It is closely associated with urban poverty. As the study conducted by Belachew et al. (2012) in Ethiopia showed, chronic food insecurity in households can result in persistent malnutrition as a consequence of the inability to secure adequate and sustained access to food. In situations where there is a surge in food prices, households that do not engage in food production, particularly those located in urban areas, are compelled to procure food through alternative means, predominantly through purchase. The purchasing power of households is contingent upon their income, so a rise in the prices of food can have adverse effects on their ability to access sufficient amounts of food (Boliko, 2019).

Indisputably, households experiencing poverty typically encounter a plethora of challenges, such as unfulfilled family planning demands, families with sizes that exceed their preferences, and inadequate financial resources to afford the necessary quantity and quality of nourishing sustenance to meet the needs of their families. The condition of poverty precipitates inadequate access to family planning and, in turn, serves as a consequence thereof. Families with lower economic status experience limited availability of family planning services. They allocate a greater portion of their budget towards sustenance while expending a lesser amount of money per individual on food as opposed to affluent households (Smith & Rhonda, 2015; USAID, 2014). Though the total fertility rate in Addis Ababa is relatively better compared to other regions of Ethiopia and is estimated at 1.8 children per woman, the fertility rate is still high at the national level, which is 4.6 children per woman (CSA, 2016a). A crucial consideration towards maintaining sustainable population growth that does not burden the world's finite resources needs foremost attention to the interrelationship between food security and reproductive health (Khatun & Mallick, 2020).

Literature review

Economic, social, and religious factors like income, education, religion, work status, age at first birth, age at first marriage, contraceptive use, and childhood mortality affect fertility (Demeke et al., 2011; Dieu, 2016;

Masoud, 2009; Mekonnen & Worku, 2011c; Ojakaa, 2008; Rabbi et al., 2013; Tomkinson, 2019). Among the various theories of population and fertility, Neo-classical Microeconomic Theory (Becker & Lewis, 1973) and Demographic Transition Theory (Notestein, 1953) are considered the most useful in examining the interrelationship between food insecurity, fertility, and contraceptive use. These theories center on the principal determinants that are responsible for the elevated fertility rates observed in developing nations. This phenomenon is commonly attributed to a dearth of economic advancement. According to demographic transition theory, high infant and child mortality, poor agricultural productivity, insufficient utilization of contraceptives, and a relatively lower socioeconomic standing in terms of women's education, occupation, and social status contributed to the high fertility norm.

Some empirical studies have also confirmed that food insecurity and fertility are related. The study conducted by Mekonnen and Worku (2011) in Butajira District, South Central Ethiopia, showed that food security is a significant predictor of the effect of having fewer children. The findings of the study indicate that women residing in food-insecure households exhibited a 6% increase in the number of children ever born relative to women inhabiting food-secure households. Another study conducted by DiClemente et al. (2021) in Tanzania also showed that food insecurity is positively related to the fertility experience of households when controlling education, place of residence, age of the mother, and number of living children. According to the finding, women who experience household hunger exhibit a higher likelihood of desiring additional children or expressing uncertainty about having more children in comparison to their counterparts who do not experience household hunger. This finding highlights the potential impact of food insecurity on reproductive decision-making among women. The study undertaken by Abdu et al. (2018) in the Assayita District of the Afar Regional State in Ethiopia has demonstrated a significant correlation between household food insecurity and household fertility. The results of the study indicate that households characterized by a parity of five or more children were found to exhibit a significantly greater likelihood of experiencing food insecurity when compared to those who had not yet born children (parity 0). According to this study, women who have two or more children under the age of five are at a statistically significant increased risk of being underweight due to malnutrition, with odds greater than nine times that of women without young children below five years of age.

Although various studies have been conducted to show the effects of food insecurity on child health and development (Kimbro & Denney, 2015; Quyen et al., 2014), education performance, and intellectual development (Belachew et al., 2011), external and internal behaviors (Murphy et al., 1998), and stunting, wasting, and underweight (Abdu et al., 2018; Abdurahman et al., 2016; Berra, 2020; Betebo et al., 2017; DiClemente et al., 2021), insufficient emphasis has been placed on investigating the relationship between urban household food insecurity and demographic outcomes within scholarly discourse. Undoubtedly, endeavors have been made to elucidate the correlation between women's reproductive health status, fertility, and the household's food security (Abdu et al., 2018; Feyisso et al., 2015); however, scant attention has been given to elucidating the reciprocal relationship between food security, fertility, and family planning. This study aims to investigate the relationship between urban household food insecurity and fertility, providing policymakers and development stakeholders with valuable insights to guide well-informed decision-making and effective interventions.

Methodology

Study design and area

A cross-sectional study design was used to collect data from February to March 2023 in Lideta sub-city, located in the central-western area of Addis Ababa. Borders are shared with Addis Ketema, Arada, Kirkos, Nifas Silk-

Lafto, and Kolfe Keranio. The sub-city is divided into ten Woredas. The study randomly selected three Woredas and collected data at respondents' residences in the sub-city. Lideta Sub-City covers 9.18 sq km with a population of 284,208, including 134,372 males and 149,836 females. The study focuses on a highly populated and poor district in Addis Ababa with a population density of 30,960 people per square kilometer (CSA, 2022b).

Sampling design and procedure

Sample size was determined by the single mean formula proposed by Bartlett et al. (2001) with the assumption that the single population proportion experiencing food insecurity is often estimated to be 50%, with a margin of error of 5% and a 95% CI ($z_{1/2}$ = 1.96). A design effect of 1.5 for cluster sampling and some allowance were also added, considering the variability in the study population and controlling non-response rates and outliers, respectively. The sampling strategy of this study was operationally predicated on the pre-established enumeration areas of the sub-city, which had been delineated by the central statistical service of Ethiopia. Samples are drawn from a population using a multi-stage random sampling technique. In multistage random sampling**,** three Woredas are randomly selected at the first stage. Secondly, each Woreda comprises different Ketenas (villages), and from each of these three Woredas, two Ketenas are selected using the random sampling method. In the last step, a total of six Ketenas were there to select the final 649 respondents. The total sample, which was selected using a multi-stage random sampling technique, was divided among all those Woredas and then among Ketenas proportionally to their population. The households from the respective Woreda were selected by systematic random sampling based on a sampling frame of house numbers developed from Ketena records. Individual respondents of women within the age range of 15 to 49 years who would be either household heads or spouses and gave birth within the last 15 years preceding the survey were sampled. If the selected household was found to be closed, the household with the next number on the list was selected, and this continued until the required number of sampled women was acquired.

Study variables

The outcome variable of this study is fertility. It refers to the reproductive performance of an individual, a couple, a group, or a population, which could be measured by using the number of children ever born, the consecutive birth interval, or the total fertility rate. Here, fertility is measured by taking the number of children ever born (CEB) as a discrete outcome variable. Predictor variables and covariates include household food insecurity status and other demographic and socioeconomic variables such as the age of the mother, marital status, women's education, women's income, religion, work status, age at first birth, contraceptive use, the desired number of children, and childhood mortality.

Analytical methods

The relationship between urban food insecurity on fertility will be analyzed using the Poisson regression model taking children ever born as dependent variables and food insecurity as the main predictors. More formally, the Poisson regression model will be expressed as

$$log(\lambda i) = \beta_0 + \beta_1 Xi_1 + \beta_2 Xi_2 + \ldots + \beta_n X i_n + u_i)$$

λ_i is the number of children for women in the Lideta Sub-city, xi is a vector of k characteristics, β_o is the intercept, β is the vector of covariate parameters, and u_i is the error term. The present study shows the outcomes of the model, which reveal the incidence rate ratio or Exp(ß) , elucidating the relative change in the number of children given a unit change in the explanatory variable, while keeping all other variables constant. The present study employed a Poisson regression model to evaluate the association between household food insecurity and the number of children ever born, along with several other independent variables. Descriptive statistics, on the other hand, will help to give bivariate analytical results for the study.

The data was collected using KoboCollect 3.5 and entered into the SPSS 24 software with caution. The completeness and errors related to inconsistencies were verified using the data cleansing method. Bivariate analysis was employed to identify the variables that exhibited a statistically significant association with fertility. In this study, the variables that exhibited a p-value of less than 0.25 were subjected to a thorough examination for multicollinearity issues utilizing the variance inflation factor (VIF). Following this preliminary assessment, the identified variables were included in the Poisson regression model to determine their effect on the outcome variable (children ever born). Incidence rate ratios with their corresponding 95% confidence intervals were computed. A significance level of 0.05 was deemed statistically significant in the present study.

Measurement of household food insecurity

The caloric value of foods that meet the threshold requirement of 2,200 kilocalories (kcal), as recommended by the Food and Agriculture Organization (FAO, 2004), for enabling healthy and moderately active adult living is determined by their corresponding national average prices to establish the food poverty line. Although the 2016 Interim Poverty Analysis Report estimated the cost at 3,772 birr per year per adult person in Ethiopia (FDRE, 2017; MOFED, 2018), this price is not feasible and had to be adjusted based on current food prices. However, the overall percentage of inflation has reached 122.2 % from June 2016 to January 2023; computing the amount of food inflation year by year brings the estimated cost to Birr 11,524.52 per year per adult (CSA, 2022a; NBE, 2022). Accordingly, the cost of one kilocalorie is estimated to be Birr 0.0143.

In this article, the national food poverty line was used to measure food insecurity status. The food poverty line determines whether a given household can have enough daily food expenditure (total household income spent on food) to meet its members' minimum daily calorie needs. Therefore, households that cannot afford the money or are unable to source consumer goods for these daily calorie needs are considered to be food insecure. However, individual access to food depends on household food distribution and gender parity, which in practice means that consumption patterns are not uniform (Battersby, 2011). Often, children, women, and older household members consume less food compared to those male adults (Claro et al., 2010). A per capita adult equivalent estimate is obtained by dividing the total daily income or calories by all household members, assuming a uniform food consumption pattern for families with different compositions. Therefore, if this adult person equivalent estimate were taken, Birr 31.46/2,200 kcal would be used as a standard threshold to identify food-insecure households from those that are not. But such an approach could make households food-insecure that were almost certainly not insecure since they fail to consider the presence of household members with distinct energy needs. Thus, in this article, an adult-equivalent estimate of the calorie availability scale that has an adult-equivalent conversion factor was used (Appendix). The application of an adult-equivalent scale effectively narrows the variance between estimated and actual food intake, thereby enabling the discernment of the relative contributions of distinct household members towards the overall dietary pattern of the household, which is not feasible with the utilization of per capita metrics. Household income and expenditure survey is standard and widely applicable to measure household food insecurity and poverty at the household level (Abuelhaj, 2007; Bellú, L. G. & Liberati, 2005; Ruggeri Laderchi et al., 2003). The World Bank, USAID, the International Development Association (IDA), and the Ethiopian government have applied this monetary approach to measure household food insecurity/poverty related to the urban productive safety net program in urban Ethiopia (UPSNP, 2021). Moreover, the government of Ethiopia and other developing countries have also applied this monetary approach to food poverty and insecurity analysis, identifying the prevalence, gap (shortfall), and severity of household food insecurity (FDRE, 2017; PDC, 2019).

Results and discussion

Demographic and socio-economic characteristics of respondents

As shown in Table 1, a total of 649 households participated in the study. Of these, nearly half, or 48.7%, are between 25 and 34 years old. Of all respondents, single, married, divorced, and widowed account for 114 (17.5%), 432 (66.6%), 87 (13.4%), and 16 (2.5%), respectively. The majority of respondents (39.6%) attended secondary school, followed by primary school (33.7%). In addition, 8.0% had a diploma or higher and 11.9% had no educational qualifications.

Table 1: Demographic and socio-economic characteristics of respondents

Variables	Freq.	%	Mean	Sig.	Variables	Freq.	%	Mean	Sig.
Employment status					**Contraceptive use**				
Unemployed	242	37.3%	1.69		Yes	322	49.6%	1.31	
Employed	407	62.7%	1.52	0.081*	No	327	50.4%	1.85	0.000*
Women income in Birr					**Marital status**				
0-1500	204	31.4%	2.18		Married	432	66.6%	1.87	
1500.01-3000	134	20.6%	1.54	0.000*	Single	114	17.6%	0.79	
3000.01-4500	133	20.5%	1.36		Divorced	87	13.4%	1.18	0.000*
>4500	178	27.4%	1.09		Widowed	16	2.5%	1.75	
Age at first birth					**Age of Mother**				
15-19	138	22.8%	1.88		20-24	33	5.1%	1.03	
20-24	240	39.6%	1.70	0.008*	25-29	159	24.5%	1.48	
25-29	137	22.6%	1.67		30-34	156	24.1%	1.96	0.152
30-34	66	10.9%	1.39		35-39	141	21.8%	2.00	
>35	25	4.1%	1.40		>40	159	24.5%	1.06	
History of Child mortality					**Household food security status**				
No	534	87.8%	1.63	0.000*	Food- secure	206	31.7%	1.14	
Yes	74	12.2%	2.11		Food-insecure	443	68.3%	1.79	0.000*
Desired number of children					**Religion**				
0-2	262	40.4%	1.50		Orthodox	418	67.5%	1.52	
3-4	251	38.7%	1.65	0.278	Protestant	108	17.4%	1.45	0.035*
>5	136	21.0%	1.62		Muslim	93	15.0%	1.89	
Women level of education									
Uneducated	77	11.9%	1.48						
Informal	44	6.8%	1.50						
Primary	219	33.7%	1.76	0.649					
Secondary	257	39.6%	1.51						
Above Diploma	52	8.0%	1.42						

*P < 0.25 significant association

Regarding their employment status, the majority (62.7%) of respondents are engaged in any income-generating activities, while 37.3%) of the respondents were not employed in any labor sector at the time of the survey. Significant proportions of the survey participants (67.5%) were Orthodox Christians, 15.0% were Muslims, and Protestants accounted for 17.4%. The majority of respondents (50.4%) are not using any modern contraceptive method and 12.2% of respondents have at least a history of childhood mortality. The majority of respondents, around 72.5%, earn a monthly income of 0–3000 Birr. Regarding age at first birth, the majority of respondents (39.6%) started childbearing at the age between 20 and 24. Moreover, measuring a household's food insecurity status also revealed that 68.3% of the sample households were food insecure and the remaining 32% were food secure.

The relationship between food insecurity and fertility

Table 1 presents the mean values of children ever born among women, categorized based on food insecurity and socio-demographic characteristics. The findings of the survey indicate that households experiencing food insecurity exhibit a higher mean number of children ever born at 1.79 compared to those who are food-secure, with a mean number of children ever born of 1.14. The mean number of children ever born exhibits variance across various religious groups. According to the findings of the survey, Muslims exhibited the highest mean number of children ever born, with a value of 1.89, followed by Orthodox Christians with 1.52 and Protestants with 1.45. Based on the findings of the survey, it was determined that women with monthly earnings ranging from 1,500 to 3,000 Birr and 3,000 to 4,500 Birr had a mean number of children ever born of 1.54 and 1.36, respectively. This result falls below the replacement level as it signifies that these women are not producing enough children to replace themselves. Comparably, the number of children that have ever been born to individuals belonging to the high-income category (earning over 4500 Birr per month) and low-income category (earning between 0 and 1500 Birr per month) was determined to be 1.09 and 2.18, respectively. According to the findings, the mean number of children ever born to married women (1.87) was compared to those of unmarried, divorced, and widowed women, whose mean numbers of children ever born were 0.79, 1.18, and 1.75, respectively. These results suggest a significant association between marital status and the number of children ever born. In contrast, the findings indicate that females with no education and those holding degrees and above exhibit the greatest and least mean numbers of children ever born, standing at 1.48 and 1.42, respectively. Concerning the demographic category of females, there is a positive correlation between maternal age and the mean number of children ever born. The findings indicate that women in the age bracket of 35 to 39 exhibits a significantly greater mean number of children ever born (2.00) in contrast to young women (1.03).

Factors of household fertility in Lideta Sub-City, Addis Ababa, Ethiopia

A bivariate analysis was conducted to ascertain potential variables for inclusion in the Poisson regression. Utilizing specific criteria, the variables of maternal age, marital status, women's income and work status, age at first birth, food insecurity, and childhood mortality were deemed suitable for inclusion in the Poisson regression analysis. After adjusting for confounding factors, including maternal age, marital status, contraceptive use, and household food insecurity status, and childhood mortality, significant statistical associations were observed with fertility at $p < 0.05$ (Table 2). Efforts have been made to assess whether or not the necessary assumptions for the application of Poisson regression are fulfilled. The present study compared the adequacy of two regression models, namely Poisson and negative binomial, in explaining a given set of data by utilizing two popular model selection criteria, namely Kaike's Information Criterion (AIC) and the Bayesian

Information Criterion (BIC). The results revealed that both AIC and BIC were lower for the Poisson distribution than for the negative binomial distribution. This finding suggests that the Poisson regression model represents a better fit for the data compared to the negative binomial regression model. Conversely, the evaluation of model fit using the goodness of fit test reveals a deviance below 1, signifying that under dispersion is present and the value approaches zero. This result is indicative of zero inflation, thereby suggesting that the Poisson regression model is best fitted. The utilization of an omnibus test in the Poisson regression model has resulted in a significant p-value of 0.001, indicating that all predictor variables incorporated in the model are meaningful full predictors of the effect of the number of children ever born.

Table 2 : Coefficients and odds ratio of fertility in Lideta Sub-City, Addis Ababa

Variables	B	Sig.	Exp(b)	95% CI for Exp(b)	
Marital status					
Married (Widowed)	-.139	.491	.870	.585	1.293
Single(Widowed)	-.509	.025*	.601	.385	.938
Divorced (Widowed)	-.371	.089	.690	.450	1.058
Women income (Birr)					
0-1500 (>4500)	.402	.000*	1.495	1.233	1.812
1500.01-3000 (>4500)	.252	.019*	1.287	1.042	1.588
3000.01-4500 (>4500)	.212	.050*	1.236	1.000	1.529
Contraceptive use					
Yes (No)	-.183	.015	.833	.719	.965
History of Child mortality					
Yes (No)	-.327	.000	.721	.601	.865
Household food security status					
Food- secure (Food-insecure)	-.423	.000*	.655	.544	.789
Age of Women					
20-24 (>40)	.306	.130	1.359	.914	2.020
25-29 (>40)	.318	.007*	1.375	1.092	1.731
30-34 (>40)	.520	.000*	1.682	1.359	2.084
35-39 (>40)	.498	.000*	1.646	1.334	2.031

Note: The reference group is listed in the parentheses.

The result of the study shows that food security status was a significant predictor of the number of children ever born at $p < 0.05$. Holding the other variables constant, the number of children ever born for women within food-secure households is 0.655 times lower compared to women with food insecurity. As we can see from Table 2 , women's monthly income was a significant predictor of the number of children ever born. Holding the other variables constant, the number of children ever born for women with monthly incomes of 0–1500, 1500–3000, and 3000–4500 Birr is 1.495, 1.287, and 1.236 times greater, respectively, compared to those women having an income of Birr higher than 4500. This means that the reduction in income levels from Birr 4500 and above to Birr 3000–4500, Birr 1500–3000, and Birr 0–1500 is associated with increases in the number of children ever born by 23.6%, 28.7%, and 49.5%, respectively.
The results of the study show that marital status has a significant effect on the number of children ever born. The finding indicates that single women have 0.601 fewer children compared to their widowed counterparts. A woman's age is one of the most significant biological and demographic factors affecting fertility. The present investigation indicates that there is a significant disparity in the number of children born by older women as compared to their younger counterparts, meaning that a younger age at first birth is associated with a higher number of children ever born. When comparing the number of children ever born across different age groups, it

is evident that there is a decreasing trend as age decreases. Specifically, the age group of 20–24 displays a low number of children ever born, whereas the age group of 35–39 exhibits a high number of children ever born. Women belonging to the age groups of 20–24, 25–29, 30-34, and 35–39 have 1.359, 1.375, 1.682, and 1.646 fewer children, respectively, when compared with their counterparts in the 45–49 age brackets.

The difference in the number of children ever born between contraceptive users and non-users was also found to be significant at $P < 0.05$. Other factors being equal, the number of children ever born for contraceptive users is 0.833 times lower than for non-users. The history of child mortality and the need for children were also found to be significant predictors of the effect of the number of children ever born. Holding other factors constant, women with childhood mortality experiences have 0.721 more children than women without childhood mortality experiences.

Discussion

The present study endeavors to evaluate the association between food insecurity and fertility in Lideta Sub-City. According to the present investigation, the average number of children ever born to women of childbearing age in the study area is 1.58, which is below the replacement level. This finding was comparable with the study conducted in Addis Ababa, which was 1.9 births (Gurmu & Mace, 2008), but lower than what was reported in the Ethiopian Demographic and Health Survey at the national level (2.84 births) (CSA, 2016a). The observed variability could potentially arise from differences in the demographic, socioeconomic, or cultural status of women or from other factors pertaining to health, such as disparities in counseling proficiency (Shiferaw et al., 2019).

The findings of the study also show that the number of children ever born from food-insecure households was higher compared to children from food-secure households. This finding was consistent with some studies (DiClemente et al., 2021; Feyisso et al., 2015; Mekonnen & Worku, 2011a). The plausible explanation for this phenomenon is that children residing in households experiencing food insecurity are perceived as contributing meaningfully to enhancing the socio-economic status of their family (Birhanu, 2013; Leibenstein, 1975; World Vision, 2022). Moreover, women who belong to households experiencing food insecurity are at a high risk of experiencing negative sexual and reproductive health consequences, including ineffective utilization of contraception and unintended pregnancies. These outcomes are predominantly attributed to limited decision-making abilities and inadequate communication with their partners (Ahinkorah et al., 2021). The socio-economic status of women is also a significant factor in contributing to their participation in fundamental approaches to regulating fertility and promoting the effective utilization of progressive healthcare services (Dixit et al., 2021).

Considerable differences in the number of children ever born exist according to women's age, income, marital status, food security status, contraceptive use, and childhood mortality. The effect of marital status on the number of children ever born was found to be significant at $p < 0.05$. This finding was in line with the findings of previous studies and reports (CSA, 2016a; Shiferaw et al., 2019), but opposed by a study conducted in the Tigray region of Ethiopia (Atsbaha et al., 2016). Single women are susceptible to precarious sexual and reproductive health outcomes, such as inadequate utilization of contraception and undesired pregnancy, primarily attributable to insufficient decision-making and inadequate communication with their spouses compared to married women (Dixit et al., 2021).

The age of the mother was also found to have a significant relationship with the expected number of children ever born at $p < 0.05$. This finding was consistent with a study conducted in Ethiopia (Abdu et al., 2018; Adhikari, 2010; Aragaw et al., 2023) but opposed the finding of a prior study (Azmoude et al., 2017). The importance of these variables could be due to the fact that the likelihood of marrying and having more children increases as women get older, meaning that as women progress in age, there is a corresponding progression in their desire to achieve independence and establish an autonomous lifestyle. The cultural dimension also serves as a significant factor in the reinforcement of reproductive-age women to bear children before the cessation of their childbearing years (Atsbaha et al., 2016).

In the majority of instances, there is an inverse correlation between education level and fertility. The present study indicates that the absence of primary education among women is associated with increased fertility rates in comparison to those who have attained secondary and higher education (CSA, 2016a, 2019). However, in this study, the level of education was not found to be statistically significant in predicting the effect of the number of children ever born. This finding was in line with prior studies (Adhikari, 2010; Azmoude et al., 2017) but in contrast with studies (Aragaw et al., 2023; Atsbaha et al., 2016; Mekonnen & Worku, 2011b; Muche & Gebremichael, 2020; Rutaremwa et al., 2015). Although educated women are usually more aware of family planning methods and the advantages and disadvantages of having children, they should have more autonomy and power in making reproductive decisions, so that they experience a lower fertility rate.

This study has further revealed that employment status was not found to be a significant predictor in determining the effect of the number of children ever born. This finding corroborates studies (Adhikari, 2010; Azmoude et al., 2017; Muche & Gebremichael, 2020) but contradicts the findings of previous studies (Andersen & Özcan, 2021; Muche & Gebremichael, 2020). This fact might be elucidated by the observation that a significant proportion of women are employed in the informal sector, which is characterized by relatively low impacts on fertility.

The finding of this study also confirms that there is a negative association between women's income and fertility, and this is in agreement with other studies (Götmark & Andersson, 2020; James et al., 2011; Shiferaw et al., 2019), but opposes a study conducted in the east of Iran (Azmoude et al., 2017), which prioritizes the demand for children as the key predictor of the effect of the number of children ever born. The relationship between income and fertility rates was also reported to be direct by Kolk (2022). The observed inconsistency may be attributed to the selection of subjects exclusively from urban areas, where educational resources are plentifully available even to individuals with low socioeconomic status. Moreover, urbanization, commonly referred to as urbanism, is likely to be linked with a shift in ideas and attitudes concerning larger families. Moreover, it is plausible that individuals living in urban areas possess enhanced means to procure contemporary contraception methods, consequently empowering them to efficiently implement their intentions to limit fertility rates (White et al., 2018).

The difference in the number of children ever born between contraceptive users and non-users was also found to be significant at $P < 0.05$. Other factors being equal, the difference in the rate of children ever born for contraceptive users is 0.641 times lower than for non-users. This finding was consistent with some studies (Adhikari, 2010; Aragaw et al., 2023; Götmark & Andersson, 2020; Muche & Gebremichael, 2020; Shiferaw et al., 2019) but in contrast with (Atsbaha et al., 2016; Azmoude et al., 2017). The rationale behind the decline in fertility rates can be attributed to the crucial role played by contraception in promoting healthy timing and spacing of pregnancies. Further, contraception has been proven to increase the likelihood of child survival through the spacing of births (Megquier & Belohlav, 2014).

The findings of this study also reveal that the history of child mortality and the need for children were also found to be significant predictors of the effect of the number of children ever born. Holding other factors constant, the number of children ever born is higher when women have a history related to child mortality. This finding corroborates studies (Adhikari, 2010; Atsbaha et al., 2016; Jara et al., 2013; Mekonnen & Worku, 2011a; Muche & Gebremichael, 2020; Shiferaw et al., 2019) but opposes the findings of studies (Aragaw et al., 2023; Azmoude et al., 2017). The aforementioned phenomenon may be explicable by the fact that women who have experienced child mortality have the desire to replenish their children. Nonetheless, they are apprehensive of a recurrence of the adverse outcome (Atsbaha et al., 2016; Endriyas et al., 2017).

Conclusions

The current research demonstrates that the ability to access family planning services and effectively manage fertility is significantly hindered by food insecurity. Moreover, within households experiencing food insecurity, women exhibited a decreased propensity towards utilizing contraceptive techniques in pursuit of attaining a suitable and satisfactory family size. The integration of suitable strategies aimed at enhancing the adoption of family planning services within food-insecure households is a crucial aspect of interventions geared toward regulating household fertility. Therefore, stakeholders are anticipated to engage in collaborative and coordinated efforts across various sectors to address the challenges of food insecurity and fertility issues. Such actions will prioritize expanding women's education, voluntary family planning initiatives, job creation programs, and initiatives to strengthen women's economic empowerment.

Finally, the study findings have been reinforced by the utilization of rigorous statistical analysis techniques and the attainment of high response rates in the data collection process. Moreover, utilizing a thoroughly validated, structured questionnaire could have effectively mitigated the presence of instrumental and inter-rater biases. Despite the extensive exploration of the interrelationship between household food insecurity and fertility, while adjusting for potential confounding variables, the cross-sectional design of the dataset restricts our ability to draw definitive cause-and-effect relationships between outcome and independent variables. Continuous, long-term surveys and standardized measurement tools, such as the Household Food Insecurity Access Scale, need to be employed in future studies to ascertain causal relationships among variables and discern the various levels of food insecurity. This is imperative to establishing a comprehensive understanding of the phenomenon under investigation.

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Consent for publication: There is no restriction on publication

Availability of data and materials: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Appendices:

Appendix 1: Conversion factor for estimation of adult-equivalent calorie requirements

Age (years)	Adult – equivalent conversion factors
New born	
0-1	0.29
Children	
1-3	0.51
4-6	0.71
7-10	0.78
Men	
11-14	0.98
15-18	1.18
19-24	1.14
25-50	1.14
51+	0.90
Women	
11-14	0.86
15-18	0.86
19-24	0.86
25-50	0.86
51+	0.75

Source: Claro et al. (2010). Per capita adult-equivalent estimates of calorie availability in household budget surveys. Cademos de Saúde Pública, 26 (11).

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RESEARCH ARTICLE

Interaction of Capitals and the Climate Change Vulnerabilities: A Study on Santal People of Ramdevpur Abasan of Barind Tract Region of Bangladesh

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Abstract

In spite of Bangladesh's vulnerability to climate change because of its geographical location, geomorphology, and greater dependence on nature, all the communities of the country are not vulnerable to climate change in the same ways. The Santals of Bangladesh are one of the most climate change-vulnerable communities because they are marginalized because they have fewer physical, natural, economic, human, and social capitals. Truly, there is much research on the climate change vulnerability of Bangladesh; however, existing research does not discuss this matter. This research was conducted with the objectives of knowing the interaction between Bangladeshi Santals' different types of capital, the effects of climate change, and the vulnerability of indigenous peoples to climate change. Following the qualitative methodology, this research found that Santals of research field are already marginalized because of having no ownership of land, homesteads and livestock, least access to fresh water, naturally-grown vegetables, trees, and crop seeds), no alternative income sources, less annual income and savings, less educational qualifications, less or no knowledge about climate change, no training on climate change and climate change adaptation, no skills for alternative income, and no access to prior warning about natural calamities, less connectivity to organizations, least access to government services, and having few helpful kin relatives, and interaction among these capitals; climate change effects are making them more vulnerable.

Key Words: Climate Change Vulnerabilities; Santals of Bangladesh; Capitals; Marginalization

Introduction

Climate change is among the most pressing concerns on the globe today. People, ecosystems, and livelihoods have already been impacted by climate change all around the world (Masson-Delmotte et al., 2019). Due to many influences, the world's climate has always fluctuated between warmer and cooler times. According to the IPCC, global temperatures will climb between 1.8 and 4 degrees Celsius by the end of the twenty-first century (Goosen et al., 2018; Ministry of Environment and Forests, 2009). On the other hand, capitals are another important thing on which human beings depend for their survival. Enrichment with natural capitals, physical capitals, economic capitals, human capitals, and social capitals ensures quality life and wellbeing, and low capitals, on the other hand, are known as poverty (Flora & Thiboumery, 2005). All kinds of capitals are connected with one another (Drexler, 2022), and a decrease in one type of capital affects other types. Basically, climate change vulnerability is strongly connected with different types of capitals since the interaction of climate change effects and different capitals significantly determines how vulnerable one community will be to climate change. Significantly, climate change doesn't affect all countries in the same way. Developing countries are more vulnerable to climatic change as they have reduced capital and social, financial, and technological means to adapt. Developing countries are most vulnerable to potential climate change impacts (UNICEF, 2016).

Geographically and geomorphologically, Bangladesh is one of the world's most climate-vulnerable countries, and climate change is worsening it (Ministry of Environment and Forests, 2009; Displacement Solutions, 2012). The agriculture industry is already feeling the effects of climate change and will face increasing issues as climate change increases through altered rainfall patterns, drought, salinity incursion, and soil degradation. Climate change has spatial and seasonal effects on the country's water cycle. Too much water in the monsoon season and too little in the dry periods, as well as altering rainfall patterns, hinder agricultural production, navigability, ecology, and biodiversity (Ministry of Environment and Forests, 2012). However, all parts of this country aren't equally vulnerable to climate change since Bangladesh is separated into various climatic areas and each region is subject to climate variability (Goosen et al., 2018; Ministry of Environment and Forests, 2009). At the same time, all communities in climate-vulnerable regions aren't equally vulnerable to climate change. Climate change can make vulnerable people more vulnerable (UNICEF, 2016). Indigenous populations are marginalized and vulnerable because they live in climate-sensitive areas, face discrimination and exploitation, and lack rights. They are more vulnerable to climate change than others (International Labour Organization, 2017; UNICEF, 2016). There is a lot of research on the effects of climate change on natural and economic capitals in Bangladesh; however, research on the effects of climate change on the indigenous peoples of Bangladesh has not been conducted yet. As a result, a complete scenario of Bangladesh's vulnerability to climate change is hardly found. However, in order to set a long-lasting and effective policy, there is also required research on the climate change vulnerabilities of Bangladeshi indigenous people. Considering its importance, this research has been conducted.

The Santals are also indigenous people of Bangladesh who mainly live in the northwestern part of the country (Islam, 2003), which is very vulnerable to climate change (Rahman & Lateh, 2016; Goosen et al., 2018). As indigenous peoples are already marginalized and vulnerable to climate change (International Labour Organization, 2017; UNICEF, 2016), the Santals of Bangladesh can be considered one of Bangladesh's most vulnerable communities.

In this research, the climate vulnerability of the Santal people of a village in Rajshahi district has been discussed.

Research Objectives

The study has been conducted with the following objectives:

- To understand how the interaction of different types of capital in the Santal community and the effects of climate change are occurring, and
- To know the nature of the vulnerability of Santals to climate change.

Literature Review

According to the Ministry of Environment and Forests (2009), climate change hinders Bangladesh's potential to achieve high economic growth due to severe floods, tropical cyclones, storm surges, and droughts. Bangladesh's natural catastrophes kill people, ruin infrastructural and economic assets, and harm the underprivileged. Frequent and intense tropical storms are causing coastal damage; heavier and more irregular rainfall during the monsoon is leading to heavier river flows, river bank erosion, and higher sedimentation; the Himalayan glaciers' melting causes heavier river flows and salt intrusion; lower and more irregular rainfall is increasing drought; and sea level rise causes saltwater to enter coastal rivers and groundwater; warmer and drier conditions are also contributing to the problem. Each of these shifts affects agriculture and agriculture-dependent communities, reducing crop yields and production. Coastal erosion and saline water intrusion cause people to migrate. However, how the specific communities of Bangladesh, such as indigenous communities, are differently affected by these climate change vulnerabilities has not been revealed by the Ministry of Environment and Forests (2009). In the same way, according to Goosen et al. (2018), as a result of climate change, the intensity of droughts, rainfall, cyclones, storms, and coastal flooding is increasing. Droughts cause soil dryness and hydrogeological inequity, resulting in water scarcity, overexploitation, very reduced stream flows, scarcity of food, livestock fodder insufficiency, and drinking water scarcity; floods have impacts on life, livelihoods, drinkable water, sanitation, health, electricity, and infrastructure; cyclones, storms, and coastal flooding also have impacts on the economy and society. During such events, cattle and poultry frequently die or are lost, further impacting local people who rely on livestock and agricultural supplies. However, how the specific communities of Bangladesh, such as indigenous communities, are differently affected by these climate change vulnerabilities has not also been revealed by Goosen et al. (2018). Similarly, UNICEF (2016) also found that, as a result of climate change, the intensity of floods, droughts, cyclones, river erosion, and tidal surges is increasing in Bangladesh, which has impacts on health, agriculture, education, cattle, water, and infrastructure. UNICEF (2016) also did not focus on how specific communities in Bangladesh, such as indigenous communities, are differently affected by these climate change vulnerabilities. The World Bank Group (2021) also found that because of climate change, the intensity of floods, droughts, cyclones, river erosion, and tidal surges is increasing in Bangladesh, which has caused death, unemployment, damaged assets, agriculture, and infrastructure, and reduced income. The World Bank Group (2021) also did not focus on how specific communities in Bangladesh, such as indigenous communities, are differently affected by these climate change vulnerabilities. In the same way, Ahmed (2006) mentioned that climate change has increased the intensity of climatic disasters such as floods, droughts, river bank erosion, and sedimentation in Bangladesh, which has already had an impact on agriculture, aquaculture, shrimp culture, livestock, forests, human health, infrastructure, and livelihood. However, Ahmed (2006) also did not value how specific communities in Bangladesh, such as indigenous communities, are differently affected by these climate change vulnerabilities.

Research Methodology

This research was conducted in Ramdevpur Abasan in Tanore Upazila of Rajshahi district, which consists of 40 households of mainly 2 categories of occupation, i.e., sharecropper[1]s and wage laborers. This research is basically qualitative; however, the researcher also gave importance to the quantitative information to understand the community's status. Both primary and secondary information were used in this research. To collect quantitative primary information, the researcher visited all the households. A questionnaire was used to collect the quantitative primary information. On the other hand, to collect qualitative primary information, the random sampling method was used while selecting samples for this research. The sample size for collecting qualitative information was not predetermined; however, information was collected from the members of this village until data saturation. The researcher had discussions with 15 people from this village using different qualitative research tools. Among these discussions, 1 was a key informant interview, 6 were in-depth interviews, and 1 was a focus group discussion (FGD) consisting of 8 people. During the researchers' first appearance at the village, the key informants were selected from the villagers among the oldest and most knowledgeable members by discussing with people. Then the researcher conducted the focus group discussion (FGD) to learn about different professional groups'

[1] Sharecropping is known as *bagi* in the research field.

perceptions of climate change and community experience. The researcher also met with six people from different professional groups in order to conduct in-depth interviews to learn about their personal experiences with climate change. On the other hand, for secondary sources or literature, the researcher has collected literature, both global and local, that goes with this study's objectives and is relevant to this study and sorted it out under a larger categorization. The document review method was used as a secondary qualitative data collection tool. After the completion of data collection, information collected by qualitative research tools such as key informant interviews, in-depth interviews, and focus group discussions (FGDs) was coded based on their similarities and analyzed following the thematic analysis method, i.e., categorized under the broader themes. At the same time, quantitative information was analyzed using Microsoft Excel software, and relationships among the same items of coded information were drawn. Unstructured interviews and observation methods were used in order to collect primary data. The household has been considered a unit of analysis in the study. The inductive analytical method has been used in this research.

Findings and Discussion

Findings

Interaction of Physical Capitals and Climate Change Vulnerabilities

Livestock ownership is the only physical capital for the Santals of Ramdevpur Abasan. Among the Santal households of Ramdevpur Abasan[2], only 66.7% of households have cattle, and the rest, 33.3%, have none. Among these cattle, goats are found in most households since they can be bought easily at a comparatively low price and can be sold when needed. Many of the Santal people prefer goats to cows since the households' small children can also cut grass for the goats. On the other hand, these goats can be gotten by bagi[3], and their offspring can be regarded as household assets within a few months. But many of them brought goats from their previous residences. There are some households that raise cows. Generally, those who cultivate more rice in the bagi fields and do not go outside for work rear cows the most. It is true of both cows and goats that people bring them from their previous residence. Their livestock rearing is affected by climate change. It is found that when it rains repeatedly for a few days, they cannot feed them grass. On the other hand, when grass dies because it is not raining, their livestock suffer from hunger. As a result, the Santal residents of the Abasan are quitting rearing livestock, and income from selling them is not coming from it, which forces them to take loans from the Mohajon[4]s at high interest rates when they need money.

Except for ownership over livestock, the Santals of Ramdevpur Abasan do not have any type of physical capital; they neither have nor have had homestead lands of their own. The place where the Abasan is located also does not belong to them since it is Khas[5] land, and they will not also live here for a long time. They also did not have homestead land in the villages from where they once came. Some of them lived on other people's land, building small houses. As a result, they do not have alternative residences. At the same time, as they do not have ownership in the lands in the Abasan, they are not permitted to build residences with concrete, and they build additional houses with straw, which results in damages every year because of wester storms. As a result, they repair their

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[2] Abasan is a government-built shelter for the poor, especially in rural areas.
[3] In the *bagi* system of rearing cattle, the *bagi* takers receive cattle and rear them. The first cab is given to the rearers, and the second one is given to the owners of cattle.
[4] Village elite who lend money with high interests.
[5] Government-owned land.

houses every year, which increases their loans, food shortages, and obstacles to savings. The Santal households that reside in the Abasan also have no land ownership from long ago. They do not even have cultivable lands in their native villages, from where they once came here. Lack of cultivable lands has forced many of them to work as wage laborers and few of them to cultivate rice in the bagi system, where produced rice is divided into three portions and the producers get two thirds of the rice. Generally, they are given comparatively high lands in the bagi system, which is not production friendly; they can produce not more than 15 mon[6] of rice in 1 bigha[7] of land and get 10 mon of rice in the bagi system. However, all the household expenses are difficult to manage with the rice they get. Especially when crops are damaged due to droughts and temporary floods, their investment in cultivation goes to waste. As a result, they are forced to take loans.

Interaction of Natural Capitals and Climate Change Vulnerabilities

Natural resources such as fresh water, naturally-grown vegetables, trees, and crop seeds are found as natural capitals among the Santals of Ramdevpur Abasan.

In Ramdevpur Abasan, water comes from tube wells (ground water), rain, and ponds. Among them, water from a tube well is treated as drinking water since their ancestors used ground water for drinking. Water from rain and deep tube wells is used in cultivation. There are four ponds in this village, and water from the ponds is used for fish cultivation, taking baths, washing cloths, and cocking instruments. It is found that a total of 72.2% of the Santal people of Ramdevpur can access drinkable water, which they fetch from a mini-deep tube well. However, the water crisis is a major problem in Ramdevpur Abasan. It is found that 5.6% of them, 11.1% of them, 27.8% of them, 50% of them, and 5.6% of them cannot get drinkable water consecutively for 6 months, 7 months, 8 months, 9 months, and 12 months in a row. Especially during the drought, Santals in this region face a variety of challenges in obtaining water. Santals are not allowed to collect water from the tube wells belonging to Bengali people because of their love for eating pork and the meat of hunted animals. When the tube wells of the Abasan cannot fetch water in the early drought period of November to January, they fetch water from neighboring villages, which are two kilometers away from the Abasan. Besides drinking water from deep tube wells, pond water, which they also use for bathing, cleaning clothes, and cleaning plates and dishes, is also unavailable to them because of their lack of ownership and the use of animal dust, heavy fertilizer, and chemicals by Bengali people with the intention of commercial fish cultivation. Because they do not have ownership over ponds, they are not allowed to forbid Bengali people from using dirt in ponds. Their poverty also does not allow them to dig deep tube wells to overcome water scarcity.

Like fresh water, naturally-grown vegetables are found to be natural capitals among the Santals of Ramdevpur Avasan. 77.8% of households in this Abasan can have access to naturally growing vegetables for 15 days. Basically, the votua shak, knata shak, and other wild vegetables can be taken until they do not get old. Only 22.2% of households can avail themselves of access to natural resources for 30 days. It is kochu shak, which grows on the pond side in the rainy season. However, people are unable to consume it because it dries up during the drought season. Households with members who work outside the community are more likely to have limited access to natural resources. Apart from naturally-grown vegetables, trees are important natural capitals at Ramdevpur Abasan. There are bamboos and palm trees at the Abasan. Santals living here make baskets with bamboo and mats with the leaves of palm trees. Their houses are also made and repaired with bamboo and palm leaves.

[6] 1 *mon* contains 40 kg of product.
[7] 1 *bigha* contains 33 decimals of land.

Crop seeds are also found to be Ramdevpur Abasan Santals' natural capitals. It is found that 16.7% of households keep the seeds as they cultivate vegetables on homesteads and rice in the jhina system. If they do not have seeds or comparatively good seeds, they collect them from their close relatives. These people sometimes buy seeds from the market since they are easily found there, which sometimes leads them to not conserve seeds at home. However, 83.3 percent of households do not have crop and vegetable seeds because they believe they will be useless due to insufficient land in the Abasan, uncertain living conditions in the Abasan, and no land of their own.

Interaction of Economic Capital and Climate Change Vulnerabilities

The economic capitals of the Santals of Ramdevpur Abasan include the number of income sources, earning members of households, annual income, and family regular savings. It is found that more than half of the households (56.6%) do not have multiple income sources, and the household members of these households work as agricultural daily wage laborers. Basically, there is no opportunity to do other activities, which makes people depend more on wage labor and rice cultivation in the Jhina[8] system. On the other hand, the total households that have multiple income sources account for 44.4% of the total households. Basically, the household members of these households work as daily wage laborers, cutting rice in the Jhina tradition and digging soil. Ramdevpur Santal's expertise also extends to making baskets and mats, which they learned from their ancestors and neighbors. It can be seen that whatever income sources the Santals of Ramdevpur have are basically agricultural and nature-based. As a result, the effects of climate change on the income of the Santals of Ramdevpur Abasan are well imagined; people cannot grow rice and other rabi crops[9] in the winter season due to water scarcity. On the other hand, in the monsoon season, it rains here a lot, just as it does in other parts of Bangladesh. As a result of excessive rain, land at lower levels goes under water. In the rainy season, when Aus[10] and Aman[11] rice are cultivated, this place remains uncultivated because of the flood-like situation. People can also not tend cattle or cut grass for their cattle on these lands. On the other hand, people who are wage laborers lose their jobs in their community when there is no water due to droughts or floods. Those who have expertise in making baskets and mats are also about to make no use of their skills since there is a lack of trees because of draught. Being engaged in nature-based income sources leads people to a shortage of food, jobs, cattle, and grass and forces them to migrate to Mohanpur, Durgapur, or Rajshahi city. Sometimes, the Santal males of this Abasan migrate to Faridpur for 15–20 days and work as agricultural day laborers. Those who migrate to Dhaka generally work as garment workers with low wages.

Besides the number of income sources, earning members of households also play an important role as economic capitals. It is found that 44.4% of Ramdevpur households have one earning member, and 38.9% of households have two. Only 5.6% of households have three, and 11.1% of households have four earning members. Most households with one earning member have a male earning member. However, female-headed households, as a result of the husband's illness and death and having no one left behind, lead women to earn. Sometimes, as partners of males, female members of these households work to reduce poverty and ensure food security. Children who are not continuing their studies are engaged in income-generating activities.

Based on the number of income sources and earning members, the annual income of the 18 Santal households of Ramdevpur Abasan also differs from each other. It is found that 5.6% households, 11.1% households, 11.1%

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[8] A traditional harvesting system where the wage labourers cut and thresh paddy in exchange for 7-8 kg of rice per 40 kg paddy and distribute among themselves.

[9] Crops that are sawn in the winter season.

[10] A type of paddy planted in the month of May and harvested in July.

[11] A type of paddy planted in the months of July-August and harvested in November-December.

households, 11.1% households, 16.7% households, 22.2% households, and 5.6% households consecutively have a yearly income of BDT 15000, BDT 16000, BDT 18000, BDT 20000, BDT 22000, BDT 24000, BDT 25000, BDT 30000, and BDT 40000. The difference in households' yearly income is caused by the difference among the incomes of their earning members and the employment opportunity, since the households with more earning members have more income opportunities, and people are employed as agro-wage laborers for 15 days in January for planting Boro rice, 15 days in April-May for harvesting Boro rice[12], 15 days in July-August for planting Aman rice, and 15 days for harvesting Aman rice. At the same time, there is discrimination in the wages of males and females, which causes the comparatively decreased yearly income of households with female earning members compared to households with male earning members. However, the household members who are going to Godagari and Tanore, where cultivation is made possible with the help of deep tube wells, are likely to have more income. The households with less income are to take loans from different sources. It is found that 7 households out of a total of 18 households have loans, whereas 11 households do not have loans. Among these 7 households, 16.7%, 33.3%, 16.7%, and 33.3% of households have loans consisting of consecutively BDT 2000, BDT 5000, BDT 10000, and BDT 14000, which are taken from the Mahajons and Abasan Co-operative. Basically, the formalities of Abasan Co-operative in taking loans lead people to the Mahajons since it is easier to take loans from them than from the co-operatives. Santals of this Abasan generally take loans to buy food in times of food scarcity and impending needs for visiting doctors and building tube wells. Salman says, "When you need BDT 500–1000, you will think selling your cattle is illogical since you will not get it back because of your family's needs. When the time of harvesting comes, the heads of these households pay the loans by working without taking wages. But those who cultivate rice in Jhina lands sell their rice and give the money back. People who cultivate fewer jhina lands are likely to be more vulnerable to food crises since they sell most of their rice to pay the loan with high interest. In the last 5 years, the occurrence of taking loans increased because of damaged crops due to droughts in November–March, hailstorms in April–May, and temporary floods in May and November.

Savings, which act as economic capital, are also found to be lower among the Santal households of Ramdevpur Abasan. 88.9% of Ramdevpur Santal households do not have savings. There is one household that has a regular monthly savings of BDT 100 and another household that saves BDT 200 per month. Their more frequent expenses than income because of repayment of debt, buying food, production costs, and damages to crops and assets do not let them save money in their account regularly. Kangana Soren asserts, "We are living hand to mouth since we do not have savings and are lending money when we do not have it."

Interaction of Human Capital and Climate Change Vulnerabilities

The human capital of the Santals of Ramdevpur Abasan includes educational qualifications, knowledge about climate change, training on climate change and climate change adaptation, skills for alternative income, and prior warning about natural calamities.

It has been observed that there is a government primary school just beside the Abasan. However, only 11.1% of the household heads have primary-level education, 5.6% have secondary-level education, and 83.3% of the household heads are illiterate, i.e., they have never gone to school. Basically, poverty, being far away from schools, the unconsciousness of their parents, their little knowledge regarding education, and the unfamiliar environment of schools resulted in their limited access to education. The nearly constant presence of primary schools inspires the Abasan people to send their children to school. As many of the Santal household heads of

[12] A type of paddy planted in January and harvested in April-May.

Ramdevpur Abasan lack formal education, they do not have the opportunity to engage in service jobs, which are not affected by climate change.

At the same time, 44.4% of household members can imagine that the climate is changing, whereas 56.6% of household members do not have knowledge regarding climate change. Those who have knowledge of climate change think that the Barind[13] region is drought-prone, but the recent hotter climatic situation has never been felt before, and their traditional adaptation strategy is not working well. Heavy rain in recent inaccurate times has been decreasing their crops, which has made many of them realize climatic changes.

The people of Ramdevpur also do not have training on climate change and climate change adaptation since there was no training in this Abasan in which they could have participated. Moreover, they do not even know their relatives who participated in such training. As a result, they have no idea how they can cope with climate change and mitigate climate vulnerabilities.

It is also found that 83.3% of societal households' members do not have alternative income skills and are dependent on agriculture for their livelihood. The rest (16.7% of households' members) got training on cow health and sericulture, but these skills are not meeting their practical needs since they lack the cows they need. On the other hand, the skills of making baskets with bamboo branches and mats with palm leaves have been acquired by seeing their relatives, which are of no use since there is a lack of these trees in this Abasan because of droughts.

At the same time, no household members get any prior warning regarding disasters, and none of them have been to any organization or agency office to get information in this regard since they did not even know that this information could be known from any offices. All they know about climate change is based on their perceptions and experiences. Their lack of confidence stemmed from a lack of educational qualifications, poverty, and the experience of being ignored solely because they were Santals, so they did not dare go to any offices for information. As a result, they cannot prepare for any natural calamities, which results in damage to their assets.

Interaction of Social Capital and Climate Change Vulnerabilities

The social capitals of the Santals of Ramdevpur Abasan include connectivity to organizations, access to government services, and having helpful kin relatives. However, not all households have access to these capitals. There is a cooperative organization in this Abasan, and all the households, regardless of their ethnic identity, are members of the Abasan Cooperative. Besides this, only one Santal man is found to be a member of the managing committee of a local school. 33.3% of households' members have membership in any ethnicity-led organization (clubs, social, and cultural). There is no Union Parishad member from this Abasan, and the Santals of this Abasan also do not have any connection with Union Parishad members. Aside from that, only a small number of Santal people are members of national-level ethnic organizations and NGO-led small groups. As a result, they cannot request any Union Parishad member to set a tube well in this Abasan.

At the same time, since the Santals of Ramdevpur Abasan do not have connectivity with the Union Parishad office, they do not get information about safety nets and government assistance. As a result, the local Union Parishad office provides almost no assistance to the Santal people of Ramdevpur Abasan; there is only one (5.6%) household whose members got allotted a residence in the Abasan in 2017, and the rest, 94.4% of households, did not get any kind of aid.

Among the 18 households, 27.8% have kin or relatives who can help them in disasters. Many of these households' members recently got married and have connections with their parents. They have shared money, rice, and vegetables with them. This sharing also happened with the fictive relatives. On the other hand, 72.2% of

[13] Ramdevpur *Abasan* is located in the Barind tract region, which contains the northern-southern part of Bangladesh with fewer trees, hard and stair-like geographical landscape, and less rainfall.

households do not have such relatives who can help them in crisis situations. Many people who reside in this area have no social connection with the place where they once lived and have left their neighbors and kin. The rest of the people who have little ties to their previous residence and kin relatives also lack the assistance of relatives because their relatives are poor as well.

Discussion

Although Bangladesh is a multicultural country, Bangladesh's Santals and other indigenous communities are among the country's most vulnerable and marginalized groups for a variety of reasons, including the ongoing loss of land and natural resources, language and culture, and a lack of access to adequate public services (International Labour Organization, 2017). Indigenous peoples are marginalized due to high levels of illiteracy, unemployment, exploitation by political leaders and middlemen, a lack of infrastructure, and the media's unsupportive role (Sahoo, 2016). Their limited access to education and knowledge stops them from getting accurate information about government and development agency opportunities (Sharif, 2014). Santals' cultural food habits restrict eating at local restaurants and food shops, and the Bengali community's carelessness and disdain of ethnic food systems create a situation where ethnic children do not sit in the same classroom as Bengali children (Sarker & Davey, 2009). Indigenous peoples have already been socially, economically, politically, and geographically isolated as a result of discrimination and hatred.

The Santals of Ramdevpur Abasan are found to have similarities with the other Santals of Bangladesh in terms of different types of capitals, e.g., physical capitals, economic capitals, natural capitals, human capitals, and social capitals. Similarly, physical capitals such as livestock ownership, homestead ownership, and cultivable land ownership among the Santals of Ramdevpur Abasan are found to be poor. There are no cultivable or living lands owned by any households in that Abasan, and only a few households have cattle. Like their physical and economic capitals, their natural capitals, such as fresh water, naturally grown vegetables, trees, and crop seeds, are limited in their access. Pond water, which is a source of fresh water in this Abasan, is also dirty and unusable for domestic purposes because of animal and chemical dust. Their economic capital is also found to be short since many of the households have loans with high interest rates, less yearly average income, less family regular savings, fewer multiple income sources, less nature-based income, and fewer earning members of households. Human capital among the Santals of Ramdevpur Abasan is also poor. Many household heads are found to have no educational experience, have no ideas regarding climate change, have no training on climate change and climate change adaptation, have no capacity for alternative income, and have no access to information. Their social capital is also found to be poor since they do not have connectivity to organizations, have a smaller number of helpful relatives, and have no access to government services.

Again, all types of capitals are also found to be linked to each other. Ramdevpur Abasan’s Santal households’ lack of land is making them more dependent on daily wage labor and producing crops in an exploitative bagi system. Less income from agricultural wage labor jobs does not help them save; rather, it sometimes leads to higher amounts of loans, which force them to give large sums of money and crops to others. In addition, people suffer from a food crisis again. Their poverty, in collaboration with being far away from schools, the unconsciousness of their parents, their little knowledge regarding education, and the unfamiliar environment of schools, creates obstacles to getting an education, and it finally keeps them from non-agricultural jobs. Their lack of participation in jobs is making them less diverse in their earning sectors. Again, jobs in different development, government, and corporate organizations are thought to be prestigious because they require education and increase the possibility of earning more money, which could be helpful in creating physical, social, economic, and human capital. At the same time, their experience of being hated and neglected by people of the Bengali community led them to have no membership in any organizations of other communities, which led them to get no government and NGO opportunities or information regarding these opportunities, which could assist them in overcoming their situation. On the other hand, their lack of ownership of physical and social capital is not allowing them to access natural capital, e.g., pond water.

In the existing situation of marginalization of the Santals of Ramdevpur Abasan, the climate change effects are about to interact with the different types of capitals of Ramdevpur Abasan's Santals and are forcing them to be more marginalized as a result. The natural hazards in Ramdevpur, namely drought, flood, and storm, which are occurring more frequently in recent years as a result of climate change, are bringing a number of changes to this village. Santal farmers cannot grow Boro rice and other Robi crops in the winter season due to drought. On the other hand, in the monsoon season, it rains here a lot, and as a result of excessive rain, land at lower levels goes under water. In the rainy season, when Aus and Aman rice are cultivated, this place remains uncultivated due to a flood-like situation. On the other hand, people cannot also tend cattle or cut grass for their cattle on these lands. This condition leads to a shortage of food, jobs, cattle, and grass. On the other hand, Santals who do not cultivate are bound to work on other people's lands. When there is no water because of droughts, they lose their jobs in their locality. Both heavy rain in the monsoon and no rain in the drought season lead to joblessness and poverty. Apart from cultivation, climate change effects also interact with natural capital. During the drought, Santals in this region face a variety of challenges in obtaining water. Since Santals are not allowed to collect water from the tube wells belonging to Bengali people only because of their love for eating pork and meat from hunted animals, they are to bring water from other Santal villages. At the same time, alternative sources of water, e.g., ponds, are coming to no use as the Santals of Ramdevpur Abasan do not have control over them. Their poverty also does not allow them to dig deep tube wells to overcome water scarcity. Having no cultivable lands allows them to work on other people's lands.

Indigenous peoples around the world, including the Santals of Bangladesh, are vulnerable to changes in climate. In terms of social, economic, and environmental vulnerability, Indigenous peoples are among the poorest and most threatened portions of the world's population. Their economic, social, and cultural activities depend on natural materials that are subject to increased risk due to climate change and extremes. They continue to live in geographical areas and ecosystems that are most vulnerable to climate warming. Indigenous peoples' sensitivity to changes in climate can necessitate migration. In most situations, this leaves individuals more exposed to prejudice, exploitation, and environmental concerns in their destination countries. Migration typically causes the loss of economic, social, and cultural activity. Climate change exacerbates gender inequality, a crucial determinant of indigenous women's impoverishment. Indigenous women play an important role in traditional and nontraditional sources of income, unpaid work duties, and food security, but they face internal and external discrimination. Indigenous peoples' rights and institutions are often ignored (International Labour Organization, 2017; UNICEF, 2016; International Labour Organization, 2016). If the climate change effects continue to be higher, the indigenous peoples will have no other options but migration to cope (International Labour Organization, 2017), as it has already started among the Santals of Ramdevpur Abasan on a temporary basis.

Conclusion

It can be analyzed from the above discussion that the Santals of Ramdevpur Abasan lack different types of capital: physical capital such as land ownership, homestead ownership and livestock ownership, economic capital, natural capital such as access to fresh water, naturally-grown vegetables, trees, and crop seeds, human capital such as alternative income sources, annual income and savings, educational qualifications, knowledge about climate change, training on climate change and climate change adaptation, skills for alternative income, and access to prior warning about natural calamities, and social capital connectivity to organizations, access to government services, and having few helpful kin relatives, which force them to be marginalized by interacting among themselves. In the context of their already marginalization, climate change effects such as draughts, floods, and storms make them more marginalized and dependent on loans from the local Mohajons, and finally force them to migrate, which puts them under the threat of cultural loss.

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RESEARCH ARTICLE

A Model Walkability Index for Sustainable Urban Mobility of a Region: The Case of Soccsksargen- A Transdisciplinary Research Approach

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Abstract
Although walkability studies have been pronounced and recognized as an important factor for sustainable urban development, few studies have focused on calculating a reliable walkability index that captures the multifaceted dimensions of urban mobility. Hence, this study aimed to formulate a Model Walkability Index for SoCCSKSarGen Region as the basis for urban development policies in achieving sustainable mobility. Using a convergent mixed methods design, data were collected from 399 pedestrians, five professional design organizations, and 2 public health experts. Through a transdisciplinary approach, it utilized statistical techniques such as descriptive statistics, inferential statistics, and multivariate analysis. For the qualitative findings, data were analyzed using Quirkos and MaxQDA software. Likewise, Exploratory Factor Analysis (EFA) was employed to derive the key Walkability factors for formulating the Walkability Index Model. Data revealed that all groups of experts were similar in identifying safety, comfort, and aesthetics as walkability attributes. On the contrary, only the transdisciplinary design professionals considered anthropometric measures and activities as walkability attributes aside from those previously mentioned. Likewise, the converged data provided substance in developing the Model Walkability Index (MWI) for SoCCSKSarGen Region. The resulting MWI discussed in the study represents the convergence of transdisciplinary efforts integrating safe roadway design concepts and sustainability considerations. Furthermore, the study offers a holistic assessment of walkability, enabling stakeholders to foster the creation of future walkable urban communities that are safe, healthy, and environmentally conscious.

Keywords: SoCCSKSarGen; walkability; convergence; transdisciplinary; sustainability; safety index

Introduction

The rapid concentration of the population in urban areas poses many challenges to sustainability among these, mobility emerges as one of the main generators of externalities that hinder the achievement of the Sustainable Development Goals (Cayetano Medina-Molina et al 2022).

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As urban populations continue to grow, the need for sustainable and efficient mobility approaches becomes increasingly imperative.

Walking is undoubtedly a sustainable and healthy mode of transport. walking as a viable means of transportation has become the focus of sustainable development policies (Macioszek et al 2022). However, the decision to walk is influenced by many built environment and streetscape attributes (Fonseca et al 2022)

This dissertation focused on developing a comprehensive model walkability index specifically tailored for the urban mobility context of the SoCCSKSarGen, a region situated in the southern part of the Philippines. The SoCCSKSarGen region, comprising the provinces of South Cotabato, Cotabato, Sultan Kudarat, Sarangani, and General Santos City, is characterized by rapid urban growth and increasing transportation demands (National Economic and Development Authority, 2022). Given the region's unique geographical, cultural, and socioeconomic aspects, a transdisciplinary research approach is adopted to address the complex interplay between architecture and civil engineering, urban planning, transportation engineering, environmental sustainability, and public health (Loorbach et al., 2017; Mehmood et al., 2022).

The overarching objective of this research is to create a robust and reliable walkability index that captures the multifaceted dimensions of urban mobility in the SoCCSKSarGen region. This index will serve as a valuable tool for designers, planners, policymakers, and researchers to evaluate the walkability of different urban areas within the region and identify opportunities for improving pedestrian infrastructure, enhancing connectivity, and promoting sustainable transportation modes (Schoner et al., 2018). Understanding how urban space influences citizens' perceptions of walkability is critical to designing efficient pedestrian planning policies and guiding future research in this field (Fonseca 2022).

A transdisciplinary research approach is employed to tackle the complexity of the research problem, involving collaboration between various disciplines such as architecture, civil engineering, landscape architecture, urban planning, transportation engineering, and public health, including pedestrian users. Transdisciplinary research can solve problems that cannot be solved in one discipline as the approach is able to connect different disciplines and stakeholders and guarantee a sufficient and efficient consideration of all relevant factors for real-world problems (Stinder et al 2022). This transdisciplinary collaboration engages a holistic understanding of the region's urban mobility challenges and enables the integration of diverse perspectives, expertise, and methodologies to develop an inclusive walkability index.

The study adopts a convergent mixed-methods research design, combining quantitative analysis, spatial modeling, and qualitative assessments to capture both objective and subjective aspects of walkability. Through the integration of pedestrian surveys, interviews, and participatory engagement, the research aimed to generate a comprehensive understanding of the factors influencing walkability in the SoCCSKSarGen Region (Cerin et al., 2017). This transdisciplinary research approach ensures a nuanced, people-centered and contextually relevant model that reflects the unique characteristics and needs of the region.

By developing a robust walkability index, this dissertation contributed to the existing body of knowledge on urban mobility and provided practical insights for sustainable urban planning in the SoCCSKSarGen region. The findings of this research can inform policy interventions, infrastructure investments, and community engagement initiatives aimed at enhancing walkability, promoting active transportation, and fostering healthier and more sustainable urban environments (Giles-Corti et al., 2019; Sallis et al., 2016).

This dissertation represents a pioneering effort in the development of a model walkability index tailored to the urban mobility context of the SoCCSKSarGen Region. Through its transdisciplinary research approach, this dissertation aimed to provide a comprehensive understanding of the complex interplay between urban planning, transportation engineering, environmental sustainability, public health, and pedestrian users. The results of this research hold significant potential for fostering sustainable urban development and improving the quality of life for residents in the region.

Literature Review

Defining Walkability

The term walkability is used to describe the extent to which the urban environment is pedestrian-friendly, usually by quantifying multiple built environment attributes at the neighborhood scale (Fonseca et al 2022). It encompasses the design, infrastructure, and amenities of an area that encourage and enable individuals to walk for their daily needs, recreation, or commuting purposes (Litman, 2020). Walkability is often assessed based on criteria such as sidewalk availability and quality, street connectivity, presence of crosswalks, pedestrian safety features, land use patterns, access to public transit, and the proximity of essential destinations like schools, workplaces, shops, and parks (McCormack et al., 2018). The concept of walkability only started to be used in transport and planning studies in the early 2000s, but rapidly became a widely used concept in sustainable mobility and other disciplines (Fonseca et al 2022) This concept plays a crucial role in creating healthier, more sustainable, and vibrant communities, as it promotes physical activity, reduces dependence on automobiles, improves air quality, fosters social interaction, and enhances the overall quality of life (Litman, 2020; McCormack et al., 2018). The urban areas in SoCCSKSarGen, depended much on personalized public commuter systems such as tricycles and habal-habal, relegating walking to the sidelines.

Walkability has become a major theme of urban research, and also a key goal of various urban design practitioners (Forsyth, 2015; Winters et al., 2017) such as architects, planners, engineers, landscape architects, etc.

However, to comprehensively address the complex and interconnected challenges associated with walkability, it is crucial to adopt a transdisciplinary approach. By involving multiple disciplines, the multifaceted aspects of walkability can be explored, and innovative solutions will truly enhance the pedestrian experience (Marans & Stimson, 2011).

Walkability as a Sustainable Mode of Urban Mobility

Non-motorized or active transportation (walking, cycling, and its variations) plays an important role, and significant and distinct responsibilities in a well-functioning transportation system Walking is a practically ubiquitous human activity that allows for mobility, exercise, and enjoyment.

The ideal practice is to have 10-20% of trips made completely through non-motorized modes, while the majority of motorized trips include non-motorized linkages, such as connecting to public transportation and between parked cars and destinations. Pedestrian environments include parking lots, transportation terminals, airports, and commercial districts. Improving non-motorized transportation is frequently one of the most cost-effective methods to improve motorized transportation.

Walking and cycling are both low-cost modes of transportation. They are typically relied on by physically, economically, and socially disadvantaged persons, so enhancing non-motorized transportation can assist in achieving social equity and economic opportunity goals. The most prevalent kind of physical activity is active transportation and the most practical strategy to promote public fitness and health is to increase the frequency of walking and cycling. Non-motorized modes can help planners meet their goals in the reduction of traffic congestion, consumption of energy, and pollutant emissions They can also aid in the achievement of land use planning goals including urban redevelopment and more compact "smart growth" development.

The most accessible public realm or spaces include a large number of pedestrian contexts (sidewalks, walkways, and hallways). Many useful behaviors (socializing, waiting, buying, and eating) take place in pedestrian contexts, and the quality of these spaces has an impact on them. To attract clients, shopping areas and resort communities rely on walkable environments. Popular recreational activities now include walking. Improving the pedestrian-built environments helps users in terms of enjoyment and health, as well as supporting related industries such as retail, recreation, and tourism.

The popularity of walking is still inherent as much research suggests that people continue to walk for transportation and enjoyment despite the availability of motorized vehicles. In many cases, improving walking conditions while restricting motor use is the greatest method to improve urban transportation. It improves overall accessibility to locations in terms of convenience, comfort, and affordability.

Walking is the most cost-effective and environmentally friendly among other modes of transportation and recreation. Its potential cost and resource savings are often highlighted (Litman 2018).

This high value placed on driving and the low value placed on walking in conventional planning reflects how transport is measured (Litman, 2018). Because short trips, non-work travel, travel by minors, recreational travel, and nonmotorized links are most often overlooked, and most travel surveys undercount nonmotorized travel. Most travel surveys, for example, label "auto-walk" or "walk-transit-walk" trips as "auto" or "transit." Walking links, regardless if they happened on public driveways or rights-of-way and consume as much time as motorized links, are also left unnoticed. According to previous research by Zapata-Diomedi et al (2017), in Brisbane, nearly 80% of adults travel for work or education by private cars about 20% of urban trips are conducted by active transport. While in Germany, just 22% of trips are entirely made on foot, although 70% include some walking.

A report from the United Kingdom states that walking accounts for 2.8 percent of overall mileage, 17.7% of travel time, and 24.7 percent of trips. Walking appears negligible when it is measured solely in terms of travel distance, however, when it is measured in terms of trips, travel time, or even outdoor exposure to public spaces and social infrastructure. Because by nature non-motorized transport has slower speeds than its motorized counterpart and considering commuters waiting at bus stations or loading bays, or just merely standing in front of store windows, non-motorized passengers may account for only 5% of person-trips but 40% of person-minutes of public exposure. As a result, how people view the transportation system and the local environment is heavily influenced by their walking conditions.

Active modes of transportation have become one of the beacons of Sustainability/. In the 2030 Agenda for Sustainable Development, the United Nations has determined that countries and regions should provide safe, affordable, accessible, and sustainable transportation for their citizens (Zafri et al; 2021)

The Influence of the Built Environment on Walking

Recent multidisciplinary transport studies that link transportation planning to health studies have acknowledged that walking helps to maintain the physical and mental health of all ages by preventing a variety of health problems (Mohammed 2017), and as a result, researchers are now more concerned with the built environment determinants of active transportation emphasizing the need to identify what are the spatial factors that would influence and condition active transportation. The term built environment refers to the human-made surroundings that provide the setting for human activity (Kaklauskas 2016).

The positive and negative effects of interactions between pedestrians and the built environment influence the pedestrian walking experience. These spatial features are thought to have an impact on a person's decision to walk. The Built environment is increasingly recognized as a key driver of walking and physical activity (Liao et al.,2020).

Walking is now being acknowledged by planners as an important means of active urban transportation as support for urban sustainability grows. The popularity of urban walkability is growing due to rising fuel costs, fuel availability, traffic congestion, pollution, and other urban difficulties induced by a significant reliance on fossil fuel-driven cars.

Environmental Factors Affecting Pedestrian Satisfaction

To obtain insight into urban design techniques that can promote both pedestrian satisfaction and activities, Kim, Park, and Lee (2014) explored the correlations between pedestrian satisfaction and several built environment characteristics. The authors illustrated the significant correlation between the satisfaction of pedestrians and the quality of urban pedestrian environmental factors using econometric instruments, indicating the importance of taking psychological factors into account when studying walkability, such as different pedestrian groups and trip motives. The built environment is shaped by transportation investments and land-use allocation and therefore hinders or encourages walking (Wang 2021). Details of environments, including sidewalk and crossing quality and aesthetics, are believed to affect people's confidence, comfort, and safety for walking in neighborhoods (Sallis et al., 2016), but they have been less well-studied. These attributes were identified using the neighborhood walk audit and through actual observational measures on users' or stakeholders' preferences.

Walkability increases exponentially when people feel a sense of control over the streets they walk. Conversely, streets fail when they seem to be controlled by no one. Walkability and street vitality are important factors in shaping urban life on and around the street.

Pedestrian Experience Principles in Measuring Walkability

Walkability is a key concept of sustainable urban development (Yamagata et al, 2020). Leyden 2003 further states that walkable communities have the potential to contribute to the well-being of communities by way of reducing carbon emissions and improving climate resiliency. Walkability refers to the degree of walking comfort in a walking environment for pedestrians (Kari 2016). Dong Yeong Jong (2017) states that pedestrian's cognition, affect, and behavior occur from the interaction between pedestrian passage and its related environment which he called the pedestrian experience and that to promote walkability, it is necessary to design walking environments according to the pedestrian experience (PX) principles.

Yamagata et al (2020) in their study of the experiential model for the walkability of Kyojima District in Japan identified the following as the five thematic Pedestrian Experience (PX) Principles for walkability :(1) Activity (2) Beauty/Aesthetics (3) Comfort (4) Anthropometric and (5) Security/Safety. These themes are further subdivided into various indices.

These Principles are a set of guidelines developed by the City of Yamagata in Japan to promote a pedestrian-friendly urban environment. The key elements of the Yamagata PX Principles and their significance in enhancing the pedestrian experience were identified as follows:

Human-Scale Design: The Yamagata PX Principles emphasize the importance of human-scale design, which involves creating urban spaces that prioritize the comfort, safety, and convenience of pedestrians. This includes features such as wide sidewalks, pedestrian-friendly crossings, ample seating, and well-maintained public spaces.

By designing for human scale, the principles aim to create a walkable environment that promotes social interaction and enhances the overall pedestrian experience.
Universal Accessibility: The Yamagata PX Principles emphasize the importance of universal accessibility, ensuring that the urban environment is inclusive and accommodating for people of all ages, abilities, and mobility levels. This involves providing barrier-free access, installing ramps and elevators, and considering the needs of individuals with disabilities when designing pedestrian infrastructure. Universal accessibility ensures that everyone can fully participate in and benefit from the pedestrian experience.
Safety and Security: Safety and security are paramount in the Yamagata PX Principles. The principles emphasize the importance of creating a safe and secure environment for pedestrians through measures such as well-lit streets, clear signage, and effective traffic management. These measures help reduce the risk of accidents and promote a sense of security among pedestrians, encouraging more people to walk and explore the urban environment.
Integration of Nature: The Yamagata PX Principles recognize the value of incorporating nature into the urban environment. They emphasize the integration of green spaces, trees, and vegetation to enhance the pedestrian experience. By incorporating nature into the urban fabric, the principles aim to create a more pleasant and visually appealing environment that contributes to the overall well-being of pedestrians.
Cultural and Historical Preservation: The Yamagata PX Principles highlight the significance of preserving and showcasing the cultural and historical heritage of the city. They encourage the integration of cultural elements, historic landmarks, and traditional architecture in urban design. This approach fosters a sense of identity and pride among pedestrians, as well as promotes a deeper appreciation for the city's cultural heritage.
Implementing the Yamagata PX Principles requires collaboration between urban planners, architects, transportation experts, and community stakeholders. By adhering to these principles, cities can create pedestrian-friendly environments that enhance mobility, health, and quality of life. The Yamagata PX Principles serve as a valuable framework for cities worldwide to guide the development of urban spaces that prioritize pedestrians and create vibrant, livable communities.

Elements of the Pedestrian Experience (PX) Principle

The Yamagata study further identified experiential attributes for each pedestrian experience theme that relates to walking in public pedestrian facilities.

a. Activity
- a.1 High Vehicular Traffic Volume
- a.2 Presence of Business Establishments along Sidewalks
- a.3 Presence of Food Establishments
- a.4 Presence of Parks and Playgrounds
- a.5 Proximity to commercial complexes

b. Aesthetics
- b.1 Colorful attractive Sidewalks
- b.2 Presence of Landscaping
- b.3 Nice Building Facades
- b.4 Presence of Public Art

c. Comfortability
- c.1 Protection from Heat and Rain (Presence of Tree Canopies)

c.2 Presence of Street furniture
c.3 Good Sidewalk surface quality (Ergonomics)
c.4 Clear unobstructed and leveled sidewalks

d. Anthropometric
d.1 Adequate Sidewalk width
d.2 Adequate Headroom
d.3 High Pedestrian Traffic
d.4 Presence of PWD Ramps

e. Safety
e.1 Good Outdoor Air Quality
e.2. Presence of Traffic Lights
e.3 Presence of Pedestrian Crosswalks
e.4 Clear and Legible Road Signages
e.5 Presence of Loading and unloading bay
e.6 Presence of Rails or Bollards
e.7 Adequate Street Lighting
e.8 Presence of CCTV Cameras

SOCCSKSARGEN Regional Development Plan

In the Philippine setting, before the introduction of automobiles by the Americans, walking, together with animal-driven vehicles, was then the dominant mode of transport. However, as cities experience rapid urbanization, the volume of vehicles also increases which resulted in traffic congestion and the deterioration of outdoor air quality due to increased carbon emissions from fossil fuel-driven vehicles. This phenomenon is happening in almost all major cities in the country, SOCCSKSARGEN Region included.

SOCCSKSARGEN's regional development plan identifies ten (10) preferred medium-term strategies focusing on peace, environment, infrastructure development, and safety and resiliency. Strategy number 3,4,5 specifically identifies improving social infrastructure and building community resiliency that integrates disaster risk reduction, and climate change action (NEDA XII).

Social infrastructure helps in recognizing the public spaces that are often overlooked and undervalued. It draws attention to the breadth, depth, and textures of sociality that can be afforded by different urban environments (Latham and Layton 2019). Klinenberg (2018) defines Social Infrastructure as "public institutions, such as libraries, schools, playgrounds, parks, athletic fields, and swimming pools, including sidewalks, courtyards, community gardens, and other spaces that invite people into the public realm".

Social infrastructure, despite its role in helping recognize the public dimensions, are most often been not prioritized and these public spaces have always been de-prioritized in urban development.

In compliance with the strategies identified by the SOCCSKSARGEN Regional Development Plan, and recognizing the need to improve the social infrastructure and safety of public spaces, the General Santos City public safety office (PSO) recently crafted its Local Public Transport Route Plan (LPTRP), and among its goal is to manage both the motorized and non-motorized mode of transport in the city. Its primary aim is to find a solution to the issues created by the huge volume of tricycles plying the city and to reduce the street hazards and environmental pollution emanating from the high density of motorized tricycles ad private cars plying the urban streets. Among the strategic plan of the PSO, is to encourage active transport, biking, and walking, especially in the dense central business district.

Recently the Department of Human Settlements and Urban Development (DHSUD) issued Memorandum Circular 2021-010 mandating all local government units to enhance the Climate and Disaster Risk Assessment Process to ensure that these are integrated into local development and land use plans.

The literature review provides a comprehensive overview of the concept of walkability, its importance in promoting sustainable urban mobility, the influence of the built environment on walking, and the principles of the pedestrian experience. However, there are notable research gaps and areas for innovation that warrant attention in this study.

The literature review highlights the reliance on personalized public commuter systems in SoCCSKSarGen, relegating walking to the sidelines. A critical research gap lies in understanding the specific challenges and opportunities for enhancing walkability in this context.

While previous studies acknowledged the need for a transdisciplinary approach to address the complex challenges of walkability, they fall short in providing specific examples or methodologies for implementing innovative collaborations between disciplines such as urban planning, architecture, public health, and sociology. This could involve developing frameworks for effective communication and decision-making among diverse stakeholders to optimize walkability outcomes.

This research focused on investigating and harmonizing the meaning of walkability from the viewpoints of transdisciplinary design professionals and groups involved in the development of the built environment (environmental planners, architects, engineers, transportation experts, public health officials, and pedestrian users.) and in the process identify the attributes of walkability and subject them to a perceptual user survey to determine the individual weights of each attribute has in conditioning pedestrian willingness to walk and integrating all these weights into the development of a walkability index in the context of the stipulated study area.

In conclusion, addressing these research gaps and exploring innovative avenues will contribute to a more nuanced understanding of walkability and inform practical strategies for creating pedestrian-friendly urban environments.

Methodology

Study location and population

The research locale is SoCCSKSarGen, short for South Cotabato, Cotabato, Sultan Kudarat, Sarangani, and General Santos, a region situated n in Mindanao. South of the Philippines with a total regional population of 4,901,486.

Due to the limitation of time and resources, the research focused only on key urban districts of General Santos City: namely: Barangay Dadiangas East, Barangay Dadiangas West, Barangay Dadiangas South, Barangay Dadiangas North, Barangay Lagao, Barangay Dadiangas City Heights and Barangay Bula as the model study area in consideration of its status as a highly urbanized city.

The study adopted convergent mixed method research, an approach combining the simultaneous conduct of qualitative and quantitative data collection and analysis methods to comprehensively understand a research topic. Convergent mixed methods research involves collecting both qualitative and quantitative data. Qualitative data were collected through interviews, focus groups, or observations, while quantitative data was gathered through surveys and secondary data analysis (Creswell & Creswell, 2018). The qualitative data collection process was guided by the research questions and was designed to capture a rich understanding of the phenomenon under investigation.

Sampling and data collection

The sample size is an important characteristic of any empirical study in which the aim is to make an inference about a population from a sample (Bujang & Adnan, 2016) it is essential for the researcher to estimate an appropriate sample size to produce reliable results using the statistical procedure (Adhikari 2021). In situations when the population is finite and the researchers do not have enough knowledge about the population's behavior (or distribution of behavior) to determine the optimal sample size, the Slovin formula can be used to estimate it (Adhikari 2021)

The sampling frame for the quantitative survey was pedestrians 15 years and above who utilized the pedestrian facilities within the study area. The sample size for the survey had a 95% confidence level and a margin of error of 5%.

Slovin’s Formula was used to determine the total number of respondents in the study from the urban population of 136,987, the computed sample size is 399.

The study utilized the probabilistic sampling design as a stratified random method. The sample was stratified within the four perimeter streets bounding the study area in particular, on the strategic intersections.

This method involves two data-gathering procedures done simultaneously, the quantitative pedestrian survey (Creswell, 2018) and the overall intent of this design is to have the qualitative data help explain in more detail the convergent quantitative results.

This study employed a stratified sampling design from the four quadrants of the study locale. This sampling design is appropriate to ensure a proportional representative for the four urban Barangays of General Santos City. Further, the sample size for the survey was determined using a 95% confidence level and a .05 margin of error.

Focus Group Discussions (FGD) and Key Informant Interviews (KII) were used to gather the opinions of the various professional disciplines. A total of five (5) Focus Group Discussions (FGD) with 6 to 10 participants each, as suggested by Krueger and Casey (2002), and three (3) key informant interviews (KII) were conducted. FGDs were conducted based on the guidelines recommended by Meyer (2021). Before conducting FGDs and KIIs, participants’ consent was sought by signing informed consent.

Data Analysis

The data gathered in this study was analyzed using multiple data analysis procedures. On the one hand, quantitative data was analyzed using descriptive statistics, interpreted based on mean value and Exploratory Factor Analysis. Qualitative data gathered through Focus Group Discussion (FGD) and Key Informant Interviews were transcribed, translated, coded, categorized, and analyzed using Quirkos 2.4.2 (2021), a software package for qualitative data analysis. A total of 399 pedestrians participated in the survey. After validation of the accomplished questionnaires, all 399 interviews were used in the data analysis; the distribution of the survey respondents by survey location is presented] Descriptive statistics were used to determine the profile of the respondents.

Ethical Consideration

This study received ethical approval from the Institutional Ethics Review Committee of Mindanao State University, General Santos City.

Results and Discussion

Socio-Demographic Profile of the Respondents

The pedestrian respondents consisted of 215 female respondents comprising 53.9%, and 184 males, comprising 46.1% of the total 399 respondents. This shows that there are slightly more female pedestrians than male pedestrians, by as much as 7.8% more. This is similar to the study conducted by Sallis et al. (2016), who found that women were likelier to walk than men.

The mean age of the respondents was 27.63%, The youngest age was 15, and the oldest was 73 years old. The survey shows that pedestrians are relatively young, with 27.63 as the mean age. However, it must also be noted that the age range is quite broad, with the youngest at 15 and the oldest at 73. This is validated by the study conducted by Sallis et al. (2016), which finds that the age group most drawn to walking is adults aged 18-34 years old.

In terms of respondent distribution by income group, the researcher utilized the Philippine Statistics Authority FIES for 2021. Most survey respondents had a monthly family income of below P7,833.00. This accounted for 195 responses, or equivalent to 48.90%. This was followed by income of P7,834.00 to P11,333.00, 64 (16%); then P13,501.00 to P15,833.00, 36 (9%). Three (3) had a monthly family income of between P37,168.00 to P71,500.00, and three (3) of at least P71,501.00, which accounted for 0.8%.

The initial observation is that many of the current pedestrians plying the streets of the study area came from the low-income group whose monthly family income is below P7,833.00. In particular, research has shown that walkability is the preferred mode of transportation for low-income groups (Gehl, 2010). This is likely because walking is a low-cost, accessible, and convenient option for those who may not have access to a car or public transportation.

Preferred Walkability Attributes

Five focus group discussions (FGD) among the design professional organization to identify themes from the similarities in their preferences;

The distribution of participants in the FGDs are as follows: 10 environmental planners, 8 architects, 6 civil engineers, 5 landscape architects, and 3 transport scientists The mean age was 42.25. The youngest participant was 27, and the oldest was 62 years old.

Three themes were extracted from the data processed through Quirkos software. These are:

Theme 1: Creatively Artistic (Aesthetic attribute)

Aesthetics in walkable environments contribute to creating a distinct sense of place and fostering a sense of local identity. Unique architectural styles, historical references, or cultural elements incorporated into the urban fabric

help to establish a sense of character and place attachment (Lynch, 1960). Aesthetically pleasing streetscapes that reflect the local context and heritage contribute to a stronger sense of community and pride, making the walking experience more meaningful and memorable for residents and visitors alike. One participant mentioned:
["In terms of aesthetic, I know maybe it's not really something that is within the design aesthetic but anything that shows festivity or the fiesta' spirit would really, you know, encourage people to walk. I mean, we've seen experiences where you know, where people who don't really walk, but if there are bandiritas there, you know, people would walk. As long as there's that aesthetics, the colorful, the goody and you know the idea of something top of the ordinary people would walk"] (FGD: PALA 10/01/22)
Aesthetics can influence the perceived safety and comfort of walkable environments. Well-maintained and visually appealing streetscapes create a positive impression of safety and security (Wener & Evans, 2007). Adequate lighting, clear sightlines, and aesthetically pleasing design elements contribute to pedestrians' feelings of comfort and security while walking (APA, 2017). By integrating aesthetics into the design of walkable spaces, designers can positively influence the perception of safety and comfort, encouraging more people to engage in active transportation.

Theme 2: Sense of Protection and Security

The physical safety of pedestrians is a fundamental component of walkability. Safe infrastructure, including well-maintained sidewalks, crosswalks, and pedestrian-friendly intersections, plays a crucial role in preventing accidents and injuries. According to the American Planning Association (APA), walkability should prioritize features that protect pedestrians, such as adequate lighting, clear signage, and traffic calming measures (APA, 2017). Ensuring physical safety not only reduces the risk of accidents but also promotes confidence and encourages more people to engage in active transportation. Perceived safety refers to the subjective sense of security that individuals experience while walking in a neighborhood. It encompasses factors such as personal safety, visibility, and the absence of crime or vandalism. Perceived safety is a critical consideration in walkability, as it directly influences people's willingness to walk and their overall satisfaction with the environment. Research has shown that individuals are more likely to engage in.
The Focus Group discussion among the design professionals gathered various viewpoints on sidewalk safety. One participant from the Philippine Association of Landscape Architects (PALA) took note of safety as a major concern; the lack of it in pedestrian sidewalks was glaring since pedestrians were seldom recognized as part of the roadway planning process:
["Basically, our road network here does not provide a safe area for pedestrians for people to walk along pedestrian, so, that's basically one big concern because he is not even identified, so, basically the question on safety is very much a big concern"] (FGD-PALA 10-1-22)

Theme 3: Enjoy its Comfort

Physical comfort is a fundamental aspect of sidewalk design. Sidewalks should be designed with attention to factors such as smooth surfaces, adequate width, and the absence of tripping hazards. Uneven surfaces, cracks, or obstacles can cause discomfort and pose safety risks to pedestrians, particularly for individuals with mobility challenges or using mobility aids. The American Planning Association (APA) highlights the need for sidewalks

to be "safe, comfortable, and convenient" for pedestrians (APA, 2017). By ensuring physical comfort, sidewalks can provide a pleasant and enjoyable walking experience for individuals of all ages and abilities.
Environmental factors significantly influence sidewalk comfortability. Providing shade through tree canopies, installing benches or seating areas, and incorporating street furniture contribute to the overall comfort of sidewalks. These features offer opportunities for rest, social interaction, and enjoyment of the surroundings
A convergence of the quantitative and qualitative findings (Table1) shows that there are similarities and differences between the preferences of the design professionals and the pedestrian users. To sum up the quantitative and qualitative findings on the preferred walkability attributes of walkability according to the viewpoints of various groups, data show that all groups are similar in considering safety, comfort, and aesthetics as walkability attributes. On the contrary, only the transdisciplinary design professionals considered anthropometric measures and activities that must be included as walkability attributes aside from those previously mentioned

Table 1. Summary Table of Convergence of Quantitative and Qualitative Findings on the Similarities and Differences in the Preferred Walkability Attributes

Indicator	Quantitative Result	Qualitative Result	Code
Safety	M = 30.81 (Rank 1)	▪ we talk about safety; we are talking about overall or holistic safety wherein in your mind, you feel safe ▪ may protective barriers kasi sometimes hindi talaga maiwasan lalo na dito sa atin sa Gensan andaming motorsiklo, ▪ hindi din full yung streetlights natin pag night. Kung day time, okay lang, but for night time parang hindi pa sya okay ▪ sa akin very important sa akin ang safety, safety from accidents kasi you can see naman doon sa mga ating mga social media captures ▪ the more people that there are in public, there's full sense of safety ▪ proper signage and crossing points ▪ you have children, let's say a stroller with you with the baby, or you are walking your dog if you have like a planting buffer, let's say, between you and the street	P24 P15 P1 P25 P4
Comfort	M = 24.09 (Rank 2)	▪ something na recreational. ▪ same time narerelax din yung utak mo ▪ linear park comfortable enough but not too big naman na where people will really congregate such an ideal lang siya for passing through	P1 P6

		▪ more trees and actually shed structures kasi when it rains you cannot go under the tree you gonna get wet	P8
Aesthetics	M = 15.46 (Rank 4) Creatively artistic	▪ Culturally relevant like sculpture ▪ Mga 3D visuals, mga steps ▪ use of virtual graphs, concept-map, images, and others ▪ design sa ting mga walkways and ang ating interconnectivity ▪ merong outdoor gym yung monkey bar, yung see-saw, yung mga pang twist ▪ designed to develop and nurture potential student-athlete	P3 P4 P19 P16
Anthropometrics	M = 12.82 (Rank 5)	▪ why it is important that you have like filling elements like sculptures, human sculptures you must put sculptures and tree ▪ So, for me in terms of dimensioning siguro kasi wala naman tayong enough na space talaga so, maybe two (2) meters is enough ▪ Ergonomics parin. Anthropometric na din kasi,	P6 P3
Activity	M = 16.83 (Rank 3)	▪ activity what would entice you to go to one place to another for a certain activity should be something that is entirely unique ▪ it should connect a person to a specific concentric center ▪ Place where you can rest like a small coffee shop or something where you can … there's a small bathroom	P11 P10 P8

Creating the Model Walkability Index

The rotated component matrix (Table 2) was extracted through Principal Component Analysis. extracted four (4) factors, each of which has underlying indicators.

By identifying the commonalities of the attributes in each of the four factors, four key factor themes can be created in relation to designing public spaces; it is essential to consider various factors that contribute to a harmonious and functional public space environment.

These four identified key factors are labeled as (1) Physical and Environmental Safety, (2) Aesthetics, (3) Convenience, and (4) Ease and comfort.

Exploratory Factor analysis was used in this research to determine the model walkability index, a mathematical combination of several indicators to form a single number. The model walkability index was then used to describe the entire set of indicators and allow for regional or possibly national differences between places and across time assessed.

Exploratory Factor Analysis is a statistical procedure that identifies the common variance amongst a set of observed variables or indicators and creates a factor (Sarstedt 2014), in this case, the walkability index, comprised of that common variance. The factor scores were calculated with a linear equation incorporating a weighted contribution of each variable included in the analysis. The contribution in weight of each variable was relative to the amount of variance in common with the other variables.

Table 2. Rotated Component Matrix of Pedestrian Survey Results

Items	**Indicators**	**Factors**			
		1	**2**	**3**	**4**
1	High vehicular Traffic Volume			.356	.565
2	Presence of Business Establishments along sidewalk				.741
3	Presence of Food Establishments				.741
4	Presence of Parks and Playgrounds		.603		.360
5	Proximity to large commercial complex		.422		.628
6	Colorful and attractive sidewalks		.746		
7	Presence of landscaping		.724		
8	Nice Building Façade		.620		
9	Presence of public/street art		.746		
10	Protection from Heat and Rain (trees, shelterred, arcade)	.534		.433	
11	Presence of street furniture		.395	.585	
12	Good Sidewalk surface quality	.439		.589	
13	Unobstructed and levelled sidewalk			.689	
14	Adequate Sidewalk Width	.311		.652	.331
15	Adequate Headroom	.304		.698	
16	High Pedestrian traffic	.334		.415	
17	Presence of PWD Ramps	.530		.452	
18	Good Outdoor Air Quality	.678			
19	Presence of Traffic Lights	.782			
20	Presence of Pedestrian Crosswalk	.739			
21	Clear and Legible Signages	.767			
22	Presence of Loading and Unloading Bays	.690			
23	Presence of Protective Rails and Bollards	.613			
24	Adequate Street Lighting	.638		.388	
25	Presence of CCTV Monitoring Cameras	.721			

Formulating the Model Walkability Index

The derivation formula for the walkability index of SoCCSKSarGen utilized the Pedestrian Environmental Quality Index (PEQI), developed by researchers at the University of Hong Kong. The PEQI incorporates factors such as sidewalk quality, pedestrian safety, aesthetics, ease, comfort, and convenience. The PEQI formula is derived through expert judgment and statistical analyses to determine the relative weights of each factor (Cerin et al., 2007).

The formula for the Model Walkability Index is:

$$MWI = \sum Waj*Naj$$

Where MWI is the Model Walkability Index, W is the weight per attribute a, in parameter j. Ni is the Normalized value of attribute an in-parameter j.

Using Group weighted Indicators, the following was formulated:

MWI= (〖F1〗 _ave·W_1) +(〖F2〗 _ave·W_2) +(〖F3〗 _ave·W_3) +(〖F4〗 _ave·W_4)

MWI= (F1ave·55.56%) +(F2ave·11.11%) +(F3ave·11.11%) +(F4ave·22.22%)

Where:

F1 = Physical and Environmental Safety
F2 = Aesthetics
F3 = Ease and Comfort
F4 = Convenience

Based on the pedestrian survey data and utilizing the MWI formula, the derived walkability index for the SoCCSKSarGen Region is 4.33, with a maximum possible score of 5. This unitless score reflects the extent to which pedestrian sidewalk conditions support walking, as per the opinions of the survey respondents. When compared to walkability ratings from a study conducted by Abaya et al. (2011) on major cities in the Philippines, General Santos City surpasses the walkability ratings of Manila (4.14), Davao City (3.42), and Cebu City (3.46) (refer to Table 3). This suggests that pedestrians in General Santos City exhibit a stronger preference for sidewalk conditions in terms of the walkability index, outperforming the existing ratings of the three major cities in the country.

Table 3. Walkability Rating of Major Cities in the Philippines

City	Zoning	Walkability Rating
Metro Manila	Commercial	4.14
Davao City	Commercial	3.42
Cebu City	Commercial	3.46

Source: Eastern Asia Society for Transportation Studies 2011

Conclusions

In conclusion, the significance of prioritizing safety in the design of pedestrian walking environments for fostering walkability is evident. However, it is crucial to acknowledge certain limitations in the current understanding and

implementation of safe design principles. Firstly, the effectiveness of specific safety measures may vary across diverse urban contexts, warranting further investigation into context-specific factors influencing their impact.
Moreover, the long-term sustainability of walkability initiatives requires ongoing evaluation and adaptation to changing urban dynamics. Future research should delve into the dynamic nature of urban environments, considering factors such as evolving traffic patterns, land-use changes, and emerging technologies that may influence pedestrian safety.
While promoting walkability is associated with numerous public health and social benefits, it is essential to recognize potential disparities in access to safe pedestrian spaces. Disadvantaged communities may face additional challenges, and future research should explore strategies to ensure equitable distribution of walkable spaces and their benefits.
Additionally, the current model walkability index, while valuable, may need refinement and adaptation to account for evolving urban design philosophies and community preferences. Future studies should focus on refining and expanding the index to encompass a broader range of factors that contribute to the overall pedestrian experience.
And lastly, the review mentions initiatives such as the SOCCSKSARGEN Regional Development Plan and the Local Public Transport Route Plan, there is a need for research evaluating the effectiveness of these policies in promoting walkability. Future studies should assess the implementation of such plans, identifying successes, challenges, and areas for improvement. This would contribute to evidence-based policy recommendations for other regions facing similar issues.
In summary, while the promotion of walkability through safe design is a commendable endeavor with multifaceted advantages, acknowledging and addressing the aforementioned limitations will be essential for the continued success of such initiatives. Future research endeavors should aim to refine existing strategies, explore innovative solutions, and ensure that the benefits of walkability are accessible to all members of diverse urban communities.

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REVIEW ARTICLE

Renewable Carbohydrates: Advancements in Sustainable Glucose Production and Optimization

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Abstract
This study explores and optimizes glucose production through various biochemical processes and assesses the potential of diverse feedstock sources to meet the growing demand for renewable carbohydrates. It focuses on glucose production's significance in biological systems and industrial applications, analyzing pathways like enzymatic hydrolysis of polysaccharides and acid hydrolysis of biomass. The kinetics of glucose production are examined, encompassing kinetic models for enzymatic hydrolysis, acid hydrolysis, and fermentation processes. Factors influencing reaction kinetics are explored, and experimental techniques for kinetic parameter estimation are discussed. To address sustainability and resource utilization challenges, the study investigates locally sourced materials like agricultural residues, forest biomass, algal biomass, and food waste as renewable feedstock sources. Optimization strategies for glucose production are presented, using statistical design of experiments and response surface methodology. Techno-economic analysis and life cycle assessments provide a holistic evaluation of environmental and economic aspects associated with glucose production processes. The study's comprehensive approach to glucose production, encompassing both technological advancements and sustainability considerations, offers insights into enzymatic, acid hydrolysis, and fermentation processes, as well as comparing diverse feedstock sources. This knowledge can foster further advancements in the field, benefit industries, and encourage policymakers to promote the integration of renewable carbohydrates in the broader bioeconomy. The research contributes to the global shift towards a greener and more sustainable future, where glucose production plays a key role in building a resilient and eco-conscious society.

Keywords: Glucose production; Enzymatic hydrolysis; Biofuel; Fermentation processes; Bioproduct industries

Introduction

Glucose, a fundamental biomolecule and major source of energy in living organisms, is essential in a variety of biological processes and industrial uses. Because of the growing demand for clean and renewable energy sources, its production and consumption have received substantial attention. Glucose production is critical not just for the food and biofuel industries (Zahonyi et al., 2022), but also for the synthesis of a wide range of bioproducts. Over the years, significant work has been expended on understanding and optimizing the processes involved in glucose synthesis. Previous studies have explored enzymatic hydrolysis of polysaccharides, acid hydrolysis of biomass, and fermentation of sugars as the main pathways for glucose synthesis (Ciolkosz et al., 2022). Various feedstock sources, including agricultural residues, forest biomass, algal biomass, and food waste, have been investigated for their potential in glucose production (Chen et al., 2022; Premjet et al., 2022). However, despite the progress made in this field, several challenges persist. The kinetics of glucose production, influenced by microorganism strains and environmental factors, remain complex and require further exploration. Optimization of the glucose production process to achieve maximum yield and economic efficiency continues to be a pressing concern (Pereira et al., 2021). Additionally, the sustainable and eco-friendly aspects of glucose production demand meticulous evaluation through life cycle assessments and techno-economic analyses.

The primary aim of this comprehensive study is to provide an in-depth exploration of glucose production, considering various biochemical processes, feedstock sources, and optimization strategies. By comparing different enzymatic, acid hydrolysis, and fermentation techniques, this study aims to identify the most efficient and sustainable pathways for glucose synthesis. Furthermore, by examining locally sourced materials and agricultural residues as potential feedstock, the study intends to offer practical insights into utilizing renewable resources for glucose production. Objectives of the study are to investigate the enzymatic hydrolysis of polysaccharides and its kinetics for efficient glucose production, examine the acid hydrolysis of biomass to explore alternative pathways for glucose synthesis, assess the potential of fermentation processes for converting sugars into glucose, compare and evaluate various feedstock sources, including agricultural residues, forest biomass, algal biomass, and food waste, for their suitability in glucose production, optimize glucose production processes using statistical design of experiments and response surface methodology, and analyze the techno-economic aspects and conduct life cycle assessments for a comprehensive evaluation of the sustainability of glucose production methods. This study holds paramount significance for academia, industries, and policymakers alike. By providing a comprehensive overview of glucose production, the research seeks to contribute to the scientific understanding of fundamental biochemical pathways. The optimization strategies and insights into feedstock utilization can pave the way for more sustainable and economically viable glucose production processes. Furthermore, this study's focus on environmentally friendly and renewable carbohydrates aligns with global efforts to transition towards green and eco-conscious solutions. Ultimately, the outcomes of this research aim to drive innovation and advancements in glucose production, fostering a sustainable future for various industries and human well-being.

Literature Review

Background on Glucose Production

Glucose, a simple sugar, holds significant importance as a versatile platform chemical with wide-ranging applications in various industries, including food, pharmaceuticals, biofuels, and bioplastics (Johns, 2021). To meet the growing demand for glucose sustainably, the utilization of renewable feedstocks has become a major focus of research. Among potential feedstocks, lignocellulosic biomass such as sawdust, rice husk, and sugarcane bagasse have drawn attention due to their abundance and potential for valorization. The enzymatic hydrolysis of these feedstocks can liberate glucose, which can then be further optimized using statistical techniques like Response Surface Methodology (RSM) and the Michaelis-Menten model for kinetic analysis (Ude et al., 2020).

Aspergillus niger, a filamentous fungus, is a widely studied microorganism with notable enzymatic capabilities, including cellulase and hemicellulase production. Its potential for converting lignocellulosic biomass into glucose makes it an attractive candidate for glucose production. By harnessing the enzymatic prowess of *Aspergillus niger*, the hydrolysis of cellulose and hemicellulose in sawdust, rice husk, and sugarcane bagasse can be efficiently achieved, leading to enhanced glucose yields. RSM is a powerful statistical tool that allows for the optimization of multiple variables simultaneously. In the context of glucose production from different feedstocks, RSM can explore the effects of parameters such as enzyme concentration, temperature, pH, and reaction time on glucose yield (Jones et al., 2018). The technique provides insights into the interactions between variables and helps identify the optimal process conditions that maximize glucose production. With the aid of RSM, researchers can streamline the experimental design and significantly reduce the number of trials required, making the optimization process more efficient and cost-effective.

Furthermore, understanding the kinetics of the glucose production process is crucial for process design and control. The Michaelis-Menten model, a well-established enzyme kinetics model, can be applied to describe the enzymatic hydrolysis of cellulose and hemicellulose by Aspergillus niger. By determining the kinetic parameters, such as the maximum reaction rate and the Michaelis constant, researchers can gain valuable insights into the enzymatic efficiency and the overall process dynamics (Efrinalia et al., 2022). Comprehensive characterization of the feedstock is essential to comprehend the complex interactions between the microorganism and the substrate during glucose production. Proximate and ultimate analyses provide information on the biomass composition, including moisture content, ash content, and elemental composition. Energy-dispersive X-ray spectroscopy (EDX) offers insights into the elemental distribution within the biomass. Fourier-transform infrared spectroscopy (FTIR) can reveal functional groups present in the biomass, aiding in understanding the structural changes during hydrolysis. Scanning electron microscopy (SEM) enables researchers to visualize the morphology and surface features of the feedstock, providing valuable information on structural changes and enzyme accessibility.

The utilization of lignocellulosic biomass, such as sawdust, rice husk, and sugarcane bagasse, for glucose production using *Aspergillus niger* holds immense promise as a sustainable approach to meet the demand for glucose (Edor et al., 2018). The application of RSM and the Michaelis-Menten model will enhance process optimization and kinetic analysis, leading to improved glucose yields and process efficiency. Additionally, a comprehensive characterization of the feedstock using techniques like EDX, FTIR, and SEM will deepen the understanding of the enzymatic hydrolysis process and aid in optimizing the glucose production from these abundant biomass sources.

Overview of Glucose as a Biomolecule

Glucose, a monosaccharide with the chemical formula $C_6H_{12}O_6$, is a fundamental biomolecule that plays a crucial role in various biological processes (Mondal, 2018; Rationalized, 2023). It serves as a primary source of energy for living organisms and serves as a building block for the synthesis of complex carbohydrates, lipids, and proteins. Glucose is found in almost all living organisms, ranging from bacteria and plants to animals, including humans. It is a central player in cellular metabolism. Through the process of glycolysis, glucose is broken down into pyruvate, generating ATP (adenosine triphosphate) molecules that provide energy for cellular functions (Dienel, 2019; Remesar & Alemany, 2020). Pyruvate can further undergo various metabolic pathways, such as the Krebs cycle and oxidative phosphorylation, to produce additional ATP through cellular respiration. Glucose metabolism is essential for energy production, maintaining cellular homeostasis, and supporting vital cellular processes, such as signal transduction and membrane transport (Parker, 2020). Glucose serves as the primary energy source for most organisms. It is readily metabolized and efficiently converted into ATP through glycolysis and subsequent respiratory pathways (Dienel, 2019). The energy derived from glucose is utilized to perform mechanical work, maintain body temperature, support growth and development, and enable the functioning of vital organs and tissues (Remesar & Alemany, 2020).

Glucose serves as the building block for the synthesis of complex carbohydrates, including starch, glycogen, and cellulose (Adams, 2022). Through the process of polymerization, glucose molecules link together to form chains or branched structures, resulting in the formation of these carbohydrates. Starch and glycogen serve as energy storage molecules in plants and animals, respectively, while cellulose provides structural support in plant cell walls. Glucose is a precursor for the synthesis of various biomolecules (Johns, 2021). It can be converted into other monosaccharides, such as fructose and galactose, through specific enzymatic reactions (Riaukaite et al., 2019). Glucose also serves as the starting point for the synthesis of lipids, amino acids, and nucleotides, which are essential components of cell membranes, proteins, and DNA, respectively (Rationalized, 2023). Glucose concentration in the bloodstream is tightly regulated to maintain optimal physiological function (Flores et al., 2018). In humans, the hormone insulin (Ramos et al., 2021), produced by the pancreas, facilitates glucose uptake by cells, thereby reducing blood glucose levels. The hormone glucagon, also produced by the pancreas, acts in the opposite manner, promoting the release of stored glucose from glycogen, thereby increasing blood glucose levels. This intricate hormonal regulation ensures that cells have a constant supply of glucose for energy production (Shirin et al., 2019).

Enzymatic Hydrolysis of Polysaccharides

Enzymatic hydrolysis is a biochemical process that involves the breakdown of complex polysaccharides into simpler sugars, primarily glucose, through the action of specific enzymes (Weiss et al., 2019). This process plays a crucial role in the production of glucose from biomass, such as cellulose and starch, as it enables the efficient release of glucose units for various industrial applications. The choice of enzymes for enzymatic hydrolysis depends on the type of polysaccharide being targeted (Amandio et al., 2023). Cellulose, for example, requires cellulases, which are enzymes capable of breaking down the β-1,4-glycosidic bonds present in the cellulose chain (ILO, 2020). On the other hand, amylases are used to hydrolyze starch, targeting the α-1,4-glycosidic bonds (Hu et al., 2021). Enzymes can be derived from various sources, including microorganisms (such as fungi and bacteria) or produced through recombinant DNA technology. The selection of the appropriate enzyme(s) depends on factors such as substrate specificity, enzyme stability, cost, and availability (Bhandari et al., 2021).

The structure and composition of the polysaccharide substrate significantly influence the efficiency of enzymatic hydrolysis (Amandio et al., 2023). Factors such as the degree of polymerization, crystallinity, accessibility of the enzyme to the substrate, and the presence of inhibitors or lignin can affect the hydrolysis process. Pretreatment methods, such as physical, chemical, or biological treatments, are often employed to enhance the accessibility of enzymes to the polysaccharide substrate, improving the overall hydrolysis efficiency (Ansanay et al., 2021). Enzymatic hydrolysis follows a complex kinetic process involving several steps, including enzyme-substrate adsorption, enzymatic reaction, and product desorption. The kinetics of enzymatic hydrolysis can be described by various models, such as the Michaelis-Menten model or the Langmuir-Hinshelwood model. These models help in understanding the enzyme-substrate interactions, determining reaction rates, and estimating kinetic parameters such as the maximum reaction rate (V_{max}) and Michaelis-Menten constant (K_m) (Efrinalia et al., 2022). Kinetic studies provide valuable insights into the efficiency of the hydrolysis process and assist in process optimization. Several factors influence the efficiency of enzymatic hydrolysis (Turini et al., 2021):

a) Enzyme Concentration: The amount of enzyme used affects the rate and extent of hydrolysis. Higher enzyme concentrations generally lead to faster hydrolysis; however, there is an optimal enzyme dosage beyond which further enzyme addition may not yield significant improvements.
b) Substrate Concentration: The concentration of the polysaccharide substrate affects the rate of hydrolysis. Initially, as substrate concentration increases, the rate of hydrolysis also increases. However, at high substrate concentrations, the enzyme may become saturated, and the rate of hydrolysis may plateau.
c) Temperature and pH (Jones et al., 2018): Enzymatic activity is highly dependent on temperature and pH. Different enzymes have specific temperature and pH optima for maximum activity. Maintaining optimal temperature and pH conditions is crucial for achieving high enzymatic efficiency during hydrolysis.
d) Enzyme Inhibitors (Ascione et al., 2020): Inhibitors, such as lignin, hemicelluloses, or degradation products, can negatively impact enzymatic hydrolysis. These inhibitors can interfere with enzyme-substrate interactions, reduce enzyme activity, or inhibit enzyme stability. Strategies to minimize or mitigate the effects of inhibitors include enzymatic detoxification, inhibitor removal.

Acid Hydrolysis of Biomass

Acid hydrolysis is a chemical process that utilizes acid catalysts to break down complex carbohydrates in biomass into simpler sugars, including glucose (ILO, 2020). This process is an alternative to enzymatic hydrolysis and is particularly suitable for biomass with high cellulose or hemicellulose content. Acid hydrolysis offers several advantages, such as faster reaction rates and the ability to handle a wide range of feedstocks. Various acid catalysts can be used for biomass hydrolysis, with sulfuric acid (H_2SO_4) and hydrochloric acid (HCl) being the most commonly employed. These strong acids dissociate in water, providing hydrogen ions (H^+) that catalyze the hydrolysis of glycosidic bonds. The choice of acid catalyst depends on factors such as reaction efficiency, cost, safety, and the downstream processing of the hydrolysate (Swiatek et al., 2020).

Optimizing reaction conditions is crucial for achieving efficient acid hydrolysis (Zhang & Sutheerawattananonda, 2020). Factors such as temperature, acid concentration, reaction time, and solid-to-liquid ratio need to be carefully controlled. Elevated temperatures generally increase reaction rates, but excessively high temperatures can lead to sugar degradation (Astuti et al., 2018). Acid concentration influences the rate of hydrolysis, with higher concentrations promoting faster reaction rates. However, high acid concentrations may also result in the formation of inhibitory compounds and increase the risk of corrosion. Reaction time is determined based on the kinetics of hydrolysis, and the solid-to-liquid ratio affects the accessibility of acids to the biomass substrate. During acid hydrolysis, the acid catalysts protonate the glycosidic bonds, leading to their cleavage (Nguyen et al., 2018). The hydrolysis of cellulose and hemicellulose follows different reaction pathways. Cellulose hydrolysis involves the cleavage of β-1,4-glycosidic bonds, resulting in the formation of glucose monomers (Nguyen et al., 2018; Remesar & Alemany, 2020). Hemicellulose, composed of various sugar monomers, undergoes acid-catalyzed hydrolysis to produce a mixture of different sugars. However, acid hydrolysis is more challenging for lignin, a complex and highly resistant polymer, which typically undergoes minimal degradation during acid hydrolysis (Zhang et al., 2023).

Despite its advantages, acid hydrolysis also presents certain challenges (Damayanti et al., 2021; Swiatek et al., 2020):

i. Corrosion and Safety: Strong acids like sulfuric acid can be corrosive and require proper handling and safety precautions. The selection of appropriate equipment and materials is essential to withstand the corrosive nature of acids.
ii. Sugar Degradation: The hydrolysis process, especially at high temperatures and acid concentrations, can lead to the degradation of sugars into unwanted byproducts, such as furans and organic acids. This degradation reduces the overall yield of desired glucose and can interfere with downstream processes.
iii. Inhibitor Formation: Acid hydrolysis can generate inhibitory compounds, including furfural, 5-hydroxymethylfurfural (HMF), and organic acids, which can affect subsequent enzymatic or microbial conversion processes (Katarzyna et al., 2020; Muhammad et al., 2022; Sant et al., 2021; Swiatek et al., 2020). Detoxification methods, such as neutralization, washing, or adsorption, may be required to minimize the impact of inhibitors.
iv. Acid Recovery and Neutralization: After hydrolysis, the acid needs to be separated from the hydrolysate for reuse or neutralization. Acid recovery and neutralization methods are important for cost-effectiveness, environmental considerations, and the overall sustainability of the process.

Despite the challenges, acid hydrolysis remains an important method for biomass conversion due to its versatility and ability to handle a wide range of feedstocks. It offers advantages such as faster reaction rates, scalability, and the potential to utilize various biomass sources. Researchers continue to explore process optimization strategies to improve acid hydrolysis efficiency, minimize sugar degradation, and reduce the formation of inhibitory compounds. To address some of the challenges associated with acid hydrolysis, several advancements have been made. For instance, the use of milder acids or catalysts, such as organic acids or solid acid catalysts, has been explored to mitigate corrosion and improve the selectivity of hydrolysis. Additionally, the integration of acid hydrolysis with other pretreatment techniques, such as steam explosion or liquid hot water treatment, has shown promise in enhancing hydrolysis efficiency and reducing inhibitor formation (Fu et al., 2018; Li et al., 2019).

Fermentation of Sugars for Glucose Production

Fermentation is a biological process in which microorganisms, such as yeasts or bacteria, convert sugars into various products, including ethanol, organic acids, and gases. The fermentation of sugars plays a significant role in glucose production, as it provides an alternative route for converting sugars derived from biomass or other feedstocks into glucose (Damayanti et al., 2021). Various microorganisms are employed in fermentation processes to convert sugars to glucose. Yeasts, such as Saccharomyces cerevisiae, are commonly used for ethanol production (Halka et al., 2018). They possess the ability to metabolize glucose through the glycolysis pathway, producing ethanol as the primary end product. Other microorganisms, such as lactic acid bacteria or certain species of Escherichia coli, can ferment sugars to produce organic acids like lactic acid or acetic acid (Gunkova et al., 2021). The selection of microorganisms depends on the desired end product and the specific requirements of the fermentation process (Behera et al., 2019). The fermentation of sugars involves several stages, including sugar preparation, inoculum development, fermentation, and product recovery (Damayanti et al., 2021). The sugar source, such as glucose, fructose, or sucrose, is prepared by hydrolysis of biomass or through other pretreatment methods (Kiš et al., 2019). The microorganisms are then introduced into the fermentation medium, which provides the necessary nutrients and environmental conditions for their growth and metabolism. The fermentation process is carried out under controlled conditions of temperature, pH, and aeration (Jones et al., 2018). As the microorganisms metabolize the sugars, they produce glucose as an intermediate or end product, depending on the specific fermentation pathway (Teleky et al., 2020).

Several factors influence the efficiency of fermentation for glucose production (Chang et al., 2018; Jones et al., 2018; Kanagasabai et al., 2019; Tse et al., 2021):

a) Sugar Concentration: The concentration of sugars in the fermentation medium affects the rate and extent of glucose production. Higher sugar concentrations can lead to faster fermentation rates but may also result in inhibitory effects on microbial growth and metabolism.
b) Microbial Strain and Characteristics: The selection of an appropriate microbial strain is critical for efficient glucose production. Different strains may exhibit variations in sugar utilization, fermentation rates, and tolerance to inhibitors. Genetic engineering approaches can be employed to enhance the metabolic capabilities of microorganisms for glucose production.
c) Nutrient Availability: Microorganisms require essential nutrients, such as nitrogen, phosphorus, and trace elements, for their growth and fermentation activity. Optimizing nutrient availability through appropriate medium formulation is crucial for maximizing fermentation efficiency.
d) Environmental Conditions: Temperature, pH, and oxygen availability are important environmental factors that impact microbial growth and fermentation. Each microorganism has an optimal range of these parameters, and maintaining the appropriate conditions ensures efficient fermentation and glucose production.
e) Inhibitors and Byproducts: Inhibitory compounds, such as organic acids, furans, or phenolic compounds, can be generated during biomass pretreatment or hydrolysis processes. These inhibitors can affect microbial growth and fermentation efficiency. Detoxification strategies, including physical, chemical, or biological methods, can be implemented to minimize their impact.

Glucose produced through fermentation has diverse applications in various industries: Glucose fermentation to ethanol serves as a key process in biofuel production (Smachetti et al., 2018). Ethanol can be used as a transportation fuel or as a blending component in gasoline, reducing reliance on fossil fuels and contributing to a more sustainable energy sector (Inyang et al., 2022; Salim, González-García, et al., 2019). Glucose is widely used in the food and beverage industry as a sweetener, preservative, or fermentation substrate. It serves as a key ingredient in the production of baked goods, confectionery, beverages, and fermented products such as beer, wine, and spirits. Glucose is utilized as a carbon source for the production of various pharmaceuticals, including antibiotics, vitamins, amino acids, and therapeutic proteins (Simpson et al., 2022). It also serves as a precursor for the synthesis of bioactive compounds and pharmaceutical intermediates. Glucose can be further converted into a wide range of valuable chemicals, such as organic acids (e.g., lactic acid, citric acid), polyols (e.g., sorbitol, mannitol), and other platform chemicals (Nam, 2022). These chemicals find applications in the production of polymers, resins, solvents, and other industrial products. Glucose can be used as an energy source and nutrient supplement in animal feed formulations. It provides readily available energy for livestock and poultry, supporting their growth and production. In agriculture, glucose-based products can be utilized as plant growth regulators, biofertilizers, or biostimulants, enhancing crop yield and quality (Blanco et al., 2020; Roslan & Salimi, 2019).

Bioplastics and Biomaterials: Glucose serves as a building block for the production of bioplastics, such as polylactic acid (PLA), which offers a renewable and biodegradable alternative to conventional plastics. Glucose-based polymers can also be employed in the development of biomaterials for tissue engineering, drug delivery systems, and other biomedical applications (Far et al., 2022; Seddiqi et al., 2021; Sood et al., 2021). The fermentation of sugars for glucose production offers a versatile and sustainable approach to utilize biomass resources and generate valuable products. Advances in microbial engineering, fermentation process optimization, and downstream processing techniques continue to enhance the efficiency and economic viability of glucose production through fermentation. Furthermore, the integration of fermentation with other biorefinery processes allows for the utilization of diverse feedstocks and the production of a wide range of valuable compounds, contributing to the development of a bio-based economy and a more sustainable future (Salim, et al., 2019).

Comparison of Different Biochemical Processes

Biochemical processes for glucose production encompass various methods, including enzymatic hydrolysis, acid hydrolysis, and fermentation. Each of these processes has its advantages, challenges, and suitability for different feedstocks and applications. The efficiency of a biochemical process is measured by the yield of glucose obtained from the feedstock (Kadhum et al., 2019). Enzymatic hydrolysis, utilizing specific enzymes, can achieve high conversion rates of polysaccharides into glucose. However, it may require longer reaction times and can be costlier due to the need for enzyme production. Acid hydrolysis, on the other hand, offers faster reaction rates but may lead to lower glucose yields due to sugar degradation and formation of inhibitory compounds. Fermentation processes can also achieve high conversion efficiencies, particularly when optimized for specific microorganisms and conditions (Recek et al., 2018).

Different biochemical processes have varying compatibilities with different feedstocks. Enzymatic hydrolysis is well-suited for a wide range of biomass sources, including lignocellulosic materials, due to its specificity and ability to target specific polysaccharides (Weiss et al., 2019). Acid hydrolysis can handle diverse feedstocks as well, but certain biomass components, such as lignin, may hinder the process efficiency. Fermentation processes generally require sugars or sugar-rich feedstocks and are commonly used for glucose production from agricultural crops, sugar cane, or molasses (Nwankwo & Ukpabi, 2018). The environmental impact of a biochemical process is a crucial consideration in sustainable production. Enzymatic hydrolysis, being a biologically driven process, is considered environmentally friendly. It operates under mild conditions, produces fewer byproducts, and has lower energy requirements compared to other processes. Acid hydrolysis, while effective, requires the use of strong acids and may generate waste streams containing inhibitory compounds, necessitating proper treatment and disposal. Fermentation processes can also be environmentally favorable, especially when utilizing renewable feedstocks and optimizing process parameters to minimize waste and energy consumption (Salim, et al., 2019).

The purity of glucose obtained from a biochemical process is important, particularly for applications in the food, pharmaceutical, and chemical industries. Enzymatic hydrolysis generally yields high-purity glucose, as specific enzymes target the desired polysaccharides without introducing contaminants (Codato-Zumpano et al., 2023). Acid hydrolysis may result in lower product purity due to the presence of inhibitory compounds or degradation products. Fermentation processes can produce glucose along with other metabolites, requiring additional purification steps to obtain high-purity glucose (Salim, et al., 2019). The economics of a biochemical process depend on factors such as capital and operating costs, feedstock availability and cost, yield, and market demand for the products. Enzymatic hydrolysis, although efficient, can be costlier due to the requirement for enzymes and longer reaction times (Weiss et al., 2019). Acid hydrolysis offers faster reaction rates but may incur additional costs for acid procurement and disposal of waste streams. Fermentation processes, while efficient and commercially viable for certain feedstocks, may require downstream processing and purification steps, impacting overall process economics (Recek et al., 2018).

Locally Sourced Materials for Glucose Production

The utilization of locally sourced materials for glucose production offers several advantages, including reduced transportation costs, increased sustainability, and support for local economies (Cheng et al., 2019). Locally available biomass resources can serve as valuable feedstocks for biochemical processes, contributing to the production of glucose in a more efficient, cost-effective, and environmentally friendly manner (Inyang et al., 2022).

Agricultural Residues as Feedstock

Agricultural residues consist of the non-edible parts of crops that remain after harvest or processing (Kim et al., 2018). They typically contain a combination of cellulose, hemicellulose, lignin, and other minor components. The exact composition varies depending on the type of residue and the specific crop. Cellulose and hemicellulose are polysaccharides that can be hydrolyzed into glucose, while lignin provides structural support to the plant and is more challenging to break down (Jeoh et al., 2017). Agricultural residues are widely available due to the large-scale agricultural activities in many regions. The abundance of these residues makes them attractive feedstocks for glucose production, as they provide a renewable and sustainable resource that can be utilized without competing with food production. The availability of agricultural residues can vary based on factors such as crop type, geographic location, and local agricultural practices.

Preprocessing and Pretreatment: Before agricultural residues can be used as feedstocks for glucose production, preprocessing and pretreatment steps may be required. Preprocessing involves activities such as size reduction (e.g., grinding, chopping) and drying to enhance the feedstock's processability (Prithviraj et al., 2020). Pretreatment methods, such as steam explosion, liquid hot water treatment, or acid pretreatment, can be applied to enhance the accessibility of cellulose and hemicellulose for subsequent hydrolysis (Li et al., 2019; Shukla et al., 2023). Enzymatic hydrolysis is a commonly employed method for converting agricultural residues into glucose. Specific enzymes, such as cellulases and hemicellulases, are used to break down the cellulose and hemicellulose components into glucose (Jayasekara & Ratnayake, 2019). Enzymatic hydrolysis offers several advantages, including high selectivity, mild operating conditions, and compatibility with a wide range of agricultural residues. However, the cost of enzymes and the need for longer reaction times are considerations for process economics.

Acid hydrolysis can also be used to convert agricultural residues into glucose. Strong acids, such as sulfuric acid or hydrochloric acid, are typically employed to break down the polysaccharides into their constituent sugars (Adeoye et al., 2019). Acid hydrolysis offers faster reaction rates compared to enzymatic hydrolysis. However, it may lead to sugar degradation, formation of inhibitory compounds, and corrosion issues, requiring proper process optimization and waste management strategies. To maximize glucose production from agricultural residues, process optimization and integration strategies can be employed (Kiran & Trzcinski, 2017). This includes optimizing factors such as temperature, pH, residence time, enzyme loading (in enzymatic hydrolysis), acid concentration (in acid hydrolysis), and solid-liquid ratios. Integration with other pretreatment techniques or biorefinery concepts, such as combining acid hydrolysis with fermentation or utilizing lignin co-products, can enhance overall process efficiency and resource utilization. The utilization of agricultural residues as feedstocks for glucose production offers several sustainability benefits (Oyola-Rivera et al., 2018). It reduces waste generation, maximizes the use of available biomass resources, and contributes to the development of a circular economy. Additionally, utilizing agricultural residues for bio-based processes helps reduce greenhouse gas emissions by replacing fossil-based feedstocks and minimizing reliance on non-renewable resources.

Forest Biomass and Lignocellulosic Materials

Forest biomass and lignocellulosic materials consist mainly of cellulose, hemicellulose, and lignin, along with smaller amounts of extractives and ash. Cellulose and hemicellulose are polysaccharides that can be hydrolyzed into glucose, while lignin provides structural support to the plant and contributes to the recalcitrance of lignocellulosic materials. The exact composition varies depending on factors such as tree species, age, and growing conditions (Augusto & Boca, 2022). Forest biomass and lignocellulosic materials are abundant and widely available in regions with significant forest resources. They can be sourced from various forestry operations, including timber harvesting, sawmills, and forest management activities. The availability of forest biomass depends on factors such as forest management practices, land-use policies, and sustainability considerations to ensure responsible sourcing. Before forest biomass and lignocellulosic materials can be used as feedstocks for glucose production, preprocessing and pretreatment steps are typically necessary (Jones et al., 2018). Preprocessing involves activities such as chipping or grinding to reduce the size of the biomass and enhance its processability. Pretreatment methods, such as steam explosion, acid pretreatment, or organosolv processes, are often employed to disrupt the lignocellulosic structure and increase the accessibility of cellulose and hemicellulose for subsequent hydrolysis (Ansanay et al., 2021).

Enzymatic hydrolysis is a widely used method for converting forest biomass and lignocellulosic materials into glucose (Zhou et al., 2023). Specific enzymes, such as cellulases and hemicellulases, are employed to break down the cellulose and hemicellulose components into glucose. Enzymatic hydrolysis offers high selectivity, mild operating conditions, and compatibility with various lignocellulosic materials. However, factors such as enzyme cost, enzyme stability, and the presence of inhibitory compounds from pretreatment may impact the efficiency and economics of the process (Li et al., 2019). Acid hydrolysis can also be employed for glucose production from forest biomass and lignocellulosic materials. Strong acids, such as sulfuric acid or hydrochloric acid, are used to hydrolyze the polysaccharides into their constituent sugars. Acid hydrolysis offers faster reaction rates compared to enzymatic hydrolysis. However, it may lead to sugar degradation, formation of inhibitory compounds, and corrosiveness issues, necessitating careful process optimization and waste management strategies (Codato-Zumpano et al., 2023). To maximize glucose production from forest biomass and lignocellulosic materials, process optimization and integration strategies can be implemented. This includes optimizing factors such as temperature, acid concentration (in acid hydrolysis), residence time, solid-liquid ratios, and pretreatment conditions. Integration with other biorefinery processes, such as lignin valorization, fermentation, or co-production of other value-added products, can enhance the overall process efficiency, resource utilization, and economic viability (Okonkwo et al., 2022).

Algal Biomass as a Potential Source

Algal biomass consists of various components, including proteins, lipids, carbohydrates, pigments, vitamins, and minerals. The carbohydrate fraction, which includes glucose and other sugars, can be extracted and utilized for glucose production (Ruiz et al., 2020). The exact composition of algal biomass varies depending on the algal species, cultivation conditions, and growth phase. Algae are found in diverse aquatic environments, including freshwater, marine, and brackish water systems. They can be cultivated in open ponds, closed photobioreactors, or other specialized systems. Algal biomass has the potential to be an abundant and renewable feedstock due to the high growth rates of certain algal species and their ability to utilize sunlight and carbon dioxide for photosynthesis (Yang et al., 2023). Algal biomass can be cultivated using different cultivation systems and techniques. Open pond systems involve the cultivation of algae in large, shallow ponds exposed to sunlight.

Closed photobioreactors provide a controlled environment, allowing for precise control of parameters such as temperature, light intensity, and nutrient availability. Algal cultivation requires appropriate nutrient supply, including carbon dioxide, nitrogen, phosphorus, and micronutrients, to support optimal growth and carbohydrate accumulation (de Souza et al., 2019).
Once the algal biomass has reached the desired growth stage, it needs to be harvested and processed to extract the carbohydrates, including glucose (Huo et al., 2022). Harvesting methods may include mechanical methods (e.g., centrifugation, filtration) or physicochemical methods (e.g., flocculation, sedimentation) to separate the algae from the growth medium. After harvesting, the biomass can undergo further processing steps, such as cell disruption, dewatering, and extraction, to obtain the desired carbohydrate fraction (Hamman et al., 2018). Glucose production from algal biomass can be achieved through enzymatic hydrolysis or acid hydrolysis methods, similar to other biomass feedstocks. Enzymatic hydrolysis involves the use of specific enzymes, such as cellulases and hemicellulases, to break down the carbohydrates into glucose (de Souza et al., 2019). Acid hydrolysis utilizes strong acids, such as sulfuric acid or hydrochloric acid, to hydrolyze the carbohydrates. The choice of hydrolysis method depends on factors such as the algal species, biomass composition, process economics, and desired end products. Algal biomass holds significant potential as a sustainable feedstock for glucose production. Algae have a high photosynthetic efficiency and can utilize carbon dioxide, thus contributing to carbon capture and potentially mitigating greenhouse gas emissions. Algal cultivation can also be integrated with wastewater treatment, nutrient recycling, and the production of other value-added products such as biofuels, bioplastics, or animal feed (Ruiz et al., 2020). However, certain considerations, such as water and nutrient requirements, cultivation system scalability, and potential ecological impacts, should be carefully addressed to ensure the sustainability of algal biomass utilization.

Food Waste and Byproducts

Food waste and byproducts comprise organic materials from agricultural, processing, distribution, and consumption activities. These include fruit and vegetable peels, trimmings, discarded grains, food processing residues, expired products, and other food-related waste. The composition of food waste and byproducts can vary greatly, but they often contain significant amounts of carbohydrates, including glucose and other sugars, along with proteins, lipids, fibers, and other nutrients (Okonkwo et al., 2022). Food waste and byproducts are abundant and readily available throughout the food supply chain. They arise from various sources, including households, restaurants, food processing facilities, and retail sectors. The quantity and availability of food waste and byproducts depend on factors such as consumption patterns, food handling practices, and waste management systems. Efficient utilization of these materials not only reduces waste but also contributes to a circular economy and resource conservation (Yu et al., 2022). Prior to glucose production, food waste and byproducts may require preprocessing and pretreatment steps. Preprocessing involves sorting, cleaning, and potentially size reduction to remove non-biodegradable components and improve processability. Pretreatment methods, such as enzymatic or acid hydrolysis, can be employed to break down complex carbohydrates and enhance the release of glucose (Zhou et al., 2023). Additionally, degrading enzymes or microbial fermentation may be utilized to convert more complex food waste components into glucose or other valuable products.
Enzymatic hydrolysis is a common method for converting food waste and byproducts into glucose. Specific enzymes, such as carbohydrases, can be employed to break down the complex carbohydrates present in these materials (Yu et al., 2022). Enzymatic hydrolysis offers high selectivity, mild operating conditions, and compatibility with a wide range of food waste and byproduct feedstocks. However, factors such as enzyme cost, enzymatic stability, and the presence of inhibitory compounds from the waste stream may affect process

efficiency and economics. Acid hydrolysis can also be utilized for glucose production from food waste and byproducts. Strong acids, such as sulfuric acid or hydrochloric acid, are used to break down the carbohydrates into their constituent sugars. Acid hydrolysis offers faster reaction rates compared to enzymatic hydrolysis and can handle a broader range of feedstocks (Ebikade et al., 2018). However, it requires careful control to prevent sugar degradation and the formation of inhibitory compounds, and appropriate waste management strategies are essential due to the corrosive nature of the acids. To maximize glucose production from food waste and byproducts, process optimization and integration strategies are crucial. This includes optimizing factors such as temperature, pH, residence time, acid concentration (in acid hydrolysis), enzyme loading (in enzymatic hydrolysis), and solid-liquid ratios. Integration with other processes, such as anaerobic digestion for biogas production (Abubakar et al., 2022), can further enhance resource utilization and overall process efficiency, reducing waste and generating additional value from food waste and byproducts.

Comparison of Different Feedstock Sources

When considering glucose production, various feedstock sources can be utilized, each with its own characteristics and considerations. Agricultural residues, such as crop straw, corn stover, and sugarcane bagasse, are abundant and widely available (Schiano et al., 2022). They do not compete with food production, making them a sustainable and renewable feedstock option. Agricultural residues often have high cellulose and hemicellulose content, which can be efficiently hydrolyzed into glucose. Agricultural residues may require preprocessing and pretreatment to enhance their processability and increase sugar accessibility (Jones et al., 2018). Some residues have high lignin content, which adds to the recalcitrance and complexity of the feedstock (Blanco et al., 2020). Proper waste management and logistics are essential to ensure a consistent and reliable supply.

Forest biomass and lignocellulosic materials, including wood chips, sawdust, and logging residues, offer a sustainable feedstock source (Blanco et al., 2020). They are abundant, widely available, and can be sourced from managed forests. Forest biomass contains significant amounts of cellulose, which can be converted into glucose (Selivanov et al., 2023). Additionally, lignocellulosic materials can be integrated with the production of other value-added products, such as biofuels or bioplastics. Preprocessing and pretreatment are often required to overcome the recalcitrance of lignocellulosic materials (Elalami et al., 2022). Supply chain logistics and sustainability considerations, including responsible forest management practices, need to be addressed. The presence of lignin may affect the efficiency of glucose production and downstream.

Algal biomass presents a renewable and highly productive feedstock source for glucose production. Algae can be cultivated in various aquatic environments and have the potential to achieve high growth rates and carbon dioxide fixation. Some algae species accumulate significant amounts of carbohydrates, including glucose, which can be extracted and utilized (Ruiz et al., 2020; Smachetti et al., 2018). Algal cultivation can be integrated with wastewater treatment and other biorefinery processes. Algal cultivation requires careful management of nutrients, including carbon dioxide, nitrogen, and phosphorus, to achieve optimal growth and carbohydrate accumulation. Scalability and cost-effectiveness of large-scale cultivation systems remain challenges (Zhang et al., 2020). Harvesting and processing methods for algal biomass can be energy-intensive and require further development for cost reduction (Moreira et al., 2019).

Food waste and byproducts offer a readily available and abundant feedstock source for glucose production (Schiano et al., 2022). They can be sourced from various stages of the food supply chain, reducing waste and contributing to a circular economy. Food waste often contains significant amounts of carbohydrates, including glucose, making it an attractive feedstock option. Food waste and byproducts may require preprocessing, sorting, and potential pretreatment to remove non-biodegradable components and enhance processability (Elalami et al., 2022). The composition of food waste can be diverse and variable, requiring tailored processing approaches. Waste collection, handling, and logistics need to be efficiently managed to ensure a reliable and uncontaminated feedstock supply.

Sugarcane Bagasse, Rice Husk and Sawdust Application

Producing glucose from sugarcane bagasse involves breaking down the complex carbohydrates present in the bagasse into simpler sugars like glucose. Sugarcane bagasse is the fibrous residue left after extracting the juice from sugarcane stalks in the sugar extraction process. It is rich in cellulose and hemicellulose, both of which can be converted into glucose through different processes. General outline of the process to produce glucose from sugarcane bagasse include preparation of Sugarcane Bagasse, pretreatment, enzymatic hydrolysis, fermentation, separation and purification and glucose concentration. Previous work done using the feedstock to produce glucose are found in Roslan & Salimi (2019), Lv et al. (2022) and Bussamra et al. (2020). Glucose produced from rice husk can find applications in various industries, similar to glucose produced from other lignocellulosic biomass sources. Some potential applications include bioethanol production, food and beverage industry, pharmaceutical and nutraceutical industries, chemical feedstock and bioplastics (Dhar et al., 2019).
It's essential to consider that the advantages of glucose production from rice husk depend on various factors, including local agricultural practices, feedstock availability, infrastructure, and the specific application of the glucose produced. Both rice husk and sugarcane bagasse have their unique characteristics, and the choice of feedstock would depend on the specific circumstances and objectives of the glucose production process. Production of glucose from rice husk will also follow the same process steps listed under sugarcane bagasse utilization, beginning with pretreatment (Aredo et al., 2020; Bohn et al., 2021; Cheoh, 2018). The same author also adopts a unique model called the Peleg kinetic model to determine the reaction rate constant. More details are found in Asim et al. (2021) who analyzed the production of food-grade glucose using wheat residues and rice waste. On the other hand, there is limited utilization of sawdust to produce glucose. One among previous studies (within 2018-2023) discovered is a study by Hassan et al. (2018).

Microorganism Strain for Hydrolysis

Biodegradation is the application of biological principle for the purpose of converting food stuff into more palatable nutritional or staple food; it has the potential to improve the nutritional value of fibrous agricultural by-product. Enzymatic hydrolysis of cellulose is carried out by enzyme which is highly specific. *Aspergillus niger* is worldwide in distribution and has been isolated from numerous habitat. Humans are continually exposed to *Aspergillus niger* spores and vegetative forms on foodstuffs and in air. The vast majority of *Aspergillus niger* strains especially those used in industrial fermentation have a history of safe use (Edor et al., 2018). Some species of the fungal genus Aspergillus produce glucoamylase enzymes that can break down starches into glucose. These enzymes are widely used in various industries for starch hydrolysis and glucose production. Apart from *Aspergillus niger* chosen by this study, several other microorganism strains such as *Escherichia coli* may be used (Carreón-Rodríguez et al., 2023).

Methodology

Initial literature review was earlier reported in two sections: 2.1 and 2.2. Of concern to bioengineers is the speed of these production and product optimization. In view of that, kinetics and optimization strategies were well discussed using sourced materials, including, book chapters, thesis, journals, book and conference papers. Usually, a good kinetics study and optimized production of glucose will translate into experts venturing into its manufacture for sustainable growth and benefits that can be driven from it. Thus, the expected results discuss techno-economic analysis, cost, life cycle assessment, and case studies for its industrial application.

Kinetics of Glucose Production

The kinetics of glucose production refers to the study of the rates and mechanisms involved in the conversion of different feedstocks into glucose. Understanding the kinetics is essential for optimizing process conditions, designing reactors, and predicting glucose yields. Several factors influence the kinetics of glucose production, including the type of feedstock, hydrolysis method, enzyme or acid concentration, temperature, pH, and reaction time (Ude et al., 2020). These factors affect the reaction rates by influencing the accessibility of carbohydrates, the catalytic activity of enzymes or acids, and the solubility and stability of the intermediates and products (Sodiqovna, 2020). Optimal process conditions need to be determined to achieve high glucose yields and conversion rates. The kinetics of glucose production can involve different reaction mechanisms depending on the hydrolysis method used. In enzymatic hydrolysis, specific enzymes, such as cellulases and hemicellulases, break down the polysaccharides into glucose molecules through enzymatic cleavage of glycosidic bonds (Hu et al., 2021; ILO, 2020). The reaction typically follows a complex mechanism involving substrate adsorption, enzymatic reaction, and product desorption. Acid hydrolysis, on the other hand, involves the hydrolysis of carbohydrates by strong acids (Andreeva et al., 2021), resulting in the cleavage of glycosidic bonds and the release of glucose.

Mathematical models are widely used to describe and predict the kinetics of glucose production. These models can be based on empirical correlations, mechanistic principles, or a combination of both. Empirical models use experimental data to develop correlations between process variables and glucose production rates. Mechanistic models (Richter et al., 2022; Salazar et al., 2023), on the other hand, are based on the understanding of reaction mechanisms and the application of mass balance and rate equations. These models can provide insights into the underlying reaction kinetics and aid in process optimization and reactor design. The determination of reaction rates is crucial for understanding the kinetics of glucose production. Experimental techniques such as batch assays, continuous flow reactors, or spectroscopic methods can be employed to measure the rates of glucose release or consumption (Halka et al., 2018). By varying process parameters such as enzyme or acid concentration, temperature, or reaction time, the rates can be determined and used to estimate reaction rate constants and activation energies. Kinetic modeling involves the development of mathematical equations that describe the rates of glucose production as a function of various process variables. Model parameters, such as reaction rate constants and activation energies, can be estimated by fitting the model to experimental data using optimization techniques. Parameter estimation methods (Murzin et al., 2021; Yu et al., 2021), such as nonlinear regression or kinetic modeling software, can be employed to obtain accurate parameter values and validate the model's predictive capabilities. The kinetics of glucose production play a crucial role in process optimization. By studying the reaction rates and understanding the underlying mechanisms, process conditions can be optimized to maximize glucose yields, conversion rates, and process efficiency (Bryan et al., 2018; Toif et al., 2021). Kinetic studies also provide insights into the effects of different variables, allowing for the identification of limiting factors and the determination of optimal operating conditions. Table 1 are literature summary of previous work on glucose production.

Table 1: Literature Review on Glucose Production Methodologies

Author	Microorganism and/or Feedstock	Method	Glucose Yield	Condition
(Ude et al., 2020)	0.428 g/50 mL enzyme + mixed peels (cassava & potato)	Kinetic of hydrolysis: Michaelis-Menten model; Optimization = RSM	79%	36 ℃ ; pH = 4.55; retention time = 5 days
(Onyelucheya et al., 2022)	Corn cob	Kinetics: Seaman & Two-Fraction model	0.038 mg/mL	130 ℃ ; phosphoric acid & nitric acid
(Dussán et al., 2014)	Sugarcane bagasse + Sc. stipitis	Analytical method	22.74 g/L	Dilute sulfuric acid; 155℃; time = 10 min
(El-Zawawy et al., 2011)	Rice straw + banana plant + corn cob + Enzyme (Trichoderma reesei)	Enzyme and acid hydrolysis	0.3-1.1 g/L	Sulphuric acid; pH = 4.5-5.0; 40-50℃
(Adeoye et al., 2019)	Pineapple + pawpaw peels	Pseudo-First order model; Arrhenius thermodynamic model; FTIR	29.47-30.8%	1M H_2SO_4 hydrolysis; 60-90℃; hydrolysis time = 0-140 min; acid conc = 1-3.5M
(Roslan & Salimi, 2019)	Sugarcane bagasse	RSM, Regression analysis and Design of Experiment (DOE)	0.783 g/L	34°C, pH = 6.39 and enzyme dosage = 0.15 mL

Kinetic Models for Enzymatic Hydrolysis

Kinetic models for enzymatic hydrolysis are mathematical representations that describe the rates of glucose production from the hydrolysis of polysaccharides by enzymes (Shokrkar & Ebrahimi, 2021). These models are essential for understanding the underlying mechanisms, optimizing process conditions, and predicting glucose yields. The commonly used kinetic models for enzymatic hydrolysis, their assumptions, and their applications will be discussed (Efrinalia et al., 2022; Shokrkar & Ebrahimi, 2021).

(a) Michaelis-Menten Model: The Michaelis-Menten model is one of the most widely used kinetic models for enzymatic reactions, including enzymatic hydrolysis. It assumes that the reaction rate is proportional to the concentration of the enzyme-substrate complex. The model incorporates two parameters: the maximum reaction rate (V_{max}) and the Michaelis constant (K_m), which represents the substrate concentration at which the reaction rate is half of Vmax. The Michaelis-Menten model is based on the assumption of steady-state enzyme kinetics and assumes that the enzyme-substrate complex is the rate-determining step.

(b) Briggs-Haldane Model: The Briggs-Haldane model is an extension of the Michaelis-Menten model and considers the reversible formation of the enzyme-substrate complex. It incorporates an additional parameter, the dissociation constant (K_d), which represents the equilibrium constant between the enzyme-substrate complex and the free enzyme and substrate. The Briggs-Haldane model provides a more accurate representation of the enzymatic hydrolysis process by considering the reversible nature of the enzyme-substrate interaction.

(c) Hanes-Woolf Model: The Hanes-Woolf model is an alternative representation of the Michaelis-Menten equation. It linearizes the relationship between the reaction rate and the substrate concentration by plotting the ratio of the substrate concentration to the reaction rate against the substrate concentration. The slope of the linear plot represents the Michaelis constant (K_m), and the intercept on the y-axis represents the reciprocal of the maximum reaction rate ($1/V_{max}$). The Hanes-Woolf model is particularly useful when experimental data have high variability or at low substrate concentrations.

(d) Luedeking-Piret Model: The Luedeking-Piret model is a phenomenological model that describes the relationship between the production rate of glucose and the consumption rate of the substrate. It assumes that both the glucose production and substrate consumption rates are dependent on the concentration of the substrate and the enzyme. The model incorporates two parameters: the Luedeking-Piret coefficient (α), which represents the extent of glucose production independent of substrate consumption, and the Luedeking-Piret coefficient (β), which represents the fraction of substrate consumed in relation to glucose production.

(e) Substrate Inhibition Model: The substrate inhibition model accounts for the inhibition of the enzymatic reaction at high substrate concentrations. It assumes that the reaction rate decreases at high substrate concentrations due to the inhibitory effect of the excess substrate. The model incorporates an additional parameter, the inhibition constant (K_i), which represents the substrate concentration at which the reaction rate is half of the maximum reaction rate. The substrate inhibition model is particularly relevant when working with concentrated substrate solutions.

(f) Modified Kinetic Models: In addition to the aforementioned models, various modified kinetic models have been proposed to account for specific factors and phenomena in enzymatic hydrolysis. These include models considering enzyme deactivation, enzyme substrate heterogeneity, multiple enzyme activities, and product inhibition. These modified models provide a more comprehensive representation of the enzymatic hydrolysis process by considering additional factors that can influence reaction rates and glucose yields.

Kinetic models for enzymatic hydrolysis provide valuable insights into the reaction mechanisms, reaction rates, and optimal process conditions for glucose production. By fitting the models to experimental data using parameter estimation techniques (Shokrkar & Ebrahimi, 2021; Yu et al., 2021), the kinetic parameters can be determined, enabling the prediction of glucose yields and the optimization of enzymatic hydrolysis processes. However, it is important to note that the selection and applicability of a specific kinetic model depend on the characteristics of the enzyme-substrate system and the specific objectives of the study (Panda & Datta, 2022).

Kinetic Models for Acid Hydrolysis

Kinetic models for acid hydrolysis are mathematical representations that describe the rates of glucose production from the hydrolysis of polysaccharides by strong acids (Yuan et al., 2021). These models are valuable tools for understanding the acid hydrolysis process, optimizing reaction conditions, and predicting glucose yields. Discussion on some commonly used kinetic models for acid hydrolysis, their assumptions, and their applications are found below.

(i) First-Order Kinetic Model:

The first-order kinetic model is a simple and widely used model for acid hydrolysis. It assumes that the reaction rate is directly proportional to the concentration of the substrate (polysaccharide) or the acid. The model Equation 1 is given by Onyelucheya et al. (2022):

$$\text{Rate} = k[\text{Substrate}] \quad (1)$$

where Rate represents the reaction rate, k is the rate constant, and [Substrate] is the concentration of the substrate. The first-order kinetic model assumes that the acid hydrolysis reaction follows pseudo-first-order kinetics, where the concentration of the acid is maintained at a sufficiently high level.

(ii) Pseudo-First-Order Kinetic Model

The pseudo-first-order kinetic model is an extension of the first-order model that accounts for the effect of both substrate and acid concentrations on the reaction rate. The model equation is given by Equation 2:

$$\text{Rate} = k[\text{Substrate}][\text{Acid}] \quad (2)$$

where Rate represents the reaction rate, k is the rate constant, [Substrate] is the concentration of the substrate, and [Acid] is the concentration of the acid. The pseudo-first-order kinetic model assumes that the reaction rate is dependent on both the substrate and acid concentrations.

(iii) Second-Order Kinetic Model

The second-order kinetic model considers the simultaneous reaction of two reactants, the substrate and the acid. The model equation is given by Equation 3:

$$\text{Rate} = k[\text{Substrate}][\text{Acid}] \quad (3)$$

where Rate represents the reaction rate, k is the rate constant, [Substrate] is the concentration of the substrate, and [Acid] is the concentration of the acid. The second-order kinetic model assumes that the reaction rate is proportional to the product of the substrate and acid concentrations.

(iv) Fractional Conversion Kinetic Model

The fractional conversion kinetic model describes the conversion of the substrate into glucose as a function of time. It assumes that the reaction rate is proportional to the remaining concentration of the substrate. The model equation is given by Equation 4:

$$X = 1 - e^{-kt} \quad (4)$$

where X represents the fractional conversion of the substrate, k is the rate constant, t is the reaction time, and e is the base of the natural logarithm. The fractional conversion kinetic model is useful for monitoring the progress of acid hydrolysis reactions and estimating the extent of substrate conversion.

(v) Modified Kinetic Models

Various modified kinetic models have been proposed to account for specific factors and phenomena in acid hydrolysis, such as temperature dependence, catalytic effects of acid, and inhibition effects. These models incorporate additional parameters or variables to improve the accuracy of the predictions and provide a more comprehensive representation of the acid hydrolysis process.

Kinetic models for acid hydrolysis provide insights into the reaction rates, reaction mechanisms, and optimal process conditions for glucose production (Efrinalia et al., 2022). By fitting these models to experimental data using parameter estimation techniques (Salmi et al., 2020; Yu et al., 2021), the kinetic parameters can be determined, enabling the prediction of glucose yields and the optimization of acid hydrolysis processes. However, it is important to consider the limitations of these models and the specific characteristics of the acid hydrolysis system being studied when selecting and applying a particular kinetic model (Yuan et al., 2021).

Kinetic Models for Fermentation Processes

Kinetic models for fermentation processes are mathematical representations that describe the rates of glucose consumption and product formation during the conversion of sugars into various products, such as ethanol, organic acids, or biofuels, by microorganisms. These models are crucial for understanding the fermentation kinetics, optimizing process conditions, and predicting product yields. In this section, we will discuss some commonly used kinetic models for fermentation processes, their assumptions, and their applications.

A) Monod Model

The Monod model is a widely used kinetic model for microbial fermentation processes. It describes the specific growth rate of microorganisms as a function of substrate concentration. The model equation is given by González-Figueredo et al. (2017) in Equation 5:

$$\mu = \frac{\mu_{max} S}{K_s + S} \quad (5)$$

where μ represents the specific growth rate, μ_{max} is the maximum specific growth rate, [S] is the substrate concentration, and K_s is the saturation constant. The Monod model assumes that the specific growth rate is limited by substrate availability and follows a hyperbolic relationship with the substrate concentration.

B) Logistic Model

The logistic model is an extension of the Monod model that takes into account the inhibition effects of high substrate concentrations on microbial growth. It incorporates an additional term, $\mu_{max}(1 - [S]/K_I)$, to represent substrate inhibition. The logistic model is useful when dealing with fermentation processes where high substrate concentrations can negatively impact microbial growth and product formation.

C) Contois Model

The Contois model is a kinetic model that considers the limitation of both substrate and product concentrations on microbial growth. It assumes that the specific growth rate is proportional to the substrate consumption rate and the square of the product concentration. The model equation is given by Equation 6:

$$\mu = \frac{\mu_{max} S}{K_s + [S] + \alpha [P]^2} \quad (6)$$

where μ represents the specific growth rate, μmax is the maximum specific growth rate, [S] is the substrate concentration, [P] is the product concentration, K_s is the saturation constant for substrate, and α is the inhibition constant for product. The Contois model provides a more comprehensive representation of fermentation kinetics by considering the inhibitory effects of product accumulation.

D) Luedeking-Piret Model

The Luedeking-Piret model is a phenomenological model that describes the production rate of a desired product during fermentation. It assumes that the production rate is a function of both the growth-associated and non-growth-associated components. The model equation is given by Equation 7:

$$P = \alpha\mu + \beta[S] \quad (7)$$

where P represents the product concentration, μ is the specific growth rate, [S] is the substrate concentration, and α and β are the Luedeking-Piret coefficients. The Luedeking-Piret model is useful for analyzing the relationship between microbial growth and product formation during fermentation.

E) Structured Kinetic Models

Structured kinetic models consider the intracellular processes and metabolic pathways of microorganisms during fermentation. These models describe the dynamic changes in cellular components, such as biomass, substrate, and product concentrations, and the corresponding fluxes. Structured models are more complex and require additional parameters and data for their calibration, but they provide a more detailed understanding of the microbial fermentation process (Ali et al., 2023; Elmer & Gaden, 2000).
Kinetic models for fermentation processes help elucidate the relationship between substrate consumption, product formation, and microbial growth (Kresnowati et al., 2015). By fitting these models to experimental data using parameter estimation techniques, the kinetic parameters can be determined, enabling the prediction of product yields and the optimization of fermentation processes (Brito & Antunes, 2014; Shatalov et al., 2013). However, it is important to consider the limitations of these models, such as the assumption of constant parameters and the simplifications made in describing complex biological processes, when applying them to specific fermentation systems.

Factors Affecting Reaction Kinetics

Understanding the factors that affect reaction kinetics is crucial for optimizing reaction conditions, predicting reaction rates, and designing efficient chemical processes. Some key factors that influence reaction kinetics are the concentration of reactants, temperature, catalysts, surface area, presence of inhibitors or catalyst poisons, pressure, solvent, reaction mechanism, activation energy and molecular orientation. The concentration of reactants plays a significant role in determining the rate of a chemical reaction. According to the collision theory, for a reaction to occur, reactant molecules must collide with sufficient energy and proper orientation. Higher concentrations of reactants increase the frequency of collisions, leading to a higher reaction rate. Temperature has a profound effect on reaction kinetics. Increasing the temperature generally increases the reaction rate. This is because higher temperatures provide reactant molecules with more kinetic energy, resulting in more frequent and energetic collisions. Additionally, higher temperatures can overcome activation energy barriers, allowing reactions to proceed more readily (Sodiqovna, 2020). Catalysts are substances that increase the rate of a chemical reaction without being consumed in the process. They lower the activation energy required for the reaction to occur, thereby facilitating the formation of products. Catalysts provide an alternative reaction pathway with a lower activation energy, allowing for faster reaction rates. In reactions involving solids or heterogeneous systems, the surface area of the reactants plays a vital role. Increasing the surface area by breaking solids into smaller particles or using catalysts in finely divided form exposes a larger area for reactant molecules to come into contact. This enhances the frequency of collisions and increases the reaction rate (Sodiqovna, 2020).

In gas-phase reactions, pressure can affect reaction kinetics. Increasing the pressure increases the number of gas molecules per unit volume, which leads to more frequent collisions. Higher pressure can increase the reaction rate by increasing the concentration of reactant molecules and their collision frequency. The specific reaction mechanism, including the sequence of elementary steps, intermediate species, and rate-determining steps, influences the overall reaction rate. Understanding the reaction mechanism is crucial for designing appropriate kinetic models and optimizing reaction conditions. The choice of solvent can significantly impact reaction kinetics, particularly in liquid-phase reactions. The solvent can affect the stability of reactants, the solubility of reactants and products, and the mobility of molecules, all of which influence reaction rates. Inhibitors are substances that decrease the rate of a reaction, while catalyst poisons are substances that deactivate catalysts. Both inhibitors and catalyst poisons reduce the effectiveness of the reactants or catalysts, leading to a slower reaction rate For reactions involving multiple reactant molecules, the molecular orientation during collisions can affect reaction kinetics (Abril-González et al., 2023). In some cases, specific molecular orientations are required for effective collisions and reaction to occur. Factors that influence molecular orientation include steric hindrance, molecular shape, and the presence of functional groups. Activation energy is the minimum energy required for a reaction to occur. Reactions with higher activation energies typically have slower reaction rates. Lowering the activation energy through factors like temperature, catalysts, or the presence of suitable reactant molecules can significantly accelerate the reaction rate. Understanding and manipulating these factors can help control and optimize reaction kinetics in various chemical processes. It allows for the design of efficient reactions, the development of suitable reaction conditions, and the prediction of reaction rates and yields.

Experimental Techniques for Kinetic Parameter Estimation

Experimental techniques for kinetic parameter estimation are essential for obtaining accurate and reliable information about the rate constants and parameters that govern chemical reaction kinetics. These techniques involve conducting experiments under controlled conditions and analyzing the resulting data to determine the kinetic parameters. Some experimental techniques for kinetic parameter estimation are (Shim et al., 2020; Yu et al., 2021):

a) Method of Initial Rates: The method of initial rates is a widely used technique for estimating kinetic parameters. It involves conducting multiple reactions with different initial concentrations of reactants and measuring the reaction rates at the beginning of each reaction. By analyzing the data, such as plotting the initial rate versus the initial concentration, the rate constant or reaction order can be determined.
b) Integrated Rate Laws: Integrated rate laws involve measuring the concentration of reactants or products at different time intervals during a reaction. By integrating the rate laws for different reaction orders or rate expressions, it is possible to obtain equations that relate the concentration of reactants or products to time. By fitting these equations to experimental data, the rate constant and reaction order can be estimated.
c) Differential Analysis (Onyelucheya et al., 2022): Differential analysis involves measuring the change in concentration of reactants or products over time. By taking the derivative of the concentration-time data, the reaction rate can be determined. Differential analysis is particularly useful for reactions with complex reaction mechanisms or when the reaction rates are not constant (Abril-González et al., 2023; Salmi et al., 2020).
d) Temperature Dependence: The temperature dependence of reaction rates can provide valuable information about the activation energy and temperature dependence of rate constants. By conducting reactions at different temperatures and analyzing the resulting data, the Arrhenius equation can be used to estimate the activation energy and pre-exponential factor (Adeoye et al., 2019; P. Zhang & Sutheerawattananonda, 2020).

e) In situ Monitoring: In situ monitoring techniques involve measuring the concentration of reactants or products during the course of the reaction without the need for sample removal. Techniques such as spectroscopy, chromatography, and mass spectrometry can be employed to monitor the reaction progress in real-time. In situ monitoring allows for continuous data acquisition and can provide insights into reaction kinetics and mechanisms.
f) Isotope Labeling: Isotope labeling techniques involve introducing isotopically labeled compounds into the reaction system. By monitoring the incorporation of isotopes into reaction products or following the isotopic exchange between reactants and products, information about reaction pathways, intermediate species, and rate constants can be obtained.
g) Design of Experiments (DOE): DOE techniques involve systematically varying reaction conditions, such as temperature, concentration, and catalyst loading, to obtain a comprehensive set of data for kinetic parameter estimation. Statistical analysis methods, such as response surface methodology and factorial designs, can be used to analyze the data and estimate the kinetic parameters.
h) Model Fitting and Simulation: Mathematical modeling and simulation techniques can be employed to fit experimental data to kinetic models. Software tools and optimization algorithms can assist in finding the best-fit parameters by minimizing the difference between the experimental data and model predictions.

It is important to note that the choice of experimental technique depends on the specific reaction system, available resources, and the desired level of accuracy. Often, a combination of different techniques is used to obtain a comprehensive understanding of reaction kinetics and estimate the kinetic parameters with greater confidence.

Optimization Strategies for Glucose Production

Optimization strategies for glucose production involve maximizing the yield, conversion efficiency, and productivity of glucose production processes. These strategies aim to optimize various aspects of the process, such as reaction conditions, process parameters, and feedstock selection, to enhance the overall performance and economic viability (Foust et al., 2020; Sant et al., 2021). Table 2 shows some commonly employed optimization strategies for glucose production.

Table 2: Common Optimization Strategy and their Significance (Elalami et al., 2022; Moreira et al., 2019)

S/No	Optimization Strategy	Description
1.	Reaction and Process Optimization	Optimizing the reaction conditions is crucial for maximizing glucose production. This includes optimizing parameters such as temperature, pH, reaction time, enzyme or catalyst concentration, and agitation speed. By systematically varying these parameters and analyzing their impact on glucose yield and conversion, the optimal reaction conditions can be determined
2.	Feedstock Selection and Pretreatment	The choice of feedstock plays a significant role in glucose production. Different feedstocks, such as agricultural residues, forest biomass, or algal biomass (Andreeva et al., 2021), have different compositions and properties that affect their enzymatic or chemical conversion to glucose. Optimizing feedstock selection involves considering factors such as availability, cost, composition, and ease of pretreatment to enhance glucose yield and minimize production costs.
3.	Pretreatment Optimization	Pretreatment of feedstock is often necessary to enhance the accessibility of polysaccharides, such as cellulose or hemicellulose, to enzymatic or acid hydrolysis. Optimization of pretreatment conditions, such as temperature,

		pressure, residence time, and the use of specific pretreatment agents, can significantly improve the efficiency of glucose release from feedstock.
4.	Enzyme and Catalyst Optimization	When enzymatic or acid hydrolysis is employed for glucose production, optimizing the choice and concentration of enzymes or catalysts is essential. This includes selecting enzymes with high activity and specificity, optimizing their dosage, and considering the use of enzyme cocktails or synergistic combinations to improve glucose release and minimize enzyme costs.
5.	Process Integration and Scale-Up	Optimizing the integration of different process steps and optimizing the scale-up of glucose production processes are critical for commercial viability. Process integration involves streamlining the process steps, minimizing energy consumption, and optimizing process flows to maximize efficiency. Scale-up optimization focuses on translating laboratory-scale processes to larger production scales while maintaining consistent and efficient glucose production.
6.	Reaction Kinetics and Modeling	Understanding the reaction kinetics and developing mathematical models can aid in the optimization of glucose production processes (Yassien & Jiman-Fatani, 2023). Kinetic modeling helps in predicting glucose yields, identifying rate-limiting steps, and optimizing reaction conditions. It allows for the exploration of different scenarios and the identification of optimal operating conditions.
7.	Techno-economic Analysis	Performing techno-economic analysis is crucial for evaluating the feasibility and economic viability of glucose production processes (Sant et al., 2021). This analysis involves assessing the capital and operating costs, calculating the glucose production costs, and considering factors such as feedstock costs, enzyme costs, equipment costs, and market demand. Optimizing the process parameters to reduce production costs and improve overall process economics is a key aspect of optimization strategies.
8.	Continuous Process Development	Optimizing glucose production often involves transitioning from batch processes to continuous processes (Halka et al., 2018). Continuous processes offer advantages such as improved productivity, better control over reaction conditions, and reduced labor and equipment costs. Optimizing the design and operation of continuous processes for glucose production can lead to higher yields, improved efficiency, and reduced operational complexities.

Process Optimization Techniques

Process optimization techniques play a crucial role in improving the efficiency, productivity, and overall performance of chemical processes. These techniques involve systematically analyzing and improving different aspects of the process to achieve desired objectives, such as maximizing yield, minimizing costs, reducing waste, and improving product quality. In the context of glucose production, process optimization techniques aim to enhance the efficiency of glucose production processes. Here (Table 3) are some commonly used process optimization techniques:

Table 3: Optimization Techniques in Common Application (Malakar et al., 2020)

S/No	Optimization Technique	Description
1.	Multi-Objective Optimization	In some cases, process optimization requires balancing multiple conflicting objectives. Multi-objective optimization techniques aim to find optimal solutions that satisfy multiple objectives simultaneously. These techniques involve defining the objectives, determining their relative importance, and using optimization algorithms to identify the optimal trade-offs and Pareto optimal solutions
2.	Process Integration	Process integration techniques focus on optimizing the interaction and integration of different process steps to maximize efficiency and minimize resource consumption. Techniques such as heat integration, mass integration, and pinch analysis are used to identify opportunities for energy recovery, minimize utility usage, and improve overall process efficiency.
3.	Computational Modeling and Simulation	Computational modeling and simulation tools enable the virtual optimization of process parameters, equipment design, and operating conditions. By developing mathematical models based on fundamental principles and simulating various scenarios, process optimization can be performed in a cost-effective and time-efficient manner. Modeling and simulation allow for the evaluation of different process configurations and the identification of optimal operating conditions without extensive experimental testing.
4.	Six Sigma	Six Sigma is a data-driven approach aimed at reducing process variability and improving process performance. It involves the use of statistical analysis and problem-solving methodologies, such as DMAIC (Define, Measure, Analyze, Improve, Control), to identify and eliminate defects or variations in the process. Six Sigma helps optimize process parameters, minimize process variability, and enhance process capability.
5.	Lean Manufacturing	Lean manufacturing principles focus on eliminating waste and optimizing process flow to improve efficiency and reduce costs. Techniques such as value stream mapping, 5S (Sort, Set in Order, Shine, Standardize, Sustain), and Just-In-Time (JIT) production are used to identify and eliminate non-value-added activities, streamline production processes, reduce inventory, and improve overall process efficiency.
6.	Response Surface Methodology (RSM)	RSM (Uchegbu et al., 2022) is a statistical technique used to optimize process parameters by constructing mathematical models that relate process variables to the desired responses. RSM involves conducting experiments based on a predefined design matrix and using regression analysis to fit a response surface model. The model is then analyzed to identify optimal operating conditions that maximize the desired response, such as glucose yield or productivity.
7.	Statistical Process Control (SPC)	SPC involves monitoring and controlling process variables to ensure that the process operates within defined limits and remains stable over time. It uses statistical tools, such as control charts, to detect and address any process variations or deviations. By continuously monitoring the process, SPC helps maintain consistent process performance and reduces the likelihood of quality issues or production failures.
8.	Design of Experiments (DOE)	DOE is a statistical approach used to systematically vary process parameters and evaluate their impact on process performance. By conducting experiments with different combinations of variables, DOE helps identify the most influential

	factors and their optimal levels. This enables the identification of optimal process conditions and provides valuable insights into the process parameter interactions.

By employing these process optimization techniques, glucose production processes can be optimized to achieve higher yields, improved efficiency, reduced costs, and enhanced product quality. Each technique offers a unique approach to systematically analyze and improve different aspects of the process, leading to more sustainable and economically viable glucose production.

Statistical Design of Experiments

Statistical Design of Experiments (DOE) is a powerful and systematic approach used to plan, conduct, and analyze experiments in order to gain insights into process behavior, optimize process parameters, and improve overall process performance. DOE involves the careful selection of experimental factors and levels, the design of an appropriate experimental layout, and the statistical analysis of the obtained data. This approach enables researchers to efficiently explore and understand the relationship between process variables and responses, leading to more informed decision-making and process optimization. Key components and benefits of the statistical design of experiments includes resource efficiency, optimization and insights, statistical analysis, randomization and replication, response variables, factors and levels and experimental design.
Factors are variables that can potentially influence the process or affect the response of interest. These may include process parameters, input variables, or environmental conditions. Levels represent the specific values or settings at which the factors are set during the experiment. By selecting appropriate factors and levels, researchers can investigate the effect of each factor on the process and identify optimal operating conditions. Experimental design involves planning the layout of the experiment to efficiently and effectively collect data. Various designs, such as Full Factorial Design, Fractional Factorial Design, Central Composite Design, and Taguchi Design, are available, each with its own advantages and limitations. The choice of design depends on factors such as the number of factors, desired resolution, available resources, and the need to estimate interaction effects. A well-designed experiment ensures that all relevant factors are systematically varied and properly controlled. Response variables are the outputs or outcomes of interest that reflect the process performance. These may include glucose yield, conversion efficiency, productivity, or other relevant parameters. By carefully selecting appropriate response variables, researchers can gain insights into the impact of the experimental factors on process performance and identify opportunities for improvement.
Randomization involves assigning experimental runs to random order to minimize the influence of unknown or uncontrollable factors. Randomization ensures that any systematic effects or biases are evenly distributed among the experimental units. Replication, on the other hand, involves repeating experimental runs to obtain multiple observations at each combination of factor levels. Replication helps estimate experimental error and improve the precision and reliability of the results. Once the data are collected, statistical analysis techniques are applied to determine the significance of factors, identify the most influential factors, and quantify their effects on the response variables. Analysis of Variance (ANOVA) is commonly used to assess the significance of the factors and their interactions (Yassien & Jiman-Fatani, 2023). Regression analysis is also employed to develop mathematical models that describe the relationship between factors and responses, allowing for prediction and optimization. DOE provides valuable insights into the process behavior and identifies optimal process settings. By analyzing the experimental data, researchers can identify significant factors, determine optimal factor settings, and understand the interactions between factors. These insights enable process optimization, facilitate decision-making, and guide subsequent experiments or process improvements. DOE helps optimize the use of available resources by reducing the number of experimental runs needed to obtain

meaningful results. By strategically selecting factor levels and employing efficient experimental designs, researchers can achieve a high degree of information with a minimal number of experiments. This results in significant time and cost savings compared to a traditional one-factor-at-a-time approach. The statistical design of experiments is a powerful tool for understanding and optimizing glucose production processes. By systematically varying factors, selecting appropriate designs, and applying statistical analysis, researchers can identify optimal process conditions, uncover relationships between variables, and make informed decisions to improve glucose production efficiency, yield, and quality.

Response Surface Methodology

Response Surface Methodology (RSM) is a statistical and mathematical modeling technique used to optimize process parameters and understand the relationship between multiple variables and a response of interest. RSM provides a systematic approach to analyze and optimize complex processes by constructing a response surface model based on experimental data (Riaukaite et al., 2019). This model enables researchers to predict and optimize the response within the experimental domain and identify the optimal factor settings for process improvement. Some key components and benefits of RSM includes experimental design, response surface model, model fitting and analysis, optimization, sensitivity analysis, validation and verification, and robustness analysis.

RSM typically involves a series of carefully planned experiments, often using a design matrix such as a central composite design (CCD) or Box-Behnken design (Uchegbu et al., 2022). The experimental design includes a set of predetermined factor levels that represent the range of values for each factor. These experiments are conducted to obtain response data at different factor combinations to capture the curvature and interaction effects. A response surface model is constructed using regression analysis to fit a mathematical equation that describes the relationship between the response variable and the factors. The model can be a linear, quadratic, or higher-order polynomial equation, depending on the complexity of the process and the observed data (Jamil & Wang, 2016; Uchegbu et al., 2022). The model captures the main effects of factors, interaction effects, and curvature effects, allowing for response prediction and optimization. Statistical techniques such as regression analysis, analysis of variance (ANOVA) (Yassien & Jiman-Fatani, 2023), and model diagnostics are employed to fit the response surface model to the experimental data. The model's goodness-of-fit is assessed using statistical metrics such as R-squared, lack-of-fit test, and residual analysis. These analyses help evaluate the significance of factors, identify important variables, and assess the model's reliability. Once the response surface model is developed and validated, optimization techniques are applied to identify the optimal factor settings that maximize the desired response. Optimization methods such as response surface optimization, desirability function approach, or numerical optimization algorithms are employed to determine the factor levels that yield the highest response value (Uchegbu et al., 2022). Optimization enables process improvement by identifying the optimal operating conditions.

RSM facilitates sensitivity analysis to assess the impact of factors on the response variable and identify critical process variables. Sensitivity analysis helps researchers understand the relative importance of factors and prioritize their optimization efforts (Muhammad et al., 2022). It also assists in understanding the interactions between factors and their effects on the response, guiding the selection of factors for further investigation (Riaukaite et al., 2019). Once the optimal factor settings are identified, it is essential to validate the response surface model and confirm its accuracy. Additional experiments are conducted at the predicted optimal conditions to verify the model's predictions. This step helps ensure that the model is reliable and can be used for process optimization and decision-making. Robustness analysis assesses the stability and robustness of the optimized process conditions. It involves evaluating the sensitivity of the response to variations in factors or process parameters. Robustness analysis helps identify the range of factors within which the process remains optimal, considering practical constraints and potential process variability.

The benefits of Response Surface Methodology include (Aydar, 2018; Lamidi et al., 2022):

- Optimization: RSM enables the identification of optimal process conditions that maximize the desired response, leading to improved process performance and efficiency.
- Efficiency: RSM allows researchers to obtain a significant amount of information with a relatively small number of experiments, saving time, resources, and costs compared to a full factorial design.
- Insights: RSM provides valuable insights into the relationships between process variables and the response of interest. It helps researchers understand the effects of factors, identify interactions, and gain a deeper understanding of the process behavior.
- Decision-Making: The response surface model provides a quantitative basis for decision-making, allowing researchers to compare different scenarios, evaluate trade-offs, and make informed decisions to optimize the process.
- Process Understanding: RSM helps researchers gain a deeper understanding of the process by quantifying the relationships between variables and the response. This understanding can guide further process improvement and provide a basis for future research.

Optimization of Glucose Production Using RSM

Optimization of glucose production using RSM is a statistical and mathematical approach that involves designing experiments and analyzing the response of the system to different experimental conditions. RSM is commonly used to optimize process variables and find the optimal conditions that maximize the production of glucose from a given feedstock, such as sugarcane bagasse, rice husk, or sawdust. Below is an outline of how RSM can be applied to optimize glucose production (Lai et al., 2016):

(1) Selection of Factors: The first step is to identify the key factors that influence glucose production from the chosen feedstock. These factors could include enzyme dosage, pretreatment conditions (temperature, time, pH), fermentation time, and any other relevant process variables.
(2) Experimental Design: RSM typically uses a DOE approach to plan a set of experiments that cover a range of factor levels. The experiments are strategically chosen to explore the factor space efficiently and minimize the number of experimental runs required.
(3) Response Surface Model: The experimental data obtained from the DOE is used to build a response surface model. This model relates the glucose production (the response) to the different process variables (factors) and their interactions. Commonly used models include polynomial equations, which allow for the estimation of glucose yield under various combinations of factor levels.
(4) Optimization: The response surface model is then used to find the optimal combination of factor levels that maximizes glucose production. Optimization techniques such as gradient-based methods or numerical optimization algorithms can be employed to determine the optimal settings for the factors.
(5) Validation: After obtaining the predicted optimal conditions, validation experiments are performed to confirm the predicted glucose yield under the optimized conditions. This ensures that the response surface model accurately represents the actual system and provides reliable predictions.

(6) Sensitivity Analysis: Sensitivity analysis can be performed to identify the factors that have the most significant impact on glucose production. This analysis helps in understanding which factors should be given priority in process improvement efforts.
(7) Process Scale-up: If the optimized conditions from the RSM are successful at the laboratory scale, further studies may be conducted to scale up the process to a pilot or industrial level. Scale-up considerations may involve factors like reactor design, process integration, and economic viability.

Multi-objective Optimization Approaches

Multi-objective optimization approaches are optimization techniques designed to handle problems with multiple conflicting objectives (Abushaker et al., 2022). Unlike traditional single-objective optimization, which aims to find a single optimal solution, multi-objective optimization seeks to find a set of Pareto-optimal solutions that represent trade-offs between different objectives. These approaches are particularly useful in decision-making scenarios where multiple criteria need to be considered simultaneously. Pareto optimality is a central concept in multi-objective optimization. A solution is considered Pareto optimal if no other solution can improve one objective without deteriorating at least one other objective. The set of all Pareto-optimal solutions is known as the Pareto front or Pareto set. Each solution on the Pareto front represents a different trade-off between the conflicting objectives, providing decision-makers with a range of options to choose from (Kumar et al., 2022).
Several algorithms have been developed to solve multi-objective optimization problems (Patane et al., 2019). These algorithms can be broadly categorized into evolutionary algorithms (e.g., Genetic Algorithms, Particle Swarm Optimization), swarm intelligence algorithms, mathematical programming-based approaches (e.g., linear programming, nonlinear programming), and decomposition-based methods (e.g., weighted sum, ε-constraint). These algorithms differ in their search strategies, exploration-exploitation balance, and handling of constraints, but they all aim to identify diverse and high-quality solutions on the Pareto front (Briones-Baez et al., 2022; El Moutaouakil et al., 2023).

Results and Discussion

Techno-Economic Analysis of Glucose Production

Techno-economic analysis (TEA) is a comprehensive evaluation method used to assess the feasibility and economic viability of a particular process or technology (Das et al., 2022). In the context of glucose production, TEA plays a crucial role in analyzing the costs, profitability, and overall economic performance of different production methods. It provides insights into the financial aspects of glucose production and helps decision-makers evaluate the economic feasibility of implementing specific production processes. TEA involves a detailed cost analysis that examines the various cost components associated with glucose production. These costs can include raw materials, equipment and infrastructure, labor, energy consumption, utilities, maintenance, waste treatment, and other operational expenses (Jarunglumlert & Prommuak, 2021). By quantifying and analyzing these costs, TEA helps identify the major cost drivers and evaluate the overall cost structure of the production process. In addition to cost analysis, TEA also considers revenue generation potential. It examines the market demand for glucose and estimates the potential sales volume and pricing (Muhammad et al., 2022). Market factors, such as supply and demand dynamics, competition, and pricing trends, are taken into account. By estimating the revenue generated from glucose sales, TEA provides insights into the profitability and financial viability of the production process.

TEA includes sensitivity analysis to assess the impact of uncertain parameters and variables on the economic performance of glucose production. This analysis explores how changes in factors such as raw material prices, energy costs, labor rates, and market conditions affect the profitability and overall economic feasibility of the process (Barba et al., 2022). Sensitivity analysis helps identify critical factors and assess the robustness of the project's financial performance under different scenarios. Cash flow analysis is a fundamental part of TEA, focusing on the inflows and outflows of cash associated with glucose production. It considers the timing of costs and revenues over the project's lifespan to determine the project's cash flow profile (Kuo & Yu, 2020). Cash flow analysis allows for the evaluation of the project's financial viability, profitability, and return on investment. It helps assess the project's ability to generate positive cash flow and recover the initial investment in a reasonable timeframe. TEA provides an evaluation of the required capital investment for establishing glucose production facilities. It assesses the capital expenditure (CAPEX) involved in purchasing equipment, constructing infrastructure, and setting up the necessary production processes. This analysis helps determine the investment requirements, payback period, and return on investment (ROI) of the project (Brandt et al., 2018).
TEA incorporates risk assessment and mitigation strategies to evaluate the potential risks and uncertainties associated with glucose production. It considers factors such as market volatility, regulatory changes, technological risks, and project-specific risks. By identifying and assessing these risks, TEA assists in developing risk management strategies and evaluating the project's resilience against potential challenges (Barba et al., 2022; Muhammad et al., 2022). The primary goal of TEA is to provide decision-makers with comprehensive information and insights to support informed decision-making (Brandt et al., 2018). By quantifying the costs, revenues, and financial performance of glucose production, TEA enables decision-makers to assess the economic feasibility of different production methods, compare alternative technologies, and identify areas for process optimization and cost reduction. In summary, techno-economic analysis of glucose production plays a vital role in evaluating the financial viability, profitability, and economic feasibility of different production processes. It helps assess the costs, revenues, cash flow, and investment requirements, providing decision-makers with the necessary information to make informed choices and optimize the economic performance of glucose production (Ou et al., 2020; Sant et al., 2021).

Cost Analysis of Feedstock Acquisition

Cost analysis of feedstock acquisition is a crucial aspect of assessing the economic feasibility of glucose production (Kuo & Yu, 2020). Feedstock, which refers to the raw materials used in the production process, typically represents a significant portion of the overall production costs. Analyzing the costs associated with acquiring feedstock provides valuable insights into the financial implications of different sourcing strategies and helps decision-makers optimize the cost-effectiveness of glucose production. The cost analysis begins by examining the pricing of various feedstock options. Different feedstock sources, such as agricultural residues, forest biomass, algal biomass, or food waste, may have varying cost structures (Codato-Zumpano et al., 2023). Factors influencing feedstock pricing include availability, seasonal variations, demand-supply dynamics, transportation costs, quality considerations, and market competition. By assessing the prices of potential feedstock sources, the cost analysis enables the comparison of different options and their impact on overall production costs. Apart from pricing, the quantity and quality of feedstock significantly influence the overall cost of acquisition. Analyzing the required feedstock quantities and their availability helps estimate the scale of feedstock acquisition operations. This analysis considers factors such as feedstock yield, moisture content, impurities, and variability in feedstock characteristics (Foust et al., 2020). Understanding these factors enables decision-makers to assess the cost implications associated with sourcing, handling, and processing feedstock.

The cost analysis also involves evaluating different sourcing strategies for feedstock acquisition. This includes assessing the feasibility and cost-effectiveness of sourcing feedstock locally or from external suppliers. Local sourcing may offer advantages such as reduced transportation costs, access to abundant resources, and potential synergies with other industries (Brandt et al., 2018). On the other hand, external sourcing may provide access to specialized feedstock varieties, larger quantities, or cost advantages due to economies of scale. Evaluating the associated costs and benefits of different sourcing strategies helps determine the optimal approach for feedstock acquisition.

Feedstock acquisition involves various costs throughout the supply chain, from harvesting or collection to transportation and storage. The cost analysis considers factors such as collection methods, equipment requirements, logistics, transportation distances, storage facilities, and associated operational expenses. Quantifying and analyzing these costs enables decision-makers to identify cost-saving opportunities, optimize supply chain efficiency, and minimize overall feedstock acquisition expenses (Cheng et al., 2019). Cost analysis of feedstock acquisition includes assessing and mitigating potential risks that may affect the availability and cost of feedstock. Risks can include crop failures, weather-related events, market volatility, regulatory changes, or geopolitical factors. Evaluating these risks helps decision-makers develop contingency plans, diversify feedstock sources, and ensure a stable supply of feedstock at reasonable costs. In addition to cost analysis, it is essential to consider sustainability aspects related to feedstock acquisition (Muhammad et al., 2022). This involves evaluating the environmental impact of different feedstock sources, assessing their renewable or non-renewable nature, and considering their alignment with sustainable development goals (Cheng et al., 2019). While cost optimization is crucial, sustainability considerations can guide decision-making towards more environmentally friendly and socially responsible feedstock acquisition practices. The cost analysis of feedstock acquisition provides decision-makers with valuable information and insights to support informed decision-making. It helps assess the financial implications of different feedstock options, evaluate the cost-effectiveness of sourcing strategies, and optimize the overall feedstock acquisition process (Zhang et al., 2020). The analysis assists in identifying opportunities for cost reduction, enhancing supply chain efficiency, and ensuring a reliable and cost-efficient feedstock supply (Cheng et al., 2019).

Life Cycle Assessment of Glucose Production

Life Cycle Assessment (LCA) is a systematic methodology used to evaluate the environmental impacts associated with the entire life cycle of a product or process, including raw material extraction, production, use, and disposal (Kiš et al., 2019; Osman et al., 2021). Applying LCA to glucose production allows for a comprehensive analysis of the environmental footprint and sustainability performance of different production methods. The LCA of glucose production considers the entire life cycle, encompassing various stages such as feedstock acquisition, preprocessing, enzymatic or acid hydrolysis, fermentation, downstream processing, and final product distribution (Ng et al., 2022). It also includes the energy consumption, emissions, and waste generated at each stage. By considering the full life cycle, LCA provides a holistic perspective on the environmental impacts associated with glucose production. LCA evaluates a range of environmental impact categories, including climate change, resource depletion, acidification, eutrophication, ozone depletion, and human toxicity (Ryan & Yaseneva, 2021). These impact categories capture different aspects of environmental sustainability and allow for a comprehensive assessment of the potential environmental burdens associated with glucose production. Assessing multiple impact categories provides a more robust and balanced understanding of the environmental performance of different production methods. LCA requires gathering data on various inputs and outputs throughout the life cycle stages of glucose production (Osman et al., 2021). This includes

information on energy consumption, raw material extraction, water usage, emissions to air, water, and soil, waste generation, and transportation (Jarunglumlert & Prommuak, 2021). Data can be obtained from literature, industry databases, process simulations, and direct measurements. Accurate and reliable data collection is crucial for ensuring the accuracy and reliability of the LCA results (Kiš et al., 2019).
Defining the system boundaries is an important aspect of LCA. It involves determining which processes and activities are included in the analysis and which are excluded. For glucose production, system boundaries can be set to include the entire production chain, from feedstock acquisition to the production of glucose, or focus on specific stages of the process (Ryan & Yaseneva, 2021). Clearly defining the system boundaries ensures consistency and comparability among different LCA studies and facilitates meaningful interpretation of the results (Ng et al., 2022). During the impact assessment phase of LCA, the collected data on inputs and outputs are translated into environmental impact indicators. This involves the use of impact assessment methods and characterization models to quantify the potential impacts on the selected impact categories. Different impact assessment methods, such as ReCiPe, Eco-indicator, or CML, can be employed to assess the environmental impacts associated with glucose production. The choice of impact assessment method should align with the specific goals and context of the study. The results of the LCA are interpreted to identify hotspots, areas of high environmental impact, and improvement opportunities. Decision-makers can use the LCA results to guide sustainability-oriented decision-making, such as selecting production methods with lower environmental impacts, optimizing processes to reduce resource consumption and emissions, or identifying opportunities for recycling and waste reduction (Astuti et al., 2018). LCA results can also inform product labeling, eco-design, and eco-innovation strategies to promote more sustainable glucose production. LCA promotes transparency and communication of the environmental performance of glucose production. The results of the LCA can be communicated through environmental product declarations (EPDs), sustainability reports, or labeling schemes. Transparently communicating the environmental impacts helps stakeholders, including consumers, policymakers, and industry professionals, make informed choices and encourages continuous improvement in sustainability performance (Blanco et al., 2020).

Sustainability Considerations

Sustainability considerations play a critical role in the assessment and improvement of glucose production processes (Ebikade et al., 2018). As the world increasingly focuses on environmental conservation, resource efficiency, and social responsibility, it is essential to evaluate the sustainability aspects associated with glucose production. Few of the key sustainability considerations in glucose production includes, resource efficiency, renewable feedstock, environmental impact mitigation, climate change mitigation, water management, social and economic impacts and LCA. Efficient use of resources is a fundamental aspect of sustainable glucose production (Salim, González-García, et al., 2019). This involves minimizing resource consumption, such as water, energy, and raw materials, throughout the production process. Implementing technologies and practices that optimize resource efficiency can reduce environmental impacts, conserve natural resources, and lower production costs. Strategies like process integration, waste heat recovery, and recycling can contribute to improved resource efficiency. The choice of feedstock for glucose production has significant implications for sustainability. Utilizing renewable feedstock sources, such as agricultural residues, forest biomass, or algal biomass, helps reduce dependence on finite resources and minimizes the environmental footprint of the production process (Codato-Zumpano et al., 2023; Selivanov et al., 2023). Renewable feedstock sources also offer opportunities for circular economy practices by valorizing waste and byproducts from other industries. Glucose production should aim to minimize its environmental impacts, such as greenhouse gas emissions, water pollution, and land use change. Adopting cleaner production technologies, implementing pollution control measures, and optimizing waste management practices can reduce the ecological footprint of the production process (Akmalina, 2019; Salim, González-García, et al., 2019). Additionally, monitoring and mitigating potential environmental risks associated with feedstock acquisition, such as deforestation or habitat destruction, is essential for ensuring the sustainability of glucose production.

Glucose production contributes to climate change through the release of greenhouse gases, particularly during the energy-intensive stages of the process. Implementing energy-efficient technologies, utilizing renewable energy sources, and adopting carbon capture and storage techniques can help mitigate the carbon footprint of glucose production (Blanco et al., 2020). By reducing greenhouse gas emissions, the industry can contribute to global efforts to combat climate change and achieve sustainability targets. Water is a valuable resource, and its sustainable management is crucial in glucose production. Adopting water-efficient practices, such as recycling and reusing water within the production process, can help minimize water consumption. Implementing wastewater treatment and management systems ensures the responsible discharge of treated water to minimize water pollution. Additionally, considering water availability and prioritizing water-stressed regions for glucose production can help mitigate the potential strain on local water resources. Sustainability considerations encompass not only environmental aspects but also social and economic dimensions (Lips, 2021). It is essential to assess the social and economic impacts of glucose production on local communities, including employment opportunities, livelihoods, and community well-being. Engaging with stakeholders, ensuring fair labor practices, and supporting local development initiatives contribute to the overall sustainability of glucose production and foster positive social outcomes. As discussed previously, conducting an LCA provides a comprehensive evaluation of the environmental impacts associated with glucose production. LCA allows for the quantification and analysis of energy consumption, emissions, waste generation, and resource depletion throughout the entire life cycle of glucose production (Blanco et al., 2020). The results of LCA can guide decision-making, identify improvement opportunities, and support the adoption of more sustainable practices.

By integrating sustainability considerations into glucose production processes, stakeholders can work towards achieving a balance between environmental protection, social responsibility, and economic viability. Through continuous improvement, innovation, and collaboration, the industry can contribute to a more sustainable future.

Case Studies and Industrial Applications

Case studies and industrial applications provide valuable insights into the practical implementation of glucose production processes, highlighting their technical feasibility, economic viability, and sustainability performance. By examining real-world examples, researchers, industry professionals, and policymakers can gain a better understanding of the challenges, successes, and best practices associated with glucose production. Case studies and industrial applications showcase the application of new technologies and innovations in glucose production. They provide examples of how advancements in enzymatic hydrolysis, acid hydrolysis, fermentation, and downstream processing have improved process efficiency, yield, and product quality. By studying these technological advancements, researchers and industry professionals can identify opportunities for process optimization, cost reduction, and environmental impact mitigation (Yassien & Jiman-Fatani, 2023). Case studies offer valuable insights into the optimization of glucose production processes. They demonstrate how various parameters, such as feedstock composition, enzyme dosage, reaction conditions, and fermentation strategies, can be adjusted to maximize glucose yield, minimize energy consumption, and reduce production costs (Singh et al., 2021; Yassien & Jiman-Fatani, 2023). Analyzing successful process optimization strategies can guide researchers and industry professionals in developing more efficient and sustainable glucose production methods. Industrial applications of glucose production provide examples of scaling up laboratory-scale processes to commercial production (Singh et al., 2021). Case studies highlight the challenges faced during scale-up, such as process robustness, equipment selection, and integration of different process stages. They also shed light on the economic considerations, market demand, and regulatory requirements associated with commercializing glucose production. Understanding these aspects is crucial for effectively transitioning from research to large-scale implementation.

Case studies and industrial applications explore different feedstock sources and their suitability for glucose production (Kuo & Yu, 2020). They examine the selection criteria, availability, cost-effectiveness, and sustainability implications of using various feedstock options, such as agricultural residues, forest biomass, algal biomass, or food waste (Andreeva et al., 2021; C. Zhang et al., 2020). These studies provide insights into the challenges and opportunities associated with feedstock acquisition, preprocessing, and handling, enabling decision-makers to make informed choices regarding feedstock sourcing. Glucose production is often integrated into biorefinery concepts, where multiple value-added products are derived from the same feedstock. Case studies and industrial applications demonstrate the integration of glucose production with other biorefinery processes, such as bioethanol production, bioplastics manufacturing, or biochemical production (Foust et al., 2020). These examples highlight the synergies, waste valorization, and economic benefits of adopting a holistic approach to biomass utilization. Case studies provide insights into the sustainability performance of glucose production processes. They showcase the application of sustainability assessment tools, such as LCA, carbon footprint analysis, or water footprint analysis, to evaluate the environmental impacts and resource efficiency of glucose production. By studying these assessments, researchers and industry professionals can identify opportunities for improving the sustainability profile of glucose production and aligning it with sustainability goals. Case studies and industrial applications serve as a platform for knowledge sharing, collaboration, and cross-learning among researchers, industry professionals, and policymakers. They facilitate the exchange of experiences, challenges, and best practices, fostering innovation and continuous improvement in glucose production. Through collaboration and shared learning, the industry can collectively address technological, economic, and sustainability challenges, accelerating the development and adoption of more efficient and sustainable glucose production processes.

Glucose Production from Corn Starch

Glucose production from corn starch is a widely utilized process in the food and beverage industry (Dusabe et al., 2023), as well as in various industrial applications. Corn starch, derived from the endosperm of corn kernels, is a rich source of starch, which can be hydrolyzed to produce glucose. Production steps includes corn starch extraction, starch slurry preparation, enzymatic hydrolysis, enzyme inactivation and filtration, purification and concentration, crystallization and final utilization (Awulachew, 2020). The first step in glucose production from corn starch involves extracting starch from corn kernels. The corn kernels are typically ground and separated into various components, including germ, bran, and endosperm. The endosperm contains the highest concentration of starch. The extracted endosperm is then washed to remove impurities and processed to obtain a purified corn starch. To initiate the enzymatic hydrolysis process, the corn starch is mixed with water to form a starch slurry. The slurry is typically adjusted to a specific pH and temperature, which are optimal for the subsequent enzymatic hydrolysis reaction. Enzymatic hydrolysis is the key step in converting corn starch into glucose (Zhu & Pan, 2022). Specific enzymes, such as amylases, are added to the starch slurry. These enzymes break down the starch molecules into smaller fragments, including glucose molecules. The enzymatic

hydrolysis reaction is typically conducted at controlled temperature and pH conditions, along with appropriate reaction time, to ensure optimal enzyme activity and starch conversion (Zhang et al., 2020). Once the desired level of hydrolysis is achieved, the enzymatic activity is typically deactivated by adjusting the pH or temperature of the reaction mixture. The resulting mixture is then subjected to filtration or centrifugation to separate the glucose-rich solution from the undigested residues, such as insoluble fibers or protein impurities.
The obtained glucose solution may undergo further purification steps to remove impurities, such as residual enzymes, colorants, or organic compounds. Common purification techniques include filtration, ion exchange, activated carbon treatment, and membrane processes. The purified glucose solution is then concentrated through evaporation or membrane processes to increase the glucose concentration (Flores et al., 2018). In some cases, glucose may be further processed through a crystallization step to produce glucose crystals or glucose syrup. Crystallization involves controlled cooling and seeding of the concentrated glucose solution to induce the formation of glucose crystals. The resulting crystals can be separated, washed, and dried to obtain pure glucose.
The produced glucose can be used as a sweetener in the food and beverage industry, replacing sucrose or high-fructose corn syrup (Kiš et al., 2019; Riaukaite et al., 2019). It serves as an essential ingredient in various products, including confectionery, baked goods, beverages, and processed foods. Additionally, glucose finds applications in pharmaceuticals, fermentation processes, and as a precursor for the production of other chemicals.
Glucose production from corn starch offers several advantages, including the abundance and availability of corn as a feedstock, scalability of the process, and versatile utilization of the glucose product. However, it is important to consider the sustainability aspects associated with corn cultivation, such as land use, water consumption, and environmental impacts (Awulachew, 2020). Efforts are being made to explore alternative feedstocks and sustainable production methods to ensure the long-term viability and environmental friendliness of glucose production.

Glucose Production from Cellulosic Biomass

Glucose production from cellulosic biomass offers a promising avenue for sustainable biofuel and biochemical production (Osman et al., 2021). Cellulosic biomass, which includes sources such as agricultural residues, forest biomass, and dedicated energy crops, contains cellulose, hemicellulose, and lignin (Selivanov et al., 2023). The process of converting cellulosic biomass into glucose involves several steps, as outlined below:

(i) Pretreatment (Zhou et al., 2023): Pretreatment is a crucial step in cellulosic biomass conversion. It aims to remove or modify the lignin and hemicellulose components, making the cellulose more accessible to enzymatic hydrolysis. Various pretreatment methods, including physical, chemical, and biological processes, can be employed. Common techniques include steam explosion, acid or alkaline hydrolysis, organosolv, and ammonia fiber expansion (AFEX) (Jarunglumlert & Prommuak, 2021). Pretreatment conditions and severity are optimized to maximize cellulose accessibility while minimizing sugar degradation and inhibitor formation (Malakar et al., 2020).

(ii) Enzymatic Hydrolysis: Enzymatic hydrolysis is the core step in converting cellulose to glucose. After pretreatment, the cellulose-rich material is treated with cellulase enzymes. Cellulase enzymes break down cellulose into glucose by cleaving the cellulose chains into smaller sugar units. The enzymatic hydrolysis reaction is typically carried out at controlled temperature, pH, and enzyme dosage to optimize glucose yield. Enzyme cocktails containing different types of cellulases are often used to improve hydrolysis efficiency (Zhu & Pan, 2022).

(iii) Enzyme Recycling and Inhibitor Management: During enzymatic hydrolysis, the enzymes can be partially deactivated or inhibited by the released sugars and by-products (Turini et al., 2021). To enhance the efficiency and economics of the process, strategies such as enzyme recycling and the use of enzyme inhibitors can be implemented. Enzyme recycling involves separating the enzymes from the hydrolysate and reusing them in subsequent hydrolysis batches. Inhibitor management techniques, such as detoxification or conditioning of the hydrolysate, can minimize the negative impact of inhibitors on enzyme activity and glucose yield.

(iv) Fermentation (Yassien & Jiman-Fatani, 2023): After enzymatic hydrolysis, the resulting glucose-rich hydrolysate can be subjected to fermentation to produce various biofuels and biochemicals. Glucose can be fermented by microorganisms, such as yeast or bacteria, into ethanol, butanol, organic acids, or other valuable products. The fermentation process may require additional steps, such as microbial strain selection, optimization of fermentation conditions (temperature, pH, nutrient supplementation), and downstream processing for product recovery.

(v) Downstream Processing: Downstream processing involves the separation, purification, and recovery of the desired product from the fermentation broth. Techniques such as filtration, centrifugation, distillation, chromatography, and membrane processes are employed to isolate and purify the target compound, such as glucose or the desired fermentation product. The purity and concentration of the final product depend on the intended application.

Glucose production from cellulosic biomass offers several advantages, including the utilization of abundant and renewable feedstock sources, reducing dependence on fossil fuels, and mitigating greenhouse gas emissions (Shokrkar & Ebrahimi, 2021). However, challenges remain in terms of improving the efficiency and cost-effectiveness of the process, addressing inhibitory compounds generated during pretreatment, and developing robust and efficient enzyme systems. Ongoing research and technological advancements are focused on optimizing the individual steps, exploring novel pretreatment methods, developing superior enzyme cocktails, and enhancing the overall process integration to make cellulosic glucose production economically viable and environmentally sustainable (Jones et al., 2018).

Glucose Production from Food Processing Waste

Glucose production from food processing waste offers a valuable opportunity for sustainable utilization of organic byproducts generated in the food industry. Food processing waste, such as fruit and vegetable peels, pomace, spent grains, and other residues, often contains significant amounts of carbohydrates, including starches and sugars, which can be converted into glucose (Andreeva et al., 2021; Lee et al., 2023). The process of glucose production from food processing waste typically involves the following steps:

[1]. Waste Collection and Preparation: Food processing waste is collected from various sources, such as fruit and vegetable processing facilities, breweries, or grain mills. The waste is typically sorted, cleaned, and prepared by removing any non-organic contaminants or inedible parts. The waste may also undergo size reduction or grinding to increase the surface area and improve subsequent processing efficiency.

[2]. Enzymatic Hydrolysis or Acid Hydrolysis: Enzymatic hydrolysis or acid hydrolysis is employed to convert the complex carbohydrates present in the food processing waste into glucose. Enzymatic hydrolysis involves the use of specific enzymes, such as amylases or cellulases, to break down starches or cellulose into glucose (Uchegbu et al., 2022). Acid hydrolysis utilizes dilute acid solutions, such as sulfuric acid or hydrochloric acid, to hydrolyze the carbohydrates into simpler sugars (Adeoye et al.,

2019). The choice of hydrolysis method depends on the composition of the waste and the specific carbohydrates targeted for conversion.

[3]. Hydrolysate Treatment: After hydrolysis, the resulting hydrolysate contains a mixture of glucose, other sugars, and impurities. The hydrolysate is often subjected to purification steps to separate the glucose from unwanted components, such as residual enzymes, solids, or organic acids. Common purification techniques include filtration, sedimentation, and adsorption processes.

[4]. Glucose Concentration (Flores et al., 2018): To increase the glucose concentration in the hydrolysate, concentration techniques such as evaporation, membrane processes (such as reverse osmosis), or crystallization can be employed. These methods remove water from the hydrolysate, resulting in a more concentrated glucose solution.

[5]. Purification and Refinement: Further purification and refinement steps may be required to obtain a high-purity glucose product. These steps can involve techniques such as chromatography, ion exchange, or activated carbon treatment to remove remaining impurities, colorants, or off-flavors.

Glucose production from food processing waste offers several benefits, including waste valorization, reduction of waste disposal and environmental impact, and the potential for cost savings (Lee et al., 2023). By converting waste into a valuable product, the process contributes to a circular economy and sustainable resource management. However, it is essential to ensure the quality and safety of the glucose produced, adhering to relevant regulations and quality standards. Additionally, the development of efficient and cost-effective processing technologies, as well as waste collection and logistics systems, is crucial for the widespread adoption of glucose production from food processing waste (Dusabe et al., 2023).

Glucose Production in Biofuel and Bioproduct Industries

Glucose production plays a crucial role in the biofuel and bioproduct industries, serving as a key intermediate for the production of a wide range of biofuels and bioproducts (Mendoza-Meneses et al., 2021). Glucose can be derived from various biomass sources, including agricultural residues, energy crops, food processing waste, and cellulosic biomass. Glucose is a primary substrate for bioethanol production. Through the process of fermentation, glucose is converted by yeast or other microorganisms into ethanol, which is a renewable and sustainable alternative to fossil fuel-based gasoline (Ali et al., 2023). Glucose can be derived from various feedstocks, such as corn, sugarcane, wheat, and cellulosic biomass, and used as the main carbohydrate source for ethanol fermentation. Bioethanol has gained significant attention as a renewable fuel, contributing to reduced greenhouse gas emissions and energy security. Glucose can also serve as a precursor for the production of biobutanol, an advanced biofuel with potential as a gasoline substitute (Tsai et al., 2020). Biobutanol is produced through a process called acetone-butanol-ethanol (ABE) fermentation, where glucose is converted into butanol, acetone, and ethanol by solvent-producing bacteria (Ibrahim et al., 2018; Yang et al., 2023). Glucose can also be used as a feedstock for the production of other biochemicals, such as organic acids, amino acids, biopolymers, and specialty chemicals, through microbial fermentation or chemical synthesis routes (Osman et al., 2021).

Although glucose itself is not directly used for biodiesel production, it can contribute indirectly by serving as a substrate for microbial oil production. Microorganisms such as algae or oleaginous yeasts can utilize glucose as a carbon source to accumulate lipids or oils (Yang et al., 2023). These lipids can be extracted and converted into biodiesel through a process called transesterification. Glucose, therefore, plays a critical role in providing the necessary carbon and energy source for microbial oil production. Glucose is a valuable platform chemical for the synthesis of various chemicals and materials. It can be converted into a range of platform chemicals, including lactic acid, succinic acid, glycerol, and 2,3-butanediol (Yu et al., 2022). These platform chemicals serve as building blocks for the production of bioplastics, biopolymers, solvents, resins, and other high-value chemical products (Inyang et al., 2022). Glucose-based platform chemicals offer a sustainable and renewable alternative to their petrochemical counterparts. Glucose can be chemically modified or transformed into various derivatives, expanding its utility in different industries. Glucose derivatives, such as glucose esters, glucose ethers, and glucose fatty acid esters, find applications in food, pharmaceuticals, cosmetics, and other sectors (Lee et al., 2023). These derivatives possess specific functionalities and properties that enhance their suitability for specific applications. The production of glucose in the biofuel and bioproduct industries involves various processes, including biomass feedstock preparation, enzymatic or acid hydrolysis, fermentation, and downstream processing (Weiss et al., 2019). The optimization of these processes, along with advancements in biotechnology, enzymology, and process engineering, continues to improve the efficiency, cost-effectiveness, and sustainability of glucose production (Bauer et al., 2022; Singh et al., 2021). The utilization of glucose as a feedstock for biofuels and bioproducts not only reduces reliance on fossil fuels but also contributes to the development of a bio-based economy and a more sustainable future (Osman et al., 2021).

Technological Challenges in Glucose Production

Glucose production is a complex process that involves several technological challenges (Das et al., 2022). Overcoming these challenges is crucial for improving the efficiency, scalability, and cost-effectiveness of glucose production. One of the challenges lies in the diverse nature of feedstock sources for glucose production (Bisht et al., 2019). Different biomass sources, such as agricultural residues, energy crops, food processing waste, and cellulosic biomass, have varying compositions and properties. Preprocessing the feedstock to remove impurities, optimize particle size, and enhance accessibility of the carbohydrates is a critical step. However, developing efficient and scalable preprocessing technologies that can handle different feedstocks remains a challenge (Osman et al., 2021). Pretreatment is essential to break down the complex structure of biomass and make carbohydrates more accessible for enzymatic or acid hydrolysis. Achieving an optimal balance between efficient pretreatment and minimal formation of inhibitors or degradation products is a technological challenge (Ansanay et al., 2021). Similarly, enhancing the efficiency of enzymatic hydrolysis or acid hydrolysis to achieve high glucose yields while minimizing enzyme requirements or acid usage is a continual focus of research and development (Ebikade et al., 2018). Enzymes play a vital role in the hydrolysis of carbohydrates to glucose. However, the cost of enzymes can be a significant barrier to large-scale glucose production. Developing robust and efficient enzyme systems that can work under a wide range of conditions, improving enzyme stability and longevity, and reducing enzyme costs through advances in enzyme engineering and bioprocessing are ongoing challenges (Rocha et al., 2022).

In the case of fermentation-based glucose production, selecting suitable microbial strains that can efficiently convert glucose into desired products, such as bioethanol or biochemicals, is crucial. Improving fermentation efficiency, including higher product yields, faster fermentation rates, and better tolerance to inhibitors, remains a challenge (Yassien & Jiman-Fatani, 2023). Genetic engineering and strain optimization techniques are being explored to enhance microbial performance and address these challenges. Integrating different process steps, optimizing their interaction, and achieving efficient process integration are essential for glucose production. Scaling up the glucose production process from lab-scale to commercial scale poses additional challenges, such as maintaining consistent performance, ensuring cost-effectiveness, and addressing engineering and logistical considerations. Glucose production generates various byproducts and waste streams that require proper management. Treating and utilizing these waste streams in an environmentally sustainable manner is a challenge (Zhu & Pan, 2022). Developing efficient strategies for waste treatment, including recycling, valorization, or conversion into value-added products, is essential to minimize the environmental footprint of glucose production.

Accurate monitoring and control of various process parameters, such as temperature, pH, enzyme dosage, and fermentation conditions, are crucial for optimizing glucose production (Tagougui et al., 2018). Implementing advanced process monitoring techniques, real-time control systems, and automation technologies to ensure consistent and efficient production is a technological challenge (Bisht et al., 2019; Didyuk et al., 2021). Glucose production must be economically viable to compete with traditional production methods (Zhu & Pan, 2022). Techno-economic analysis, including factors such as capital and operational costs, feedstock availability, product yields, and market demand, must be considered. Balancing the costs and benefits of different process parameters and optimizing the overall process economics remains a challenge. Addressing these technological challenges requires interdisciplinary research and collaboration among scientists, engineers, and industry stakeholders. Continued advancements in biotechnology, enzymology, process engineering, and automation are essential for overcoming these challenges and driving the development of efficient, sustainable, and economically viable glucose production technologies (Bauer et al., 2022; Tagougui et al., 2018).

Conclusion

Investigation and optimization of glucose production via multiple biochemical processes and sustainable feedstock sources has yielded substantial insights and possible opportunities. As a critical biomolecule and renewable energy source, glucose holds great promise for meeting the growing demands of a sustainable and environmentally conscious world. The research looked on the kinetics and efficiency of enzymatic hydrolysis, acid hydrolysis, and fermentation routes. Researchers can create novel techniques to improve glucose synthesis and utilization by better understanding these mechanisms. The evaluation of various feedstock sources, such as agricultural residues, forest biomass, algal biomass, and food waste, has offered significant information for the selection of sustainable feedstock. Industries can lessen their environmental impact and contribute to a circular bioeconomy by utilizing locally sourced materials. Optimization tactics were critical in this study, providing useful insights into optimizing glucose production systems. Statistical design of experiments and response surface approach have paved the way for more efficient and cost-effective manufacturing procedures.

Furthermore, the techno-economic analysis and life cycle assessments have highlighted the need of taking both environmental and economic factors into account when evaluating glucose production technologies. Sustainability considerations are critical in the quest for a greener, more resilient future. This study's multidisciplinary approach, which combined biochemical insights with sustainability considerations, provided a comprehensive understanding of glucose production. It has bridged the gap between scientific breakthroughs and real-world applications, making the research relevant to both industries and politicians. As we progress toward a more sustainable bioeconomy, glucose production plays an important role in a variety of sectors, including food, energy, and bioproducts. The study's findings provide useful direction for researchers, industry, and governments in driving the adoption of more environmentally friendly and efficient glucose manufacturing processes. To summarize, the study not only increased our understanding of glucose production, but it also underlined the need of sustainable practices and optimization tactics in designing a more sustainable and prosperous future for humanity. We can usher in an era of sustainable glucose production by embracing renewable carbohydrates and innovative technology, paving the road for a greener and more peaceful coexistence with our planet.

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RESEARCH ARTICLE

Empirical Investigation of Bank Survival and Agro-Production on Economic Resilience

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Abstract

The interaction between bank survival and agro production was used to investigate the extent of economic resilience. To achieve the general objectives of the study times series, data from the world bank data base and macro trends .net was sorted for the independent variables (bank survival, agro-production and capital formation) and the dependent variable (economic resilience) from 2013 through 2021. Different statistical test was conducted through the aid of econometric views version 9.0. The study found that BASU, AGPR, and CAPF has an insignificant influence on ECRE but only CAPF seem to have a positive relationship with ECRE. The study recommended that government authorities should facilitate additions to the fixed assets of the economy plus net changes in the level of inventories. The study suggested amongst others that: the variables of the study for further research should include other factors like inflation, exchange rate so on that impacts economic resilience; the time frame for subsequent research should be adjusted to reflect contemporary events and comparative analysis should be embark on say empirical analysis between Nigeria and some other west Africa or Africa countries.

Key Words: Bank survival; Agro-production; economic resilience

Introduction

Nigeria as an open economy is engaged in foreign trade. In its foreign transactions (import & export) of finished goods adequate finance is required. Financial institutions, banks in particular offers credits to various economy agent comprising individual, firms and government which they invest on productive activities. By providing credit to private enterprises and small firms, the banking industry in emerging nations contributes significantly to economic growth (Beck & Demirguc-Kunt, 2006; Hoang et al., 2022). The lack of necessary funds for corporate operations has a negative impact on output and, as a result, the economy. Economic development and growth, according to Aroghene and Akpoyibo (2023), are assessed by increases in the market value of products and services produced within a specific economy, as well as income per capita GNP. According to Obamuyi, Edun, and Kayode (2009), the sector's poor performance in Nigeria is primarily due to massive imports of finished goods and insufficient financial support for the manufacturing sector, which has contributed to a reduction in capacity utilization in the country.

Agricultural sector on the other hand has the potentials to provide benefits such as conservation, rural development as well as management of renewable natural resources. Despite the significant role played by the sector in an economy it is still without challenges like every other sector in the economy.

Years of poor management, inconsistent and poorly implemented government policies, government indifference, and a lack of basic infrastructure have all harmed the agricultural sector. Years of poor management, inconsistent and poorly implemented government policies, government indifference, and a lack of basic infrastructure have all harmed the agricultural sector. In view of Sabasi et al. (2021), the aforementioned would contribute to underproduction of food.

The role played by banks in any economy together with agriculture cannot be undermined. It is against this backdrop that the study investigated the interaction of bank survival BASU measured by Z score, Agro- production (AGPR) measured by Agriculture, forestry, and fishing, value added (% of GDP) and capital formation(CAPF) measured by gross capital formation (% of GDP) and economic resilience (ECRE) measured by per capita GDP growth in Nigeria.

For the purpose of the study the following research questions was raised:

1. Does bank survival (BASU) affects economic resilience (ECRE) in Nigeria?
2. Does Agro- production (AGPR) affects economic resilience (ECRE) in Nigeria?
3. Does capital formation (CAPF) affects economic resilience (ECRE) in Nigeria?

The research questions asked necessitated the following hypothesis in the null form:

HO1: Bank survival (BASU) does not have effect on economic resilience (ECRE) in Nigeria**.**

HO2: Agro- production (AGPR) does not have effect on economic resilience (ECRE) in Nigeria**.**

HO3: Capital formation (CAPF) does not have effect on economic resilience (ECRE) in Nigeria**.**

Literature Review

Conceptual framework

Bank Survival and Economic Resilience

Banks enhance a country's monetary advancement by facilitating the pace of capital arrangement, money and credit, and satisfaction of financial goals needed for economic growth. Access to finance is essential to set up a favourable atmosphere for the rate of development of enterprises. Economic growth is the sustained increase in per capita national output or net national product over a long period of time (Jones & Ndubuisi, 2023a). The objective of facilitating economy growth would not be achieved if there are disruption in the provision of financial activities in the economy. Hence the survival of bank operation is vital to the growth and development of any economy. Ehiedu, Onuorah, and Mbagwu (2022) described commercial survival as means of achieving an organization mission and vision.

Agro-Production and Economic Resilience

When the production possibility frontier of an economy shifts outward it is said to be experiencing economic growth of which accumulates in a country's resilience. Jones and Ndubuisi (2023b) asserted that economic growth is the increase in a country's productive capacity . Imene and Udjo-Onovughakpo (2023) opined that productivity in most firm has fallen as a result of recurrent conflict within an organization. Imene (2023) also acclaimed that poor productivity and performance is as a result of inadequate evaluation system. As noted by Tochukwu (2012), Nigeria's economic future is not looking good due to the country's disregard for the agricultural sector and reliance on a monocultural economy centered around crude oil. In a similar vein, the agricultural sector is ideally situated to influence any country's pursuit of socioeconomic and industrial growth through its domains of activity at both the macro and micro levels. Low productivity levels and the agricultural sector's sluggish growth are thought to be the primary reasons behind emerging nations' low incomes and sluggish economic growth (Alston and Pardey, 2014).

Gross Capital Formation and Economic Resilience

Any nation's gross capital formation is made up of expenditures that indicate increases to the economy's fixed assets as well as net changes in the amount of inventories. Land improvements (fences, ditches, drains, and the like), the acquisition of plant, machinery, and equipment, and the building of roads, railroads, and similar structures, such as offices, hospitals, schools, and private residences, are examples of fixed assets. Stocks of goods kept by businesses to accommodate sporadic or unforeseen swings in production are known as inventories (World Bank, 2023). With adequate amount of capital, productivity of an economic would increase resultant in economic resilience of a country.

Empirical Review

Gardner (2000) found a significant positive relation between the growth in the value added per agricultural worker and national GDP per capita. Onuorah and Ebimobowei in 2012 affirmed that accountability and public sector financial management enhance growth. Spanos and Lioukas (2001) contributed that the focus of performance has shifted from industry to firm specific assets . Tsakok and Gardner (2007) examined four distinct nations over four distinct time periods to investigate if agricultural development has consistently been a prerequisite for additional economic transformation of a nation. They come to the conclusion that economies can change and grow without the need for a sophisticated and modern agriculture sector. Gollin et al. (2007) and Self and Grabowski (2007) contended that there is proof of a positive correlation between rising agricultural productivity and economic expansion. Musah (2008) indicates that organizational performance should be measured through various indicators depending on the organizational structure. Onuorah, Arubayi and Egbule (2020) stressed that employee relationship management has become imperative for competitive advantage and improves performance. Existant literatures has showed that certain strategies should be applied by firms/ organisation to boast their return on assets which will also impact inclusive growth (Onuorah, 2009; Onuorah, 2010 ; Anayochukwu & Onuorah, 2016; Ehiedu, Onuorah & Mbagwu, 2022).

Awokuse et al. (2009) used real export, agriculture value added per worker, gross capital formation per worker, and real GDP per capita as proxies in an effort to study the dynamic interaction between agricultural productivity and economic growth. They said that agriculture functions as an engine for economic development and is a key component of economic growth. People living in poverty can have better access to food and a better quality of life thanks to innovations in rural and agricultural finance (Kloeppinger-Todd & Sharma, 2010). Fatima, Khan and Arif (2017) opined that in emerging economies, the most influential side is the banking sector because banks providing the role of intermediary for trade and business transactions. Qamruzzaman (2017) assessed the relationship between institutional innovation and economic growth of Bangladesh and found that innovation either in a financial institution or financial market can influence economic growth. In order to measure organizational performance, Rezaei et al. (2018) proposed using a variety of indicators, including both financial and non-financial measurements. Finance is rooted on how well an institution uses financial assets to maximize value (Osiegbu, Onuorah & Nnmadi, 2010; Onuorah, 2011; Osiegbu & Onuorah, 2011).

According to earlier studies (Asaleye et al., 2020; Kaya & Kadanalı, 2022; Onyiriuba et al., 2020), financing for agriculture increases productivity. While the disruption caused by cash shortages affected consumer and corporate moods, financial development (FD) can boost industrial activity (Khemani & Kumar, 2022; Aroghene & Imene, 2023). Furthermore, green FD and green FD development (ED) have a positive correlation (Sadiq et al., 2022). Better financial systems are essential for effective economic growth (Wen et al., 2022). some studies examined foreign direct investment, gross capital formation and trade openness as factors that determine economic resilience (Dritsakis ,Varelas and Adamopoulos, 2006; Erhijakpor & Aroghene, 2023), of which was proxied by some researchers by Per capita GDP (Gardner ,2000; Awokuse et al , 2009) while some studies proxied bank survival by Z-score (Aroghene & Ikeora, 2022; Aroghene, 2022a; Aroghene, 2022b; Aroghene, 2023c).
From critical investigation of the aforementioned studies, each researcher used variables of particular interest and not all the investigation were done in Nigeria using specifically the present study variables. This study filled the gap in literature by using specifically per capita GDP as the dependent variable and Agriculture, forestry, and fishing, value added (% of GDP) and gross capital formation (% of GDP) to measure the independent variables.

Methodology

In order to account for the interaction between bank survival and Agro- production on economic resilience in Nigeria, the study employed Z- score, Agriculture, forestry, and fishing, value added (% of GDP) and gross capital formation (% of GDP) to measure the independent variables while per capita GDP annual growth rate was used to measure the dependent variable. Time series data for Nigeria was obtain from the world bank data base for the period of 2013 through 2021. Different statistical analysis was carried out to investigate the influence of the independent variable on the dependent variable using the statistical package Econometric Views version 9.0. The study model is stated as ;

$$ECRE = F(BASU, AGPR, CAPF) \quad \text{eqn (1)}$$

$$ECRE = b_0+b_1BASU+b_2\,AGPR+b_3\,CAPF+Ut \quad \text{eqn (2)}$$

Where;
ECRE = Economic Resilience
b_0 = the intercept
BASU = Bank Survival
AGPR = Agro- Production
CAPF = Capital Formation b_{1}-
b_3 = the coefficient
Ut = the error term

Results and Discussion

The data for BASU, AGPR, and CAPF were obtained from World Bank data base while ECRE was obtained from macro trends.net are presented below;

Table 1: Data presentation: Data for BASU, AGPR ,CAPF and ECRE

YEAR	BASU	AGPR	CAPF	ECRE
2013	16.3	20.8	14.9	9.12
2014	16.4	20	15.8	7.53
2015	16.8	20.6	15.5	-16.29
2016	16.4	21	15.4	-19.96
2017	18.4	20.8	15.5	-9.46
2018	14.8	21.2	19.8	9.47
2019	15.4	21.9	25.4	9.79
2020	13.6	24.1	27.5	-11.11
2021	12.2	23.4	33.8	-0.43

The results are presented and discussed as follows:

Table 2: Summary of Descriptive Statistics

Variables	Mean	Median	Maximum	Minimum	Std.Dev	Skewness	Kurtosis	JarqueBera Prob.
ECRE	-2.3711	-0.4300	9.7900	-19.9600	11.9983	-0.2462	1.4263	0.6006
BASU	15.5888	16.3000	18.4000	12.2000	1.8469	-0.4602	2.5821	0.8257
AGPR	21.5333	21.0000	24.1000	20.0000	1.3647	0.9424	2.5343	0.4933
CAPF	20.4000	15.8000	33.8000	14.9000	6.8898	0.9181	2.4057	0.4974

Source: Eviews Extract (2023)

From the summarised descriptive statistics in table 2, ECRE has a negative mean of 2.3711, max. , min., and Std. Dev. value of 9.7900 , -19.9600 and 11.9983 respectively. BASU has mean, max. , mini. and Std. Dev. value of 15.5888, 18.4000, 12.2000 and 1.8469. More so, AGPR has mean, max. , mini. and Std. Dev. value of 21.5333, 24.1000, 20.0000 and 1.3647. Likewise, CAPF, AGPR has mean, max. , mini. and Std. Dev. value of20.4000, 33.8000, 14.9000, and 6.8898. The values for the skewness shows that ECRE and BASU are negatively skewed but AGPR and CAPF are positively skewed. The value for the kurtosis showed that the variables are platokurtic. The Jarque- Bera Prob. values for all the variables indicated that the data set are normally distributed.

Table 3: Correlation Analysis

	ECRE	BASU	AGPR	CAPF
ECRE	1.000000			
BASU	-0.201293	1.000000		
AGPR	-0.109413	-0.824554	1.000000	0.893217
CAPF	0.150911	-0.897938	0.893217	1.000000

Source: Eviews Extract (2023).

Table 3 showed values of correlation of the variables. BASU and AGPR showed negative correlation with ECRE. While CAPF had a positive correlation with ECRE. The correlation values indicates that there existed weak correlation between the study variable.

Table 4: Heteroskedasticity Test: Breusch-Pagan-Godfrey

F-statistic 0.545840	Prob. F(3,5)	0.6721	
Obs*R-squared	2.220359	Prob. Chi-Square(3)	0.5279
Scaled explained SS	0.289769	Prob. Chi-Square(3)	0.9619

Source: Eviews Extract (2023).

The Prob. Chi-square (3) value of 0.5279 greater than 0.05 indicated that the variables of the study is homoscedastic. Hence the assumption of heteroskedascity of the variables is therefore refuted.

Table 5: Summary of Augumented Dicker-Fuller Unit Root Test

Variables	T-Statistics	Order of Intergration	Probability	Decision
ECRE	-3.284560	1(0)	0.0578	Stationary
BASU	0.591554	1(0)	0.9746	Non-Stationary
AGPR	-0.450937	1(0)	0.8533	Non-Stationary
CAPF	1.951757	1(0)	0.9985	Non-Stationary
		@ First Difference		
ECRE	-3.707583	1(1)	0.0036	Stationary
BASU	-3.953141	1(1)	0.0260	Stationary
AGPR	-3.259319	1(1)	0.0596	Stationary
CAPF	-0.276254	1(1)	0.5497	Non-Stationary

Source: Eviews Extract (2023).

Table 5 showed the values for the summarised Augumented Dicker-Fuller unit root test. In the table only ECRE was stationary at level and at first difference. BASU, AGPRand CAPF were stationary at first difference only CAPF was non stationary but at level and at first difference.

From the summarised regressed result, BASU has a negative coefficient value of 3.1586, t-Statistic of -0.595636 with prob. value of 0.5774. The coefficient depicts an inverse relationship whereas the prob. value confirm that BASU has an insignificant impact on ECRE. Similarly, AGPR, has a negative coefficient value of 11.0959, tStatistic of -1.5795 prob. value of 0.1751. The relationship is converse while the influence is insignificant. Also, CAPF possessed positive relationship with coefficient value of 1.4657 and an insignificant value of 0.4498. The R-square showed that 36% change in ECRE is explained by BASU, AGPR, and CAPF. The remainder of 64% could be accounted for by other factors that influence ECRE not included in the study model.

Table 6: Summary of Regression Results

Dependent Variable: ECRE

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	255.9004	175.9584	1.454324	0.2056
BASU	-3.158628	5.302953	-0.595636	0.5774
AGPR	-11.09591	7.024894	-1.579512	0.1751
CAPF	1.465678	1.788770	0.819377	0.4498
R-squared	0.362973	Adjusted R-squared		-0.019242

Source: Eviews Extract (2023).

Conclusion and Recommendation

From the analysis of the influence of BASU, AGPR, and CAPF on ECRE, the results showed that the regressors had an insignificant effect on the regress and only CAPF had a positive relationship with ECRE. The study recommend that government should facilitate additions to the fixed assets of the economy plus net changes in the level of inventories.

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