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Forecasting cane sugar production under climate change and human-ecotoxicological impact

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Forecasting cane sugar production under climate change and human-ecotoxicological impact

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การพยากรณ์การผลิตน้ำตาลทรายจากอ้อยภายใต้การเปลี่ยนแปลงของสภาพภูมิอากาศและผลกระทบทางพิษวิทยาต่อมนุษย์-ระบบนิเวศ

น.ส.อริสรา เตชะบุญญะ

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การศึกษานี้พยากรณ์ผลผลิตอ้อยและการผลิตน้ำตาลทราย โดยใช้การวิเคราะห์สมการถดถอยพหุคูณแบบเป็นขั้นตอนและแบบจำลองค่าเฉลี่ยเคลื่อนที่แบบบูรณาการอัตโนมัติ และประเมินผลกระทบปลายทางต่อสุขภาพของมนุษย์และระบบนิเวศด้วยโปรแกรมสำเร็จรูป openLCA เวอร์ชัน 1.10.3 ด้วยวิธี ReCiPe 2016 โดยกำหนดหน่วยหน้าที่เป็นการผลิตน้ำตาลทรายดิบ 1 กิโลกรัม น้ำตาลทรายขาว 1 กิโลกรัม และน้ำตาลขาวบริสุทธิ์ 1 กิโลกรัม ของบริษัทน้ำตาลท่ามะกา จำกัด จังหวัดกาญจนบุรี ประเทศไทย ซึ่งพบว่า ความชื้นสัมพัทธ์สถานีอุตุนิยมวิทยาทองผาภูมิ อุณหภูมิสูงสุดของสถานีอุตุนิยมวิทยากาญจนบุรี และดัชนี Oceanic Niño เป็นตัวแปรสำคัญที่มีอิทธิพลต่อปริมาณผลผลิตอ้อย โดยผลการพยากรณ์ผลผลิตอ้อยประจำปีระหว่างปีเพาะปลูก 2563/64 ถึง 2567/68 ผันผวนระหว่าง 1,978,907–2,091,432 ตัน และเมื่อผ่านเข้ากระบวนการผลิตเป็นน้ำตาลทรายจะส่งผลกระทบปลายทางต่อสุขภาพของมนุษย์และระบบนิเวศรวมอยู่ระหว่าง 21.13–22.33 DALY และ 0.056–0.059 Species.yr สำหรับน้ำตาลทรายดิบ 221.56–234.15 DALY และ 0.583–0.617 Species.yr สำหรับน้ำตาลทรายขาว และ 300.32–317.40 DALY และ 0.791–0.836 Species.yr สำหรับน้ำตาลทรายขาวบริสุทธิ์ ตามลำดับ ซึ่งประเภทผลกระทบต่อสุขภาพของมนุษย์สูงสุด 3 อันดับแรกเกี่ยวข้องกับ การเกิดฝุ่นละอองขนาดเล็ก การเกิดภาวะโลกร้อน และความเป็นพิษของสารก่อมะเร็ง และประเภทผลกระทบต่อระบบนิเวศสูงสุด 3 อันดับแรกเกี่ยวข้องกับ ภาวะความเป็นกรด ภาวะโลกร้อน และการเกิดโอโซน การศึกษานี้ให้ข้อมูลฐานที่เป็นประโยชน์ต่อหน่วยงานที่เกี่ยวข้อง เพื่อปรับปรุงและพัฒนาประสิทธิภาพและแผนในการผลิตให้ส่งผลกระทบต่อมนุษย์และระบบนิเวศให้น้อยที่สุด

สาขาวิชา	พิษวิทยาอุตสาหกรรมและการประเมินความเสี่ยง	ลายมือชื่อนิสิต ....
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Arisara Tachabunya : Forecasting cane sugar production under climate change and human-ecotoxicological impact . Advisor: Assoc. Prof. PASICHA CHAIKAEW, Ph.D. Co-advisor: CHIDSANUPHONG CHART-ASA, Ph.D.

This study forecasted sugar cane yield and cane sugar production using stepwise multiple linear regression (MLR) and autoregressive integrated moving average (ARIMA). Then, impacts on human health and ecosystems at the endpoint level were evaluated using openLCA software version 1.10.3 and the ReCiPe 2016 method. The functional units were the production of 1 kg raw sugar, 1 kg granulated sugar, and 1 kg refined sugar at Tamaka Sugar Industry Co., Ltd., Kanchanaburi province, Thailand. The result revealed that relative humidity at the Thong Pha Phum meteorological station, maximum temperature at the Kanchanaburi meteorological station, and oceanic Niño Index (ONI) were significant variables influencing sugarcane yield. The forecasting models indicated that annual sugarcane yields during crop years 2020/21 to 2024/25 fluctuated from 1,978,907 to 2,091,432 tons. When these sugar cane yields were processed to produce raw sugar, granulated sugar, and refined sugar, at the endpoint level, the harms to human health were estimated at 21.13–22.33 DALY, 221.56–234.15 DALY, and 300.32–317.40 DALY, respectively. The damages to ecosystems were approximated at 0.056–0.059 Species.yr, 0.583–0.617 Species.yr, and 0.791–0.836 Species.yr respectively. The outstanding contributions to human health impacts were fine particulate matter formation, global warming, and carcinogenic toxicity, whereas the prominent contributions to ecological impacts were acidification, global warming, and ozone formation. These findings offer valuable insights to relevant agencies, enabling them to enhance production efficiency and develop strategies to minimize the impact on both human health and ecosystems.

Field of Study:	Industrial Toxicology and Risk Assessment	Student's Signature ....
Academic Year:	2022	Advisor's Signature ....
		Co-advisor's Signature ....

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Arisara Tachabunya

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CHAPTER 1

INTRODUCTION

1.1 Background

For over a decade, the Thai government has encouraged farmers to switch from rice farming to sugarcane plantations. Sugarcane plantations expanded from 9.5 million rais in 2010 to 12 million rais in 2019 and provided up to a three-fold increase in farmers (ASEANaccess, 2020). Sugarcane yield relates with cropland expansion, yet there are other environmental, technology, and marketing factors imposing as key drivers in limiting the agricultural production. Climate variability can directly affect sugarcane yield through temperature, precipitation, and extreme climate condition, and El Niño-Southern Oscillation (ENSO) event (Linnenluecke et al., 2020; Pipitpukdee et al., 2020) , From the national cane sugar production statistics, the average yield during the past 12 years was 10.49 tons/rai nationwide and 10.63 tons/rai in the central region of Thailand. Years with extreme weather experienced lower or higher cane output per unit area that inevitably affected sugar production. The average cane sugar yields in central region reached 12.23 and 12.44 tons/rai in crop years 2010/11 and 2011/12 due to high amount of rainfall, while the crop production dropped to 9.13 and 9.51 tons/rai in years 2015/16 and 2016/17 due to a long dry period. The latest crop year, 2019/20, Thailand hit the bottom of sugarcane yield to 7.03 tons/rai nationwide and 6.43 tons/rai within central part of Thailand (Office of The Cane and Sugar Board (Office of The Cane and Sugar Board, 2020a), which has been impacted by droughts and the COVID-19 pandemic. The sugar production is anticipated to decrease by 10.2% in 2020/2021, due to the prolonged damage from the previous year. However, it is estimated to rise 10% annually in 2021/22 and 2022/23 (Sowcharoensuk, 2021).

Sugarcane has become one of Thailand's most significant cash crops (Bourgois, 2017) as it has played an increasing role as a major source for sugar

production and bioenergy, such as ethanol (Formann et al., 2020). Variations in the productivity and efficiency of sugarcane production are linked to climatic factors and often cope with socioeconomic and policy dimensions (Linnenluecke et al., 2020; Pipitpukdee et al., 2020). Extensive droughts and excessive rainfall in the central and southern regions of Thailand generate direct stress on sugarcane yields (ASEANaccess, 2020), whereas a recent study indicated that factors such as farm size, crop conversion expertise, sugarcane pricing, household assets, and sugarcane price guarantees had a significant influence on farmers' decisions about sugarcane production. Despite its economic benefits, the main impacts of sugarcane production across the literature include sugarcane and food crops are under growing competition in limited areas, a harmful impact on biodiversity, negative environmental externalities, stress on water resources, and farmers' health and well-being (El Chami et al., 2020). Forecasts of sugarcane yield under changing climate and market-driven mechanisms are of great significance in this sector. Knowing the estimated sugarcane yield forecasts not only helps policymakers make decisions on price fixation, distribution, storage, and marketing (Priya et al., 2023) but also helps predict environmental impacts generated by farming practices and emissions from the cane sugar production process. Various statistical methods have been used to detect the response of sugarcane yield to climatic variables, for example, multiple linear regression (MLR), principal component analysis, Markov chain analysis, agro-meteorological models, and other simulation models. Stepwise regression has been recommended for use in the significant variables selection stage (Suresh & Krishna Priya, 2009).

Even though there has been a fluctuation in sugar production throughout these years, the cane and sugar industry are indispensable for direct consumption and food/beverage factories. Most importantly, it is essential to the country's economic development. The products from sugar mill factories comprise raw sugar, brown sugar, soft brown sugar, white sugar, refined sugar, icing sugar, caster sugar,

crystalline sugar, honey and syrup (Kaeonu & Phonrak, 2017). From sugarcane cultivation to the production of sugar, there is an impact through the loss of natural habitats, the extensive use of agrochemicals, the discharge and runoff of polluted wastewater, and air pollution. Effluents from sugar mills and processing byproducts have been shown to suffocate freshwater biodiversity, particularly in tropical rivers that are already low in oxygen. (World Wide Fund For Nature (World wildlife fund, 2021). Quantifying impacts on human and ecosystems caused by sugar production is certainly not easy, but possible. The life cycle assessment (LCA) method has been used to assess the environmental impacts of cane sugar production across its life cycle (Chandra et al., 2018; Contreras et al., 2009; Renouf, 2007). It is noted that the LCA in the same industry can provide different results based on the scope, purpose, inventory analysis, and impact analysis (Astuti et al., 2017).

The forecast of sugarcane yield using climatic variables has been done in many studies based on different areas and aspects. The LCA studies in sugarcane industry have also been reported for several years. Despite the importance of these studies on sustainability, the connection of them is disconnected. Our mainstream research is to link the temporal dynamic of cane sugar production and the human-ecotoxicological impacts. Cane sugar production in response to climate change variability and some marketing factors from the past 12 years will be explored and will be used for cane yield and sugar production projection. The amount of sugarcane used in the processing line will reveal to what magnitude the impacts have been affected to human health and natural resources, and how much would it present in the future. For a specific cane sugar mill, this research can be beneficial to future operation plan, achieve efficiency in the production, and at the same time, mitigation plan can be discussed to minimize impacts for both human and the environment.

1.2 Objectives

1.2.1. Forecast the sugarcane yield and cane sugar production for a specific sugar mill factory from 2020/21 to 2024/25.

1.2.2. Determine the temporal toxicological impacts to human health and ecosystem caused by a cane sugar production from 2020/21 to 2024/25.

1.3 Scope of the study

1.3.1 The projected cane sugar production and human-ecotoxicological impacts will focus on a specific sugar mill factory "Tamaka Sugar Industry Co., Ltd." in Kanchanaburi Province.

1.3.2 Study timeframe is from 2008/09 to 2024/25.

1.3.3 The LCA study is a gate-to-gate system boundary.

CHAPTER 2
THEORETICAL BACKGROUNDS

2.1 Cane and sugar industry

Sugarcane is grown in 47 provinces of Thailand, accounting for around 8% of all agricultural area. Production is divided into 93% of the plantation for sugar mill and 7% of the plantation for seedlings for field planting, and the planting area is in accordance with the OCSB Notification. Sugarcane cultivation has been expanding almost every year since the 2008/09 - 2018/19 production year. For sugarcane cultivation area in central region increased by 100-200K rais per year and sugarcane cultivation area in Kanchanaburi Province continued to increase. Each year, sugarcane yield 70-130 million tons by the central region sugarcane yield 20-35 million tons and Kanchanaburi Province sugarcane yield is 5-8 million tons and average sugarcane yield crop year 2019/20 of the nation average sugarcane yield is 7.03 tons/rai. Central region average sugarcane yield is 6.43 tons/rai and Kanchanaburi Province average sugarcane yield is 7.13 tons/rai (Office of The Cane and Sugar Board, 2020b). Thailand now has 57 sugar plants spread over four regions: the northern, central, eastern, and northeastern regions. Total sugar is predicted to reach 10.5-11.5 million tons per year between 2018 and 2020, forcing millers to expand exports, which are expected to average 7.5-8.5 million tons per year between 2018 and 2020 (Sowcharoensuk, 2018).

2.2 Climate change in Thailand and the effect on sugarcane productivity

Thailand is located in the Southeast Asia region, which is near the center of variability of the global climate system. The phenomenon of ENSO and tropical monsoon caused by the interaction between the ocean atmosphere and land in the equatorial region between the Indian Ocean and the Pacific Ocean occurs around this area. This is an important component of the global climate system that tends to intensify and increase the frequency of occurrence with proportion to the rise of greenhouse gases and global temperature (Wikanda, 2021). The Earth's climate

system has produced anomalous impacts from climate change in Thailand over the past 40 years as can be seen from the country seeking to face more severe drought and flooding. The country's average temperature has been rising, in particular, Bangkok, the capital city encounters the highest temperature rise impacted by climate change. According to the Climate Change Management and Coordination Division (Climate change management and coordination division, 2016), the number of tropical cyclones entering Thailand will decrease, but the disaster will increase. Drought is another problem posed by climate change. Drought causes water shortages for consumption, industrial production, and agricultural irrigation. In consequently, this problem leads to other bigger issues such as a shortage of food sources, public health, and sanitation problems (Reanrooclimatechange, 2020).

Crop productivity is sensitive and vulnerable to climate change, especially sugarcane cultivation (Intergovernmental Panel on Climate Change (IPCC, 1990). Since sugarcane is C4 plant, temperature, humidity, and precipitation all play roles in sucrose synthesis and plant growth. (Srivastava & Rai, 2012) found that rainfall during monsoon and relative humidity resulted in flowering in certain varieties of sugarcane. Low temperature and high humidity supported juice acidity in sugarcane to be higher. A better comprehension of the effects of weather on sugarcane growth would allow the sugar industry to increase sugar recovery (Pathak et al., 2019). Sugarcane is affected by climate change over the long term as well as local weather and seasonal variations. Climate affects the growth and development of plants, perhaps causing agricultural damage. It also has a negative effect on microorganisms, either directly or indirectly(Srivastava & Rai, 2012). During El Nio years, the sugarcane is severely impacted, which may result from a warmer (World Bank, 2004). Sugarcane production is anticipated to decrease in an El Niño year and increase in a La Niña year. In the southwest of the northeast region, sugarcane productivity in La Nia years is thought to be 6% greater than in El Niño years(World Bank, 2004).

2.3 Forecasting sugarcane yield

The accurate forecasting and projection of sugarcane would assist the government in determining decisions about future pricing, input provision, exports, and imports.(Hussain, 2023). Several significant studies on sugarcane modeling have previously been conducted, as follows

SANJEEV et al. (2015) applied ARIMA models to forecast sugarcane yield in three districts of Haryana. The models were validated using data from subsequent years and found to be effective in providing short-term forecast estimates. According to the study, using ARIMA models can help developing an efficient crop forecasting infrastructure for better information systems concerning food availability, export-import policies, purchasing, and price fixing.

Mwanga et al. (2017) forecasted quarterly sugarcane yields in Kenya based on past data. The Seasonal ARIMA (2,1,2) (2,0,3) 4 model was the suited model for the data from 1973-2014. According to the study, seasonal ARIMA models were beneficial for modeling time series with seasonal trends and could be utilized in any industry.

Pagani et al. (2017) presented a sugarcane forecasting system based on agro-climatic data, and the Canegro model has been tested in the state of São Paulo, Brazil. The system's ability to record inter-annual yield fluctuations was improved by the addition of Canegro model outputs, especially during the sugarcane cycle's boom growth phase.

Mehmood et al. (2019) presented forecast the production of the sugarcane crop in Pakistan for the years 2018–2030 using Box-Jenkin's methodology. The study proposes a suitable ARIMA (2, 1, 1) model to forecast the production of sugarcane crops. The forecast values obtained from the model show a significant increase in sugarcane production from 75394 tons to 86792 tons.

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Kaeonu et al. (2017) found that the ANN technique was effective in predicting sugar cane yield in the region. The simple ANN model, MLP 8-3-1, was the best-performing model for predicting sugar cane yield in the region. The government can to plan and control the production of sugarcane.

Harlianingtyas et al. (2020) predicted the production of sugarcane for the next five years for the Asembagus sugar factory using ARIMA model. The Holt-Winters exponential smoothing method and the forecasting results were compared to determine which method was suitable for predicting sugarcane production. The ARIMA (1,1,1) model was the most appropriate method for predicting sugarcane production for the Asembagus sugar factory for the 2019 to 2023.

Verma et al. (2021) developed the statistical models to forecast sugarcane yield during autumn and spring planting in Muzaffarnagar District of Uttar Pradesh using weather data from 1981 to 2015.T-tests, regression coefficients, and forecast model summaries were used to evaluate the models. The models show a strong correlation between the predicted and observed values of yield and found that weighted weather indices are significantly more effective than unweighted weather indices.

Paswan et al. (2022) studied the stability and long-term viability of sugarcane production in Bihar, India. The ARIMA model and the artificial neural network methodology were both employed in the study to forecast sugarcane production from 2020 to 2025. The best model for forecasting was determined to be ARIMA (1, 1, 0), which predicted a significant increase in sugarcane production from 126.03 lakh to 131.67 lakh tons. Other studies on forecasting sugarcane yield are listed in Table 1.

Table 1 Other studies on forecasting sugarcane yield

Author name/country	Article	Function	Parameter	Period
Priya et al. (2009)/ Coimbatore	A study on pre-harvest forecast of sugarcane yield using climatic variables	Linear regression	Aaverage daily maximum and minimum temperature, relative humidity in the morning and evening, and total fortnightly rainfall	1981 to 2004
Kumar et al. (2016)/ India	Crop yield forecasting of paddy and sugarcane through modified Hendrick and Scholl technique for south Gujarat	Linear regression	Maximum temperature, minimum temperature, morning relative humidity, afternoon relative humidity, bright sunshine hours, and rainfall	1985 to 2011
Saithanu et al. (2017)/ Thailand	Estimation of Sugar Cane Yield in the Northeast of Thailand with MLR Model	Linear regression	Cultivated area, sugar cane quantity sent to factories, average price of sugar cane, maximum temperature, minimum temperature, number of rainy days, maximum rainfall and total rainfall	2002 to 2013
Moonsri et al. (2019) / Thailand	The effect of climate change on sugarcane productivity in Northeastern Thailand	Straight-line regression	20-year ENSO phenomenon Index, rainfall amount, relative humidity, rate water evaporation and temperature	1996 to 2015

Table 1 (Cont.)

Author name/country	Article	Function	Parameter	Period
Pochanarta et al. (2019)/ Thailand	The effect of climate change on sugarcane productivity in northeastern Thailand	Linear regression	Rainfall, relative humidity, evaporation rate, temperature, and wind speed, and sugarcane production and Oceanic Nino Index	1996 to 2015
Pandey et al. (2020)/ Thailand	Effect of input factors and price policy in Nepalese sugarcane	Linear regression	Human labor, quantity of fertilizers, quantity of seed, machine hour, previous price of sugarcane, Irrigation frequency, weeding frequency, minimum procurement, direct cash subsidy, delay in cash payment and number of farms growing sugarcane	-
Pipitpukdee et al. (2020) / Thailand	Climate change impacts on sugarcane production in Thailand	Spatial regression	Average temperature, maximum temperature, and mean precipitation	1989 to 2016

Table 1 (Cont.)

Author name/country	Article	Function	Parameter	Period
Harlianingtyas et al. (2021) / Indonesia	Modeling of factors affecting the productivity of sugarcane in Jember Regency	Linear regression	Rainfall, number of rainy days, planting area, sugarcane production, humidity, and temperature	1999 to 2020

2.4 Raw sugar production process

Raw sugar obtained from the juice of sugar cane and is characterized by its light brown color and coarse texture. There are impurities remaining, and the quality is low. For raw sugar production using sugarcane as the main raw material in production divided into 5 steps as follows (Spencer, 2020).

2.4.1. Juice Extraction

Sugarcane is crushed in large roller mills to produce sugarcane juice, which is then used to make sugar and ethanol. Bagasse is a byproduct of this process that is used to produce electricity.

2.4.2. Juice Purification

After that, the sugarcane juice is sent for clarification by coagulation and sedimentation, which are used to remove precipitates from the sugarcane juice.

2.4.3. Evaporation

Sugarcane juice goes through a boiling process to remove moisture. Around 75% of the water is removed during the boiling and evaporation processes, resulting in a thicker syrup concentrate.

2.4.4. Crystallization

The syrup is transferred to large vessels or pans, where it is cooled. This cooling process encourages the formation of sugar crystals. During this phase, seed crystals may be added to initiate the crystallization process.

2.4.5. Centrifugation

Once crystallization is complete, the mixture of sugar crystals and molasses is separated in centrifuges. Centrifugal force separates the sugar crystals from the molasses, resulting in raw sugar.

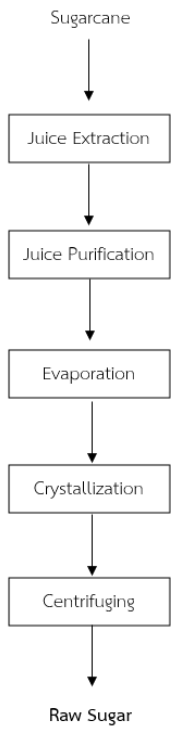


Figure 1 Raw sugar production process

2.5 Granulated sugar and refined sugar production process

Both granulated sugar and refined sugar are made from raw sugar that has been purified to eliminate impurities and turn it white and clear. For granulated sugar and refined production process using raw sugar as the main raw material in production divided into 5 steps as follows (Rodgers, 2020).

2.5.1. Remelting

Raw sugar is mixed with water to create a sugar syrup. The heat from the water helps dissolve the sugar crystals and forms a concentrated sugar solution.

2.5.2. Carbonatation Process

More calcium hydroxide is added to the liquid sugar mixture and heated to the boiling point in carbonators. The gas combines with the lime to generate fine, crystalline calcium carbonate particles that occlude or block organic contaminants.

Pressure filters and desugarising remove the suspended calcium carbonate as well as other contaminants. At this point, the byproduct of press cake is created.

2.5.3. Crystallization

The syrup is transferred to large vessels or pans, where it is cooled. This cooling process encourages the formation of sugar crystals. During this phase, seed crystals may be added to initiate the crystallization process.

2.5.4. Centrifugation

Once crystallization is complete, the mixture of sugar crystals and molasses is separated in centrifuges. Centrifugal force separates the sugar crystals from the molasses, resulting in granulated and refined sugar.

2.5.5. Drying

Moist sugar is fed into a granulator. In a rotating cylindrical, the sugars are tumbled continuously through the flow of hot and cold air. Dry sugars are weighed and sorted by size using vibrating screens before being put in storage holds.

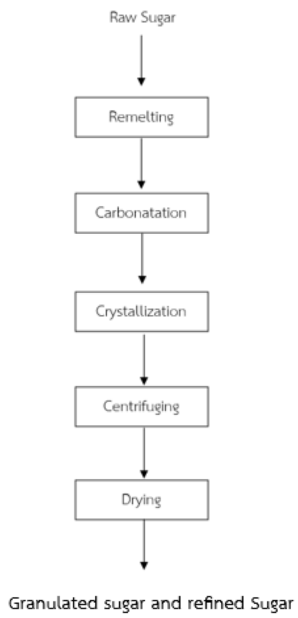


Figure 2 Granulated sugar and refined Sugar production process

2.6 Environmental Impacts of cane sugar production

The sugar industry is a huge sector that has a substantial impact on the environment worldwide from growing, harvesting, refining, and distribution. Around 110 nations are now producing sugar from either cane or beets, with sugarcane accounting for roughly 80% of world sugar output on average. The top 10 producing nations, including India, Brazil, Thailand, China, the US, Mexico, Russia, Pakistan, France, and Australia, produced about 70% of the world's output from October to September 2019; more than 170 million tons were consumed yearly (International Sugar Organization (ISO, 2021). Sugar mills generate wastewater, pollutants, and solid waste that have an environmental impact. Massive amounts of plant matter and sludge rinsed from mills decompose in freshwater bodies, consuming all available oxygen and causing catastrophic fish deaths. Furthermore, while processing, mills emit flue gases, soot, ash, ammonia, and other pollutants (World wildlife fund, 2015). Effluents are relatively high organic matter as compared to other sources, and the decomposition of this materials reduces the oxygen levels in the water, influencing natural biochemical processes and the animals that live those freshwater systems. Heavy metals, oil, grease, and cleaning chemicals are potential contaminants in these effluents (World wildlife fund, 2004) . Several studies on environmental Impacts of sugar production process are described as follows:

Yadav et al. (2015) collected water samples from three different locations near the sugar factory were collected on a monthly basis for a period of 12 months. These samples underwent thorough analysis to determine various physicochemical parameters, including pH, electrical conductivity, dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), alkalinity, water hardness, chloride content, sulphate levels, phosphate concentration, and total dissolved solids (TDS). The effluent discharged from the sugar mill was found to contribute

between 50% to 70% of the overall pollution load, leading to significant impacts on the environment and ecosystem in the vicinity of the sugar industry.

Crom et al. (2019) comparative life cycle assessment to assess the environmental impact of Suiker Unie's beet sugar production in comparison to cane sugar production in Brazil and India. The evaluation encompassed the entire lifecycle of these products, from their initial production to regional storage on the Dutch market. According to the study, the production of beet sugar at Suiker Unie had less of an effect on climate change, fine particulate matter, land usage, and water use. Meza-Palacios et al. (2019) analyze the imapact caused by cane sugar production in Mexico using the life cycle assessment. According to the findings, the stages of sugarcane growing and harvesting had the worst effects on the environment (52%), electricity cogeneration (25.7%), sugarcane transportation (12.1%), and sugar processing (10.2%). Human health has the biggest percentage of impacts (53%), followed by climate change (21%), ecosystem quality (16%), and resources (10%).

Shukla et al. (2019) assessment of sugar production from sugarcane in the central India region. The functional unit is 1 ton of raw sugar. Data were obtained from field surveys, databases, and Kareli sugar mill. The study analyzed the environmental impacts of sugarcane cultivation, transportation, crushing, and sugar crystal conversion. The greenhouse gas emissions from the cultivation process were found to be the most significant contributor to environmental impacts.

Hiloidhari et al. (2021) Analyze the energy and environmental performance of sugar production and bagasse electricity cogeneration in Maharashtra, India, under different scenarios. The study considers four sugarcane seasons and four cogeneration boilers. The functional units are the production of 1 ton of sugar and 1 MWh of surplus electricity. The ReCiPe 2016 midpoint (H) technique was utilized to

estimate effect. The findings suggest that scenarios producing both sugar and surplus electricity have a lower environmental impact than scenarios producing only sugar.

Rahim et al. (2021) collection of 120 samples of effluent. The collected samples were analyzed using standard methods for physicochemical, cations, and anions parameters. The research also performed a field survey of 200 homes in fourteen villages to obtain public opinion on the environmental impact of sugar industry effluents. The result found discharge of untreated industrial effluents from sugar mills has severe negative impacts on the environment, including water and soil contamination. The effluents contained high levels of pollutants, including toxic metal ions such as Fe^{3+}, Mn^{2+}, and Pb^{2+}. Higher levels of BOD_5 (Biochemical Oxygen Demand) observed in the effluents were indicative of a decline in dissolved oxygen (DO) levels. As a result, the reduced DO levels adversely impacted the survival of fish and other aquatic species in the water bodies.

Namdari et al. (2022) analyzed the environmental impact of sugar production from beets using the life cycle assessment method in the Iranian Hamadan Province. The major contributors to the environmental impacts were electricity consumption in sugar beet farming and the production and use of natural gas in the sugar mill. The major contributors to the environmental impacts were electricity consumption in sugar beet farming and the production and use of natural gas in the sugar factory.

2.7 Life Cycle Assessment (LCA)

Life cycle assessment is a method for assess the environmental impacts of all the stages of a product's life, from cradle to grave. Basically, life cycle assessment methodology is conducted in four steps (Muralikrishna & Manickam, 2017).

2.7.1 Steps of LCA

2.7.1.1 Goal and scope

To determine the goals and product function, functional unit, system boundary, and product system for specifying the scope of the assessment.

2.7.1.2 Inventory analysis

The systematic collection of data related to the inputs and outputs of a product, process, or activity throughout its entire life cycle. The inventory analysis is to create an inventory of all material and energy flows associated with the system being studied.

2.7.1.3 Life Cycle Impact Assessment (LCIA)

After the completion of the inventory analysis. LCIA aims to evaluate the potential environmental impacts associated with the inputs and outputs identified in the inventory analysis.

2.7.1.4. Interpretation

Analyzing the results and findings obtained from the assessment to understand the environmental impacts of a product, process, or activity throughout its entire life cycle.

2.8 Assessing the toxicological impacts to human health and ecosystem by ReCiPe2016

ReCiPe2016 has 18 midpoints and 3 endpoints. The three categories of endpoints are human health, ecosystem quality, and resource scarcity. Endpoint characterization factors were created from midpoint characterization factors with a consistent midpoint to endpoint factor in every impact category. The unit for human health damage, DALY (disability-adjusted life years), represents the years that are lost or that a person is disabled due to a disease or accident. The unit for ecosystems is species. year, represents quality as local relative species loss in terrestrial, freshwater, and marine ecosystems. The unit for resource scarcity is dollars ($), which represents the extra costs involved in future mineral and fossil resource extraction (National Institute for Public Health and the Environment (RIVM, 2018)). An overview of the impact categories by the ReCiPe2016 method shown in Figure 3.

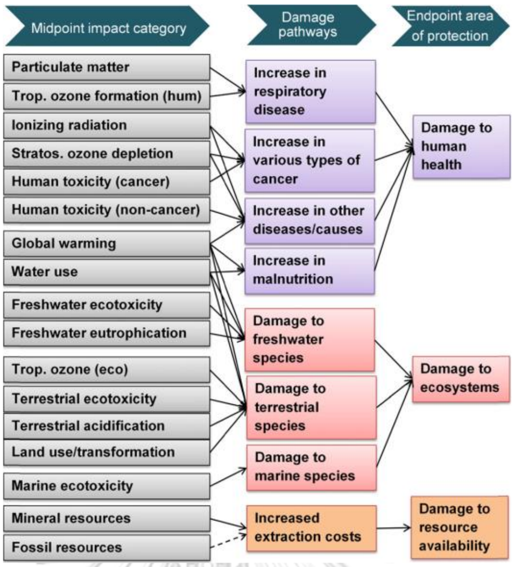


Figure 3 An overview of the impact categories by the ReCiPe2016 method (RIVM, 2018)

CHAPTER 3
METHODOLOGY

In this research, the data were collected from monthly data on plantation, climatic variables, and sugarcane price based on crop year between 2010/11 and 2019/20 for forecasting sugarcane yield in Kanchanaburi Province, Thailand. The life cycle impact assessment (LCIA) was performed using openLCA software version 1.10.3 and AGRIBALYSE version 3.0.1 and assessed using the ReCiPe 2016 endpoint method to determine the toxicological impacts to human health and ecosystems of the cane sugar production at Tamaka Sugar Industry Co., Ltd. in Kanchanaburi Province.

3.1 Data collection

From the literature review on forecasting sugarcane yield, the factors related to sugarcane yield were as follows: plantation area, average sugarcane price, number of rain days, average rainfall, maximum rainfall, percentage relative humidity, maximum temperature, minimum temperature, average temperature, and Oceanic Nio Index. Forecasting sugarcane yield, data were collected on the monthly basis during crop year 2010/11 to 2019/20. The sugarcane yield figures and plantation area were collected from the Office of the Cane and Sugar Board (Office of The Cane and Sugar Board, 2020a). The average sugarcane price was obtained from the Office of Agricultural Economics (Office of Agricultural Economics, 2019). The monthly data on weather parameters, such as maximum temperature, minimum temperature, average temperature, relative humidity, average rainfall, number of rain days, and maximum rainfall, of two meteorological stations in Kanchanaburi Province, namely Kanchanaburi and Thong Pha Phum meteorological stations, were gathered by the Thai Meteorological Department (Thai meteorological department, 2019). ONI data were collected from the National Oceanic and Atmospheric Administration (Pipitpukdee et al., 2020).

To determine the toxicological impacts on human health and ecosystems caused by cane sugar production, collected data for raw sugar, granulated sugar, and refined sugar production were obtained from Tamaka Sugar Industry Co., Ltd. Recognizing the environmental issues arising from cane sugar production, Tamaka Sugar Industry Co., Ltd. already has a carbon footprint policy, assessing the impact on human health and ecosystems in this study will be an additional part of a comprehensive impact assessment.

3.2 Data analysis

3.2.1 Forecasting sugarcane yield in Kanchanaburi province

The data analysis was executed using R statistical software. The analysis was divided into three parts. In the first part, the significant explanatory factors impacting sugarcane yield in Kanchanaburi Province were evaluated using a stepwise MLR model, as shown in eq.1:

$$Y_t = \beta_0 + \beta_1 Climate_t + \beta_2 Market_t + \varepsilon \qquad \text{eq.1}$$

where Y_t is the sugarcane yield in Kanchanaburi Province at time t; $\beta_0, \beta_1,$ and β_2 are the regression coefficients; and $Climate_t$, $Market_t$ represents the vector of explanatory parameters. The following 17 explanatory variables were evaluated: plantation area (PA), average sugarcane price (Price), number rain days at Kanchanaburi station (RDk), number rain days at Thong Pha Phum station (RDt), maximum rainfall at Kanchanaburi station (RFmaxk), maximum rainfall at Thong Pha Phum station (RFmaxt), average relative rainfall at Kanchanaburi station (RFavgk), average rainfall at Thong Pha Phum station (RFavgt), percentage relative humidity at Kanchanaburi station (RHk), percentage relative humidity at Thong Pha Phum station (RHt), maximum temperature at Kanchanaburi station (Tmaxk), maximum temperature at Thong Pha Phum station (Tmaxt), minimum temperature at Kanchanaburi station (Tmink), minimum temperature at

Thong Pha Phum station (Tmint), average temperature at Kanchanaburi station (Tavgk), average temperature at Thong Pha Phum station (Tavgt), and ONI. ε is the vector of residuals.

Future values of significant regressors obtained from the previous step were predicted. The Box–Jenkins technique by autoregressive integrated moving average (ARIMA) (Box George et al., 1976) was used to determine the best fit of a time-series model to past values of a time series. The Box–Jenkins model starts with the identification of the ARIMA model. In developing the ARIMA model, a stationary test was performed. After stationarity was addressed, the order of the autoregressive and moving average terms was evaluated. The order of the autoregressive terms was represented by p. The moving average was represented by q, and the differencing order was represented by d. Diagnostic checking was performed related to R_2, Akaike information criterion, and residual checking. Data from 2010 to 2018 were used for model calibration, while 2019 data were used for model validation.

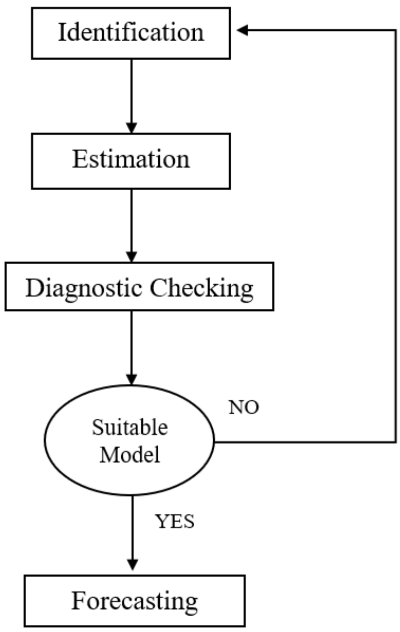


Figure 4 Forecasting procedure using the Box–Jenkins approach

The last step of the data analysis was forecasting sugarcane yield for the crop years between 2020/21 and 2024/25. Predicted results of significant explanatory parameters from the seasonal ARIMA model were inputted into a linear regression model.

3.2.2 Forecasting cane sugar production in Tamaka Sugar Industry Co., Ltd.

The relationship between sugarcane yield in Kanchanaburi Province and the sugarcane amount received at Tamaka Sugar Industry Co., Ltd. will be detected by a simple ratio. According to the historical statistics, a strong correlation is detected between these two parameters at 0.79 degree. From the total sugarcane yield harvested in Kanchanaburi Province, 21% is contributed to Tamaka Sugar Industry Co., Ltd., as shown in eq.2:

$$S_t = 0.21 \times Y_t \qquad \text{eq.2}$$

where S_t is the sugarcane Tamaka Sugar Industry Co., Ltd. received to process in the sugar production. Nearly 100% of sugarcane received at the factory is produced to cane sugar product.

3.3 Toxicological impacts to human health and ecosystem caused by a cane sugar production

The openLCA software version 1.10.3 was used to do the LCIA, and the ReCiPe 2016 approach was employed to determine the toxicological effects on human health and ecosystems of the cane sugar production at Tamaka Sugar Industry Co., Ltd. in Kanchanaburi Province, Thailand.

3.3.1 Goal and scope

The goal of this study is to assess the toxicological impacts on human health and the ecosystem caused by cane sugar production. The LCA study is a gate-to-gate system boundary. The functional unit is 1 kg of raw, granulated and refined sugar. As shown in Figure 5, the system boundary considers the cane sugar production.

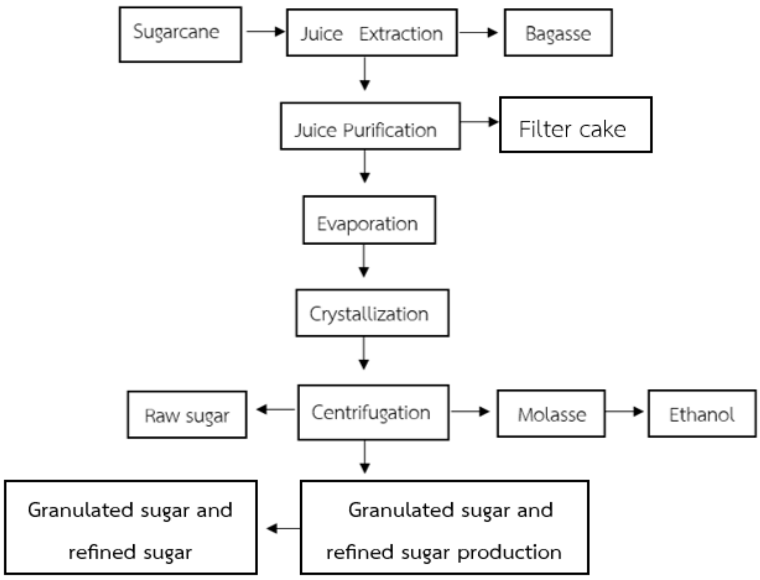


Figure 5 Flow diagram of cane sugar production

3.3.2 Inventory analysis

The inventory of input and output data includes raw materials, energy, water, chemicals, fuel, wastewater, air pollution, and waste from the cane sugar production process. In this study, information is collected from Tamaka Sugar Industry Co., Ltd., Kanchanaburi province, Thailand.

3.3.3 Life Cycle Impact Assessment (LCIA)

The impacts on human health and the environment were analyzed by translating the inventory analysis results into a set of specific impacts on human health and ecosystem categories and indicators. The impact assessment of this study focused on the end point. The ReCiPe2016 LCIA method is used for assessing the impact of human health and ecosystems.

3.3.4 Interpretation

Analyzing the results and findings obtained from the assessment to understand the environmental impacts of a product, process, or activity throughout its entire life cycle.

CHAPTER 4

RESULTS AND DISCUSSION

The results of the study were divided into three main parts: 1) forecasting sugarcane yield and cane sugar production, and 2) assessment toxicological impacts to human health and ecosystem caused by a cane sugar production and 3) forecasting impacts to human health and ecosystem.

4.1 Sugarcane yield forecast in Kanchanaburi province

The forecast results using multiple linear regression and time series method. The models were validated by comparing them with actual values. The validation sets of January 2018 to December 2018 (12 months) and the testing set of January 2019 to December 2019 (12 months) presented by the root mean square error (RMSE), mean absolute error (MAE), mean absolute percentage error (MAPE), and adjusted R^2. An overview of dataset summary, yield forecast model, predicting future values of significant regressors, and forecasting sugarcane yield show in Table2.

Table 2 Summary descriptive statistic of selected variables in Kanchanaburi Province based on crop year between 2010/11 and 2019/20.

Variables	Unit	Max	Min	Mean	Median	SD
Sugarcane yield	tons	3,695,004	11,831	1,977,543	2,145,102	1,184,628
PA	rai	581,719	791,364	719,456	723,828	53,913
Price	baht/ton	1,011.00	575.00	823.20	859.50	119.77
RD_k	days	16	0	2	2.79	3.31
RD_t	days	24	0	3.604	2	4.47

Table 2 (Cont.)

$RFmax_k$	days	240.60	0	26.26	10.30	19.64
$RFmax_t$	days	248.50	0	39.50	12.65	23.47
$RFavg_k$	mm	75.00	57.00	64.67	64.50	43.94
$RFavg_t$	mm	85.00	56.00	69.81	70.50	55.55
RH_k	%	42.70	34.00	38.00	37.80	4.33
RH_t	%	41.20	33.20	37.73	37.95	6.37
$Tmax_k$	℃	42.70	34.00	38.00	37.80	2.50
$Tmax_t$	℃	41.20	33.20	37.73	37.95	2.09
$Tmin_k$	℃	24.50	12.00	18.48	18.45	3.07
$Tmin_t$	℃	23.00	9.10	16.74	16.80	3.21
$Tavg_k$	℃	30	21.80	26.94	26.70	2.15
$Tavg_t$	℃	30.85	22.40	27.64	27.38	2.14
ONI	℃	2.6	−1.6	−0.03	−0.30	0.93

Note: Crop year refers to the period between sugarcane harvest, which runs from December to April. Rai is area unit are equal to 1,600 m^2 or 0.16 hectares. PA is a plantation area; Price is an average sugarcane price; RD_k is the number rain days at Kanchanaburi station; RD_t is the number rain days at Thong Pha Phum station; $RFavg_k$ is average rainfall at Kanchanaburi station; $RFavg_t$ is average rainfall at Thong Pha Phum station; $RFmax_k$ is the maximum rainfall at Kanchanaburi station; $RFmax_t$ is the maximum rainfall at Thong Pha Phum station; RH_k is the percentage relative humidity at Kanchanaburi station; RH_t is the percentage relative humidity at Thong Pha Phum

station; $Tmax_k$ is the maximum temperature at Kanchanaburi station; $Tmax_t$ is maximum temperature at Thong Pha Phum station; $Tmin_k$ is the minimum temperature at Kanchanaburi station; $Tmin_t$ is the minimum temperature at Thong Pha Phum station; $Tavg_k$ is the average temperature at Kanchanaburi station; $Tavg_t$ is the average temperature at Thong Pha Phum station; ONI is the Oceanic Niño Index.

4.1.1 Yield forecast model

Stepwise multiple linear regression analysis presented three significant factors affecting sugarcane yield in Kanchanaburi Province for the overall model (p-value < 0.001). Significant parameters comprised relative humidity at the Thong Pha Phum meteorological station (RH_t), maximum temperature at the Kanchanaburi meteorological station ($Tmax_k$), Oceanic Niño Index (ONI) (Table2). Weather and climatic events have an important role in sugarcane production across the world, particularly in many developed countries. (Zhao & Li, 2015). As shown in Table 1, the regression equation for sugarcane yield forecasting was written following eq.3:

$$Y = 26850854 - 149317\,(RH_t) - 380508\,(T_{max}) - 275115\,(ONI) \quad \text{eq.3}$$

Table 3 Significant factor selected by stepwise regression procedure

Model	Unstandardized Coefficient B	Unstandardized Coefficient Std. Error	t	Sig.
(Constant)	26850854	3981290	6.744	2.71e-08
RH_t	−149317	27503	−5.429	2.31e-06
$Tmax_k$	−380508	66033	−5.762	7.53e-07
ONI	−275115	151397	−1.817	0.076

Note: RH_t = relative humidity at Thong Pha Phum meteorological station, $Tmax_k$ = maximum temperature at Kanchanaburi meteorological station, ONI = Oceanic Niño Index

From eq. 3 negative relationships were found between yield and maximum temperature, relative humidity, ONI. Our findings coincide with those of other studies. High temperatures were the main factor in the reduction of sugarcane productivity due to their adverse effect on the sugarcane growth cycle. Maximum temperature of about 26.8°C was found ideal at germination stage and maximum temperatures in the range of 36 to 40°C affects the active growth stages during germination and reduces yield (Samui et al., 2003). Temperature and relative humidity are the mian factors that influence sugarcane blooming and pollen viability (Abu-Ellail & McCord, 2019). Flowering or intensity is restricted when particular temperature and relative humidity conditions are not met (Fairey et al., 1997). A long period of high temperature leads to drought and causes water stress, evaporation demand, and changes in the plant lifecycle (Hussain et al., 2018). For ONI, the sugarcane yields tend to decrease in the year of El Niño (ONI ≥ 0.5) and increase in the year of La Niña (ONI ≤-0.5)(Moonsri & Pochanart, 2019). Low sugarcane production was also detected in the strong El Niño and La Niña years (Pipitpukdee et al., 2020; Wongkhunkaew et al., 2020)

4.1.2 Predicting future values of significant regressors

The results of the stationarity test of RH_t, $Tmax_k$, and ONI are shown in Table3. After achieving stationarity, the best fitted ARIMA models were selected according to the model selection criteria, such as AIC, BIC, and the Box–Jenkins technique (Table4). The ‘forecast’ package within the R statistical software generated the best ARIMA model for predicting future values of significant factor. The seasonal ARIMA (1,0,0) (2,1,1) model for the RH_t, seasonal ARIMA (2,0,0) (2,1,0) model for the $Tmax_k$, and seasonal ARIMA (2,0,0) (2,1,0) model for ONI were selected based on a low RMSE, MAE, and MAPE and a high R^2. In the Ljung–Box test, the p-value showed values larger than 0.05 for all selected models, which concluded the independency of data values.

Table 4 Test of stationarity

Parameters	Augmented Dickey-Fuller	Lag order	p-value
RH_t	−6.6636	4	0.01
$Tmax_k$	−3.8972	4	0.01
ONI	−7.4565	4	0.02

Note: RH_t = relative humidity at Thong Pha Phum meteorological station, $Tmax_k$ = maximum temperature at Kanchanaburi meteorological station, ONI = Oceanic Niño Index

Table 5 The best fitted seasonal ARIMA models based on dataset 2010-2018 and accuracy indices for predicting future values of relative humidity, maximum temperature, and ONI in 2019

Parameters	Seasonal ARIMA model	Ljung-Box test		Model fit statistic			
		df	p-value	R^2	RMSE	MAE	MAPE
RH_t	(1,0,0) (2,1,1)	1	0.78	0.94	3.88	3.25	0.05
$Tmax_k$	(2,0,0) (2,1,1)	1	0.91	0.91	0.78	0.63	0.02
ONI	(2,0,0) (2,1,0)	1	0.89	0.90	0.30	0.27	0.01

Note: RH_t = relative humidity at Thong Pha Phum meteorological station, $Tmax_k$ = maximum temperature at Kanchanaburi meteorological station, ONI = Oceanic Niño Index

4.1.3 Forecasting sugarcane yield in Kanchanaburi province

The predicted sugarcane yields fluctuated due to the influence of climatic variables and market price. The monthly time series results of RH, $Tmax_k$, and ONI for 2020–2025 were used as explanatory inputs in eq3. Forecasting annual sugarcane yield accounted for by crop year (December of the beginning year to April of the following year) in Kanchanaburi Province are presented in Table5. The forecasted annual sugarcane yields of Kanchanaburi Province were 9,959,199 tons in crop year 2020/21, 9,423,369 tons in 2021/22, 9,844,360 tons in 2022/23, 9,895,804 tons in 2023/24, and 9,772,803 tons in 2024/25.

Table 6 Predicted annual sugarcane yield in Kanchanaburi Province

Crop year	Sugarcane yield in Kanchanaburi province (tons)
2020/21	9,959,199
2021/22	9,423,369
2022/23	9,844,360
2023/24	9,895,804
2024/25	9,772,803

The observed and the monthly total sugarcane yield forecast in Kanchanaburi Province between 2010 and 2025 is presented in Figure 6. The projected sugarcane yields in this study showed fluctuations, with no clear trend. However, (Pipitpukdee et al., 2020) projected a significant decrease in sugarcane yield in Thailand, and Kanchanaburi was ranked number one in the central region during 2046–2055 under climate change scenarios.

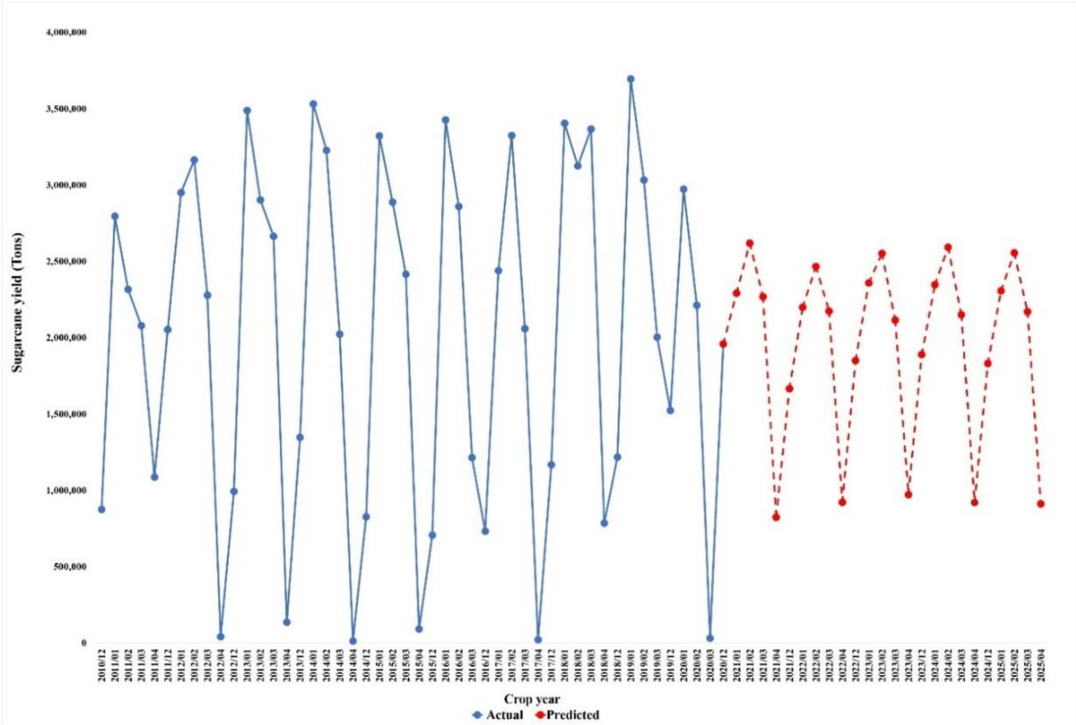


Figure 6 The observed and the monthly total sugarcane yield forecast in Kanchanaburi Province

The solid blue line displays the observed total sugarcane yield during crop year 2010/11 to 2019/20 while the dotted red line shows the sugarcane yield forecast obtained by the seasonal ARIMA model during crop year 2020/21 to 2024/25.

It should be noted that the reason may be that the input parameter data used for forecasting is monthly data for 12 months. But the amount of sugarcane yield displayed quarterly from December to April depends on each production year. Other months will also be the season for sugarcane planting. There may be a discrepancy in the display of sugarcane yield.

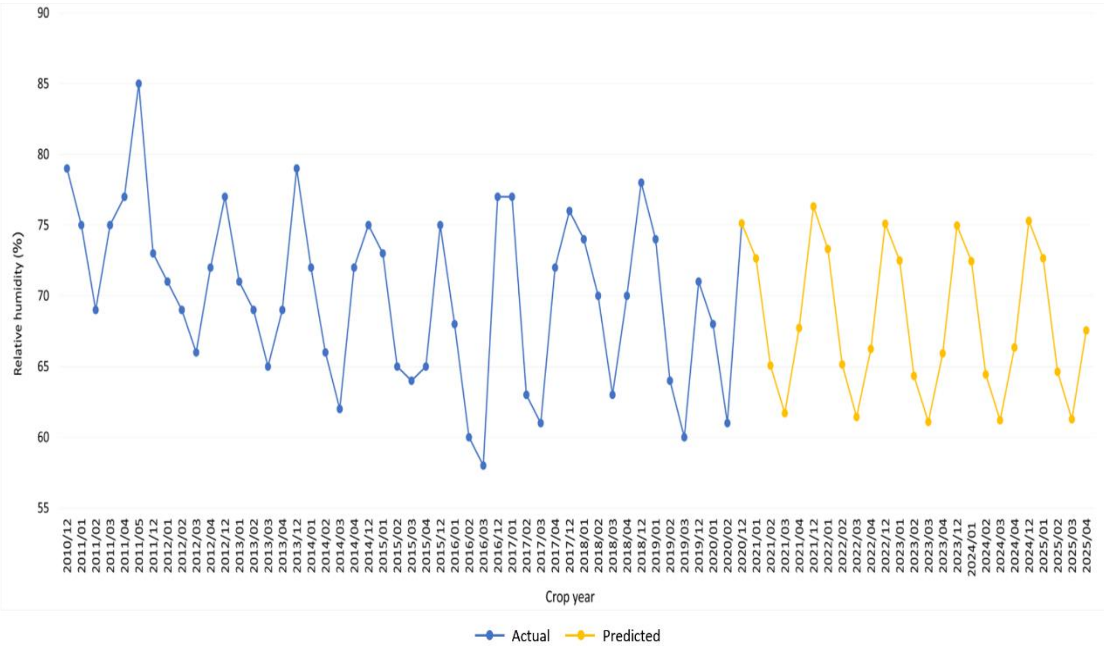


Figure 7 The observed and the monthly relative humidity at Thong Pha Phum meteorological station

The solid blue line displays the observed humidity at Thong Pha Phum meteorological station during crop year 2010/11 to 2019/20 while the yellow line shows the humidity at Thong Pha Phum meteorological station predicted obtained by the ARIMA model during crop year 2020/21 to 2024/25.

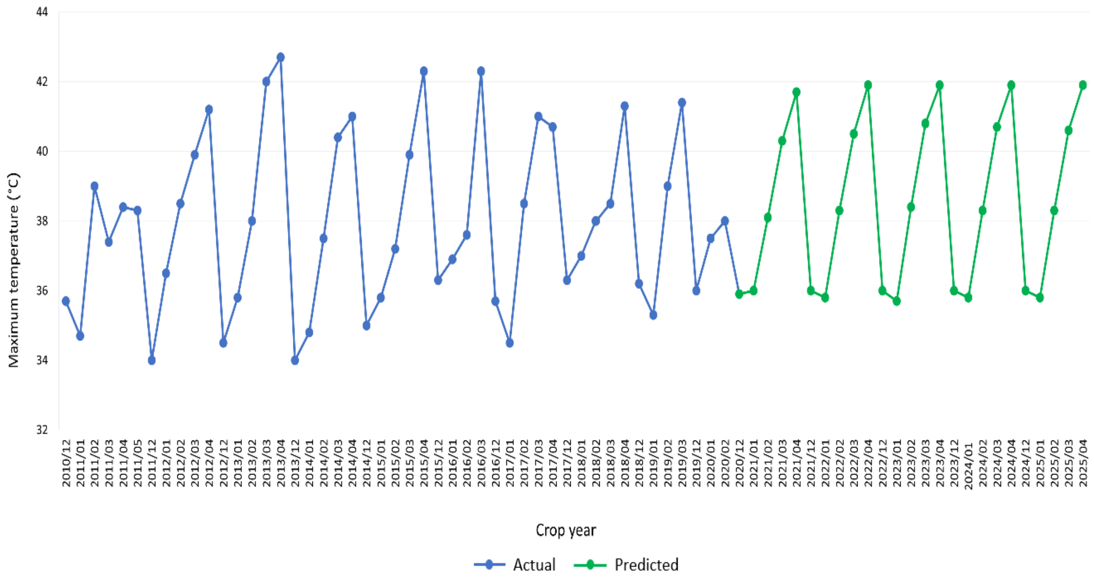


Figure 8 The observed and the maximum temperature at Kanchanaburi meteorological station

The solid blue line displays the observed maximum temperature at Kanchanaburi meteorological station during crop year 2010/11 to 2019/20 while the green line shows the maximum temperature at Kanchanaburi meteorological station predicted obtained the ARIMA model during crop year 2020/21 to 2024/25.

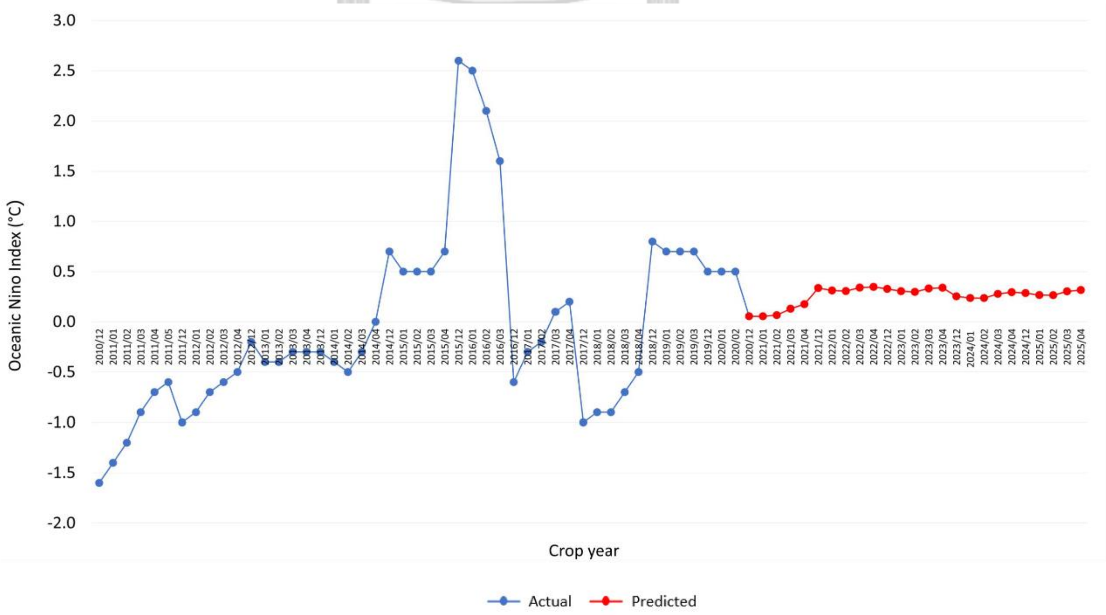


Figure 9 The observed and the monthly Oceanic Niño Index

The solid blue line displays the observed Oceanic Niño Index station during crop year 2010/11 to 2019/20 while the dotted red line shows Oceanic Niño Index predicted obtained the ARIMA model during crop year 2020/21 to 2024/25.

4.1.4 Cane sugar production forecast in Tamaka Sugar Industry Co., Ltd.

The forecasting of cane sugar production in Tamaka Sugar Industry Co., Ltd. begins use sugarcane yield forecast in Kanchanaburi province input into eq.2 to obtain the sugarcane forecast Tamaka Sugar Industry Co., Ltd. received. The Tamaka Sugar Industry Co., Ltd. produces an average of 0.098 tons of sugar per one ton of sugarcane. Therefore, multiply 0.098 tons with the sugarcane forecast that Tamaka Sugar Industry Co., Ltd. receives to obtain the cane sugar production forecast, which is presented in Table7.

Table 7 Cane sugar production forecast in Tamaka Sugar Industry Co., Ltd.

Crop year	Sugarcane yield forecast in Kanchanaburi province (tons)	Sugarcane forecast Tamaka Sugar Industry Co., Ltd. received (tons)	Cane sugar production forecast in Tamaka Sugar Industry Co., Ltd. (tons)
2020/21	9,959,199	2,091,432	204,960
2021/22	9,423,369	1,978,907	193,933
2022/23	9,844,360	2,067,316	202,597
2023/24	9,895,804	2,078,119	203,656
2024/25	9,772,803	2,052,289	201,124

Forecasts sugarcane received of Tamaka Sugar Industry Co., Ltd. were 2,091,432 tons in crop year 2020/21, 1,978,907 tons in 2021/22, 2,067,316tons in 2022/23, 2,078,119 tons in 2023/24, and 2,052,289tons in 2024/25. Cane sugar production forecast in Tamaka Sugar Industry Co., Ltd. were 204,960 tons in crop year

2020/21, 193,933 tons in 2021/22, 202,597 tons in 2022/23, 203,656 tons in 2023/24, and 201,124 tons in 2024/25.

The calibration and validation model exhibited excellent prediction performance. However, when comparing the forecasted values with the actual sugarcane yield and sugarcane received during the crop years 2020/21, 2021/22, and 2022/23, a significant gap was surprisingly revealed. The predicted values overestimated the actual sugarcane yield in Kanchanaburi province by 50%, 31% and 27% respectively, over the course of three consecutive crop years. We investigated the ranges of significant meteorological factors (i.e., RH_t $Tmax_k$, ONI) and found that the values fell in the acceptable range between the years for building a model and the years for the prediction. Apart from meteorological variables, we presume other external factors such as international politics and attractive alternative crops may have influenced the actual low sugarcane yield. Additionally, the impact from extreme weather conditions cannot be disregarded, given the unprecedented changes in climate patterns. Effective forecasting models are necessary to accurately capture and account for such extreme situations. The amount of sugarcane received at Tamaka Sugar Industry Co., Ltd. was consequently underestimated when compared to the predicted values, with an average deviation of 50%. Thus, a conversion factor of 0.5 was applied to adjust the predicted values for the cane sugar production in the life cycle impact assessment. The details are presented in Table8.

Future studies may consider other factors that may affect sugarcane yield, such as crop prices of other economic crops, soil quality, and pest infestation, to improve the accuracy of crop yield forecasting.

Table 8 Compare the forecast and actual sugarcane yield.

Crop year	Sugarcane yield forecast in Kanchanaburi province (tons)	Actual sugarcane yield	% Difference	Sugarcane forecast Tamaka Sugar Industry Co., Ltd. received (tons)	Actual sugarcane at Tamaka Sugar Industry Co., Ltd. received (tons)	% Difference	Cane sugar production forecast in Tamaka Sugar Industry Co., Ltd. (tons)	Factor = 0.5 of Forecast values
2020/21	9,959,199	4,961,871	-50	2,091,432	939,656.35	-55.07	204,960	10,2480
2021/22	9,423,369	6,521,781	-31	1,978,907	1,109,166.01	-43.95	193,933	96,966.50
2022/23	9,844,360	7,144,544	-27	2,067,316	962,380.74	-53.45	202,597	101,298.50
2023/24	9,895,804			2,078,119			203,656	101,828
2024/25	9,772,803			2,052,289			201,124	100,562

4.2 Toxicological impacts to human health and ecosystem caused by a cane sugar production

This study focuses on a gate-to-gate system boundary. The functional is 1 kg of raw sugar, 1 kg of granulated sugar and 1 kg of refined sugar.

The impact assessment of cane sugar production begins with the impact assessment of raw sugar production because raw sugar is used as a raw material for the production of granulated sugar and refined sugar. Then, assess the impact of granulated sugar production and refined sugar production. The impact of granulated and refined sugar production will include the impact of raw sugar production.

The process of producing raw sugar begins with the crushing of sugarcane to get sugarcane juice. The sugarcane juice was boiled and filtered before being sent through crystallization procedures to form crystals of raw sugar. This is followed by centrifugation to separate the raw sugar from the juice.

Granulated sugar uses raw sugar as its main material. The raw sugar was melted and treated to eliminate any leftover color and impurities. The sugar is centrifuged to eliminate any leftover liquid from the sugar crystals.

Refined sugar production goes through the same refining process as granulated sugar but the end product has less impurities and turns into clear white granulated form.

Once we identified the materials and energy use along the process of each sugar production line. The impacts from raw sugar, granulated sugar and refined sugar production that potentially generated to the human health and ecosystem are analyzed and discussed in the following sections.

4.2.1 Mass flow and energy data for the cane sugar production

Once the sugarcane is delivered to the factory by trucks, it was subsequently loaded into the reception unit, where it underwent washing and crushing to extract the sugarcane juice. This study emphasized the production scope, therefore, the impacts from agricultural sector were not taken into account.

The raw sugar production consists of juice extraction, juice purification, evaporation, crystallization and centrifugation. Input included chemical organic, cast iron, disinfectant, lime, ethanol (without water in 99.7% solution state from ethylene), polyacrylamide, sodium chloride, brine solution, electricity, lubricating, water, river. Output from process included iron waste, oil waste, wastewater, waste solid, ash, chemical waste, mill mud and molasse.

The granulated sugar production consists of remelting, carbonatation process crystallization centrifuging and drying. Input in process is chemical organic, diatomite, disinfectant, electricity, lime, polyacrylamide, sodium chloride, brine solution, water river and water, unspecified origin. Output from process is wastewater, ash and mill mud.

The refined sugar production consists sugar production consists remelting, carbonatation process crystallization centrifuging and drying. Input in process contained chemical organic, diatomite, disinfectant, electricity, lime, polyacrylamide, sodium chloride, brine solution, water river and water, unspecified origin. Output from process released wastewater, ash and mill mud.

The input and output data of the cane sugar production correspond to those provided by Tamaka Sugar Industry Co., Ltd. In the cane sugar production, there will be some waste that will be reused in the production process. For example, in the production of raw sugar, the bagasse that has been released will be used in the production of electricity. Exhaust gas is returned to the boiler, condensate water

returns to the boiler, water evaporates into the condenser water system, and steam is sent to granulated and refined sugar production. Granulated and refined sugar production processes are similar; condensate water is used in the production of water; the water evaporates into the condenser water system. Details of materials and energy use in the different production processes are listed in the Table 9.

Table 9 Material flow and energy data for the production of raw sugar, granulated sugar, and refined sugar

Flow	Amount unit	Raw sugar	Granulated sugar	Refined sugar
Input				
Chemical, organic production	kg	0.000026	0.0000095	0.0000095
Disinfectant	kg	0.00007	-	-
Cast iron	kg	0.00078	-	-
Lubricating oil	kg	0.00021	-	-
Lime	kg	0.0087	0.017	0.017
Polyacrylamide	kg	0.00012	-	-
Sodium chloride, brine solution	kg	0.003	0.057	0.057
Diatomite	kg	-	0.00041	0.00041
Phenolic resin	kg	-	0.00034	0.00034
Ethanol, without water, in 99.7% solution state, from ethylene	kg	-	0.000036	0.000036

Table9 (Cont.)

Electricity, high voltage heat and power co-generation, biogas, gas engine	MJ	0.82	0.18	0.31
Electricity, medium voltage	MJ	0.03	0.00084	0.009
Water, river	m^3	0.00031	0.0000035	0.0000035
Water, unspecified origin	m^3	-	0.00048	0.00049
Output				
Iron waste	kg	0.00021	-	-
Oil waste	kg	0.00078	-	-
Wastewater/m^3	m^3	0.00045	0.00055	0.00055
Waste, solid	kg	0.024	-	
Ashes, from sugarcane, animal feed, at sugar plant/PK U	kg	0.00026	0.00052	0.00052
Chemical waste, regulated	kg	0.00330	-	-
Molasse, from sugarcane, animal feed, at sugar plant/PK U	kg	0.49	-	-
Mill mud, from sugarcane, animal feed, at sugar plant/PK U	kg	0.73	0.057	0.057

Table 9 shows the input data from the entire process studied. It can be seen that this system requires more electricity and water to produce raw sugar than granulated and refined sugar products. The other chemical requirements such as lime, sodium chloride, diatomite, phenolic resin, and ethanol were added for producing granulated and refined sugar. This discrepancy of inputs can influence the impacts in the life cycle inventory assessment.

The process of making sugar also produced various emissions per 1 kg of sugar product, in particular raw sugar, including chemical waste of about 0.0033 kg, molasse of 0.49, and mill mud of 0.73 kg. Overall, raw sugar product requires more input and released greater output because it is used as raw material for the other two sugar types.

4.2.2 Data inventory analysis

Impact assessment relies on the selection of the appropriate database. For this study, we have taken into consideration data closely related to sugar production, specifically from Tamaka Sugar Industry Co., Ltd. The details are presented in Table 10.

Table 10 Data inventory analysis of sugar production, Tamaka Sugar Industry Co., Ltd.

Data	Database	Provider database
Input		
Lubricating oil	AGRIBALYSE version 3.0.1	Ecoinvent
Cast iron	AGRIBALYSE version 3.0.1	Ecoinvent
Disinfectant	AGRIBALYSE version 3.0.1	SimaPro
Electricity, high voltage heat and power co-generation, biogas, gas engine	AGRIBALYSE version 3.0.1	Ecoinvent
Electricity, medium voltage	AGRIBALYSE version 3.0.1	Ecoinvent
Water, river	AGRIBALYSE version 3.0.1	AGRIBALYSE version 3.0.1
Chemical, organic	AGRIBALYSE version 3.0.1	Ecoinvent
Lime	AGRIBALYSE version 3.0.1	Ecoinvent
Polyacrylamide	AGRIBALYSE version 3.0.1	Ecoinvent
Sodium hydroxide	AGRIBALYSE version 3.0.1	Ecoinvent

Table 10 (Cont.)

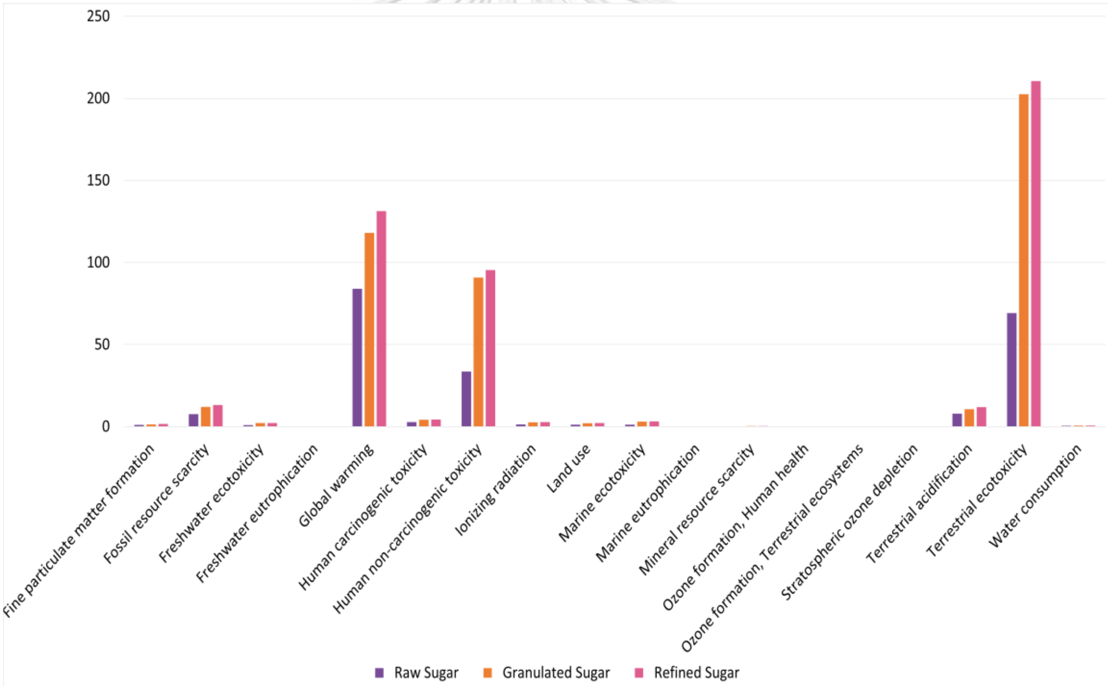
Output		
Iron waste	**AGRIBALYSE version 3.0.1**	**AGRIBALYSE version 3.0.1**
Oil waste	AGRIBALYSE version 3.0.1	AGRIBALYSE version 3.0.1
Wastewater/m^3	AGRIBALYSE version 3.0.1	AGRIBALYSE version 3.0.1
Waste, solid	AGRIBALYSE version 3.0.1	AGRIBALYSE version 3.0.1
Ashes, from sugarcane, animal feed, at sugar plant/PK U	AGRIBALYSE version 3.0.1	SimaPro
Chemical waste, regulated	AGRIBALYSE version 3.0.1	AGRIBALYSE version 3.0.1
Mill mud, from sugarcane, animal feed, at sugar plant/PK U	AGRIBALYSE version 3.0.1	SimaPro
Molasse, from sugarcane, animal feed, at sugar plant/PK U	AGRIBALYSE version 3.0.1	SimaPro

Note: RoW = for rest of world, PK U= database from Pakistan.

4.2.3 Comparative human-ecotoxicological impacts obtained from life cycle impact assessment

4.2.3.1 Midpoint impacts

The ReCiPe2016 provided 18 impact categories at the midpoint level. This study assessed on 1 kilogram of sugar production. To facilitate comparisons with the factual quantity of sugar produced and enable benchmarking with other scholarly investigations, the midpoint impact is documented based on the production of one ton of sugar.



Note: Reference units

Global warming	kg CO_2 eq	Fine particulate matter formation	kg $PM_{2.5}$ eq
Terrestrial ecotoxicity	kg 1,4-DCB	Freshwater ecotoxicity	kg 1,4-DCB
Human non-carcinogenic toxicity	kg 1,4-DCB	Water consumption	m^3
Terrestrial acidification	kg SO_2 eq	Mineral resource scarcity	kg Cu eq
Fossil resource scarcity	kg oil eq	Ozone formation, Terrestrial ecosystems	kg NO_x eq
Human carcinogenic toxicity	kg 1,4-DCB	Ozone formation, Human health	kg NOx eq
Ionizing radiation	kBq Co-60 eq	Freshwater eutrophication	kg P eq
Land use	m^2a crop eq	Marine eutrophication	kg CFC-11 eq
Marine ecotoxicity	kg 1,4-DCB	Stratospheric ozone depletion	kg N eq

Figure 10 Impacts of raw sugar production at midpoint level

According to the ReCiPe2016 midpoint method life cycle impact assessment (LCIA) analysis, raw sugar product generated the top five impacts on humans and ecosystems at midpoint level including global warming 84.04 kg CO_2 eq, terrestrial ecotoxicity 69.16 kg 1,4-DCB, human non-carcinogenic toxicity 33.57 kg 1,4-DCB, terrestrial acidification 7.96 kg SO_2 eq and fossil resource scarcity 7.62 kg oil eq per 1 ton raw sugar (Figure 10). Overall, three sugar products generated 333.32 kg CO_2 eq per 1 ton product which was higher than the sugar production process (included agricultural aspect) in Brazil in which 304.73 kg CO_2 eq per 1 ton of sugar product was emitted (Sudibya et al., 2020). Considering raw sugar product, (Seabra et al., 2011) reported lower values of global warming generated 234 kg CO_2 eq when compared to our study. However, one ton of raw sugar product can emit as high as 1,156.1 kg CO2 eq (Meza-Palacios et al., 2019).

Producing granulated sugar had impacts on humans and ecosystems at midpoint level. These top five impacts in descending order are terrestrial ecotoxicity 202.60 kg 1,4-DCB, global warming 118.04 kg CO_2 eq, human non-carcinogenic toxicity

90.88 kg 1,4-DCB, fossil resource scarcity 12.01 kg oil eq and terrestrial acidification 10.62 kg SO_2 eq per 1 ton of granulated sugar (Figure 10). Compared to (Namdari et al., 2022), our major impact in terrestrial ecotoxicity was much higher than their study in which 9.68 kg 1,4-DCB per 1 ton granulated sugar was reported.

For making refined sugar, 'the top five impacts on humans and ecosystems at midpoint level in descending order included terrestrial ecotoxicity 210.46 kg 1,4-DCB per 1 ton of raw sugar production, global warming 131.23 kg CO_2 eq per 1 ton of raw sugar production, human non-carcinogenic toxicity 95.37 kg 1,4-DCB per 1 ton of raw sugar production, terrestrial acidification 13.12 kg SO_2 eq per 1 ton of raw sugar production and fossil resource scarcity 11.88 kg oil eq per 1 ton of raw sugar production.

The assessment of the midpoint impact of the production of raw sugar, granulated sugar, and refined sugar reveals that the foremost five impacts include global warming, terrestrial ecotoxicity, human non-carcinogenic toxicity, fossil resource scarcity, and terrestrial acidification (Figure 10).

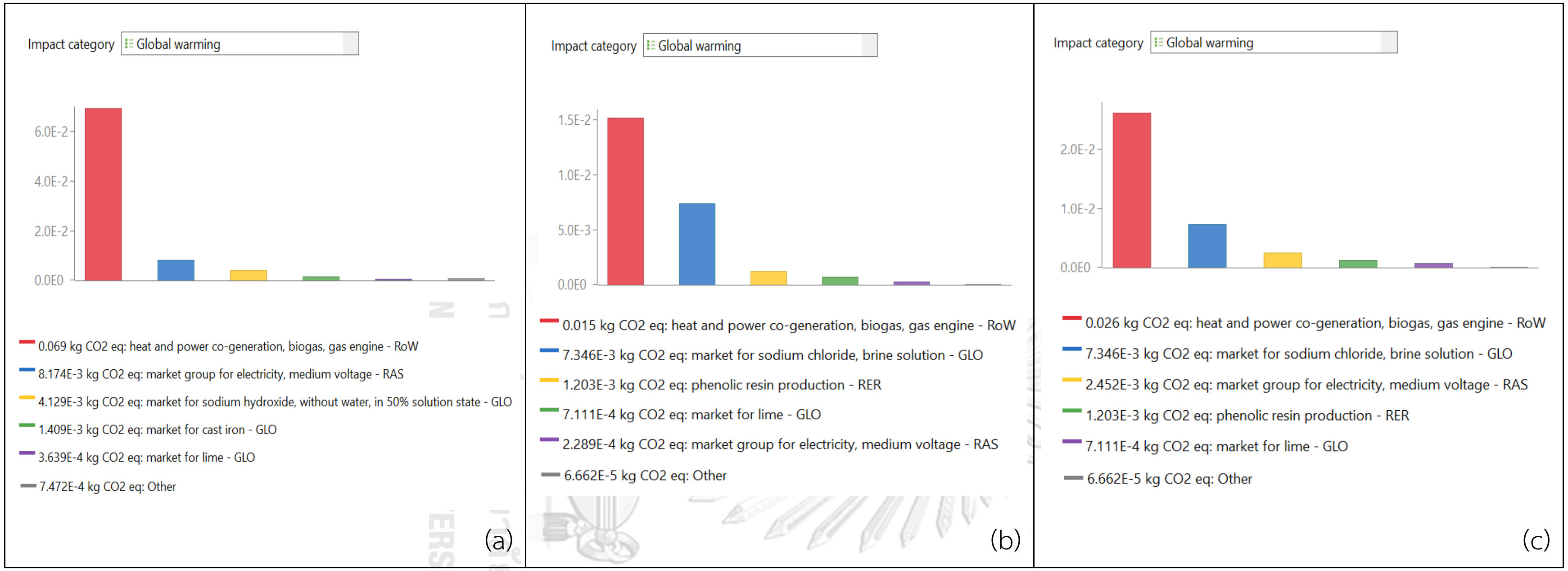


Figure 11 Contributors to global warming from the production of (a) raw sugar, (b) granulated sugar, and (c) refined sugar on a 1 kg functional unit.

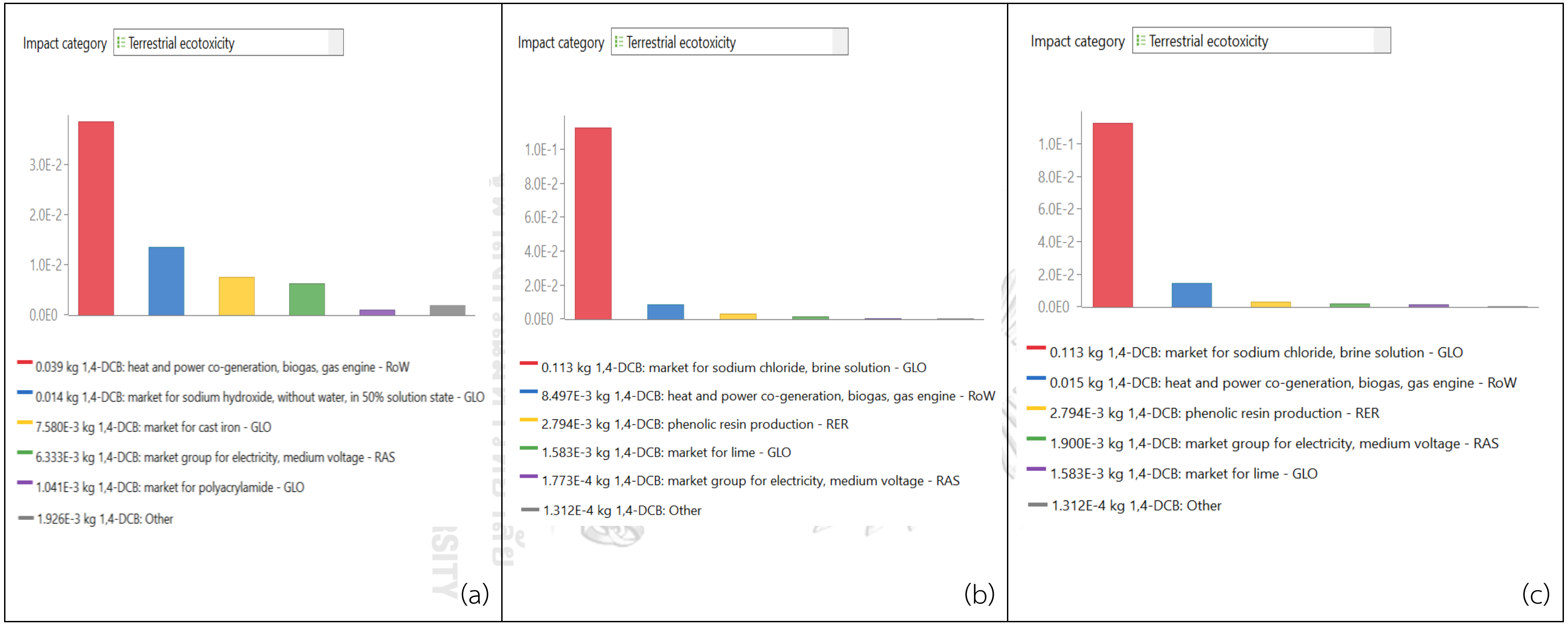


Figure 12 Contributors to terrestrial ecotoxicity from the production of (a) raw sugar, (b) granulated sugar, and (c) refined sugar on a 1 kg functional unit.

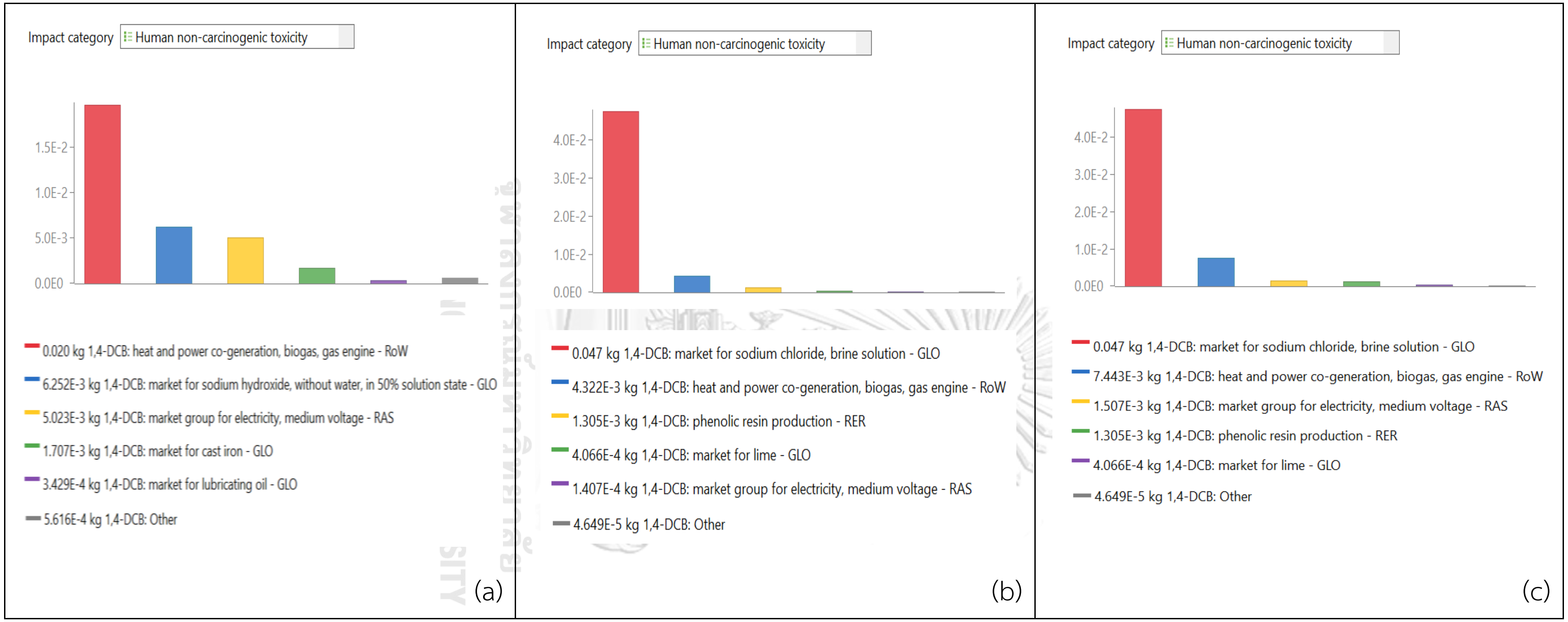


Figure 13 Contributors to human non-carcinogenic toxicity from the production of (a) raw sugar, (b) granulated sugar, and (c) refined sugar on a 1 kg functional unit.

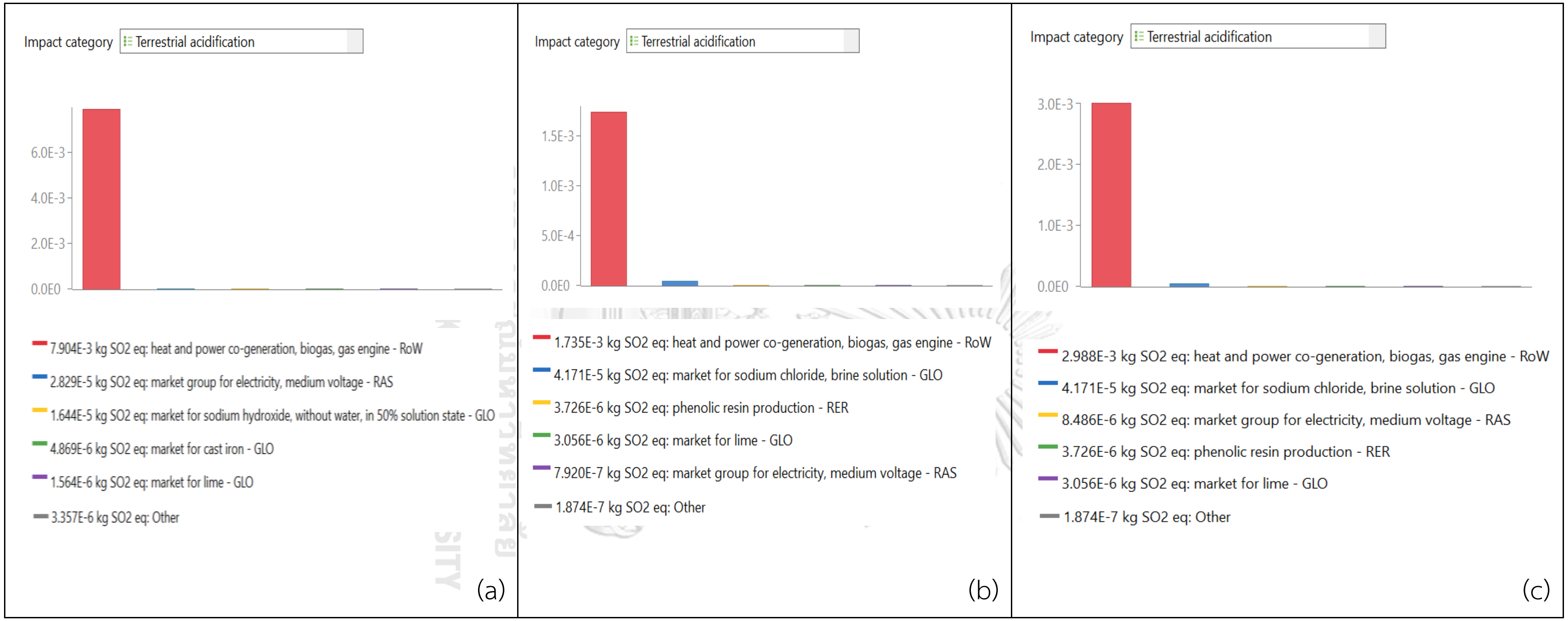


Figure 14 Contributors to terrestrial acidification from the production of (a) raw sugar, (b) granulated sugar, and (c) refined sugar on a 1 kg functional unit

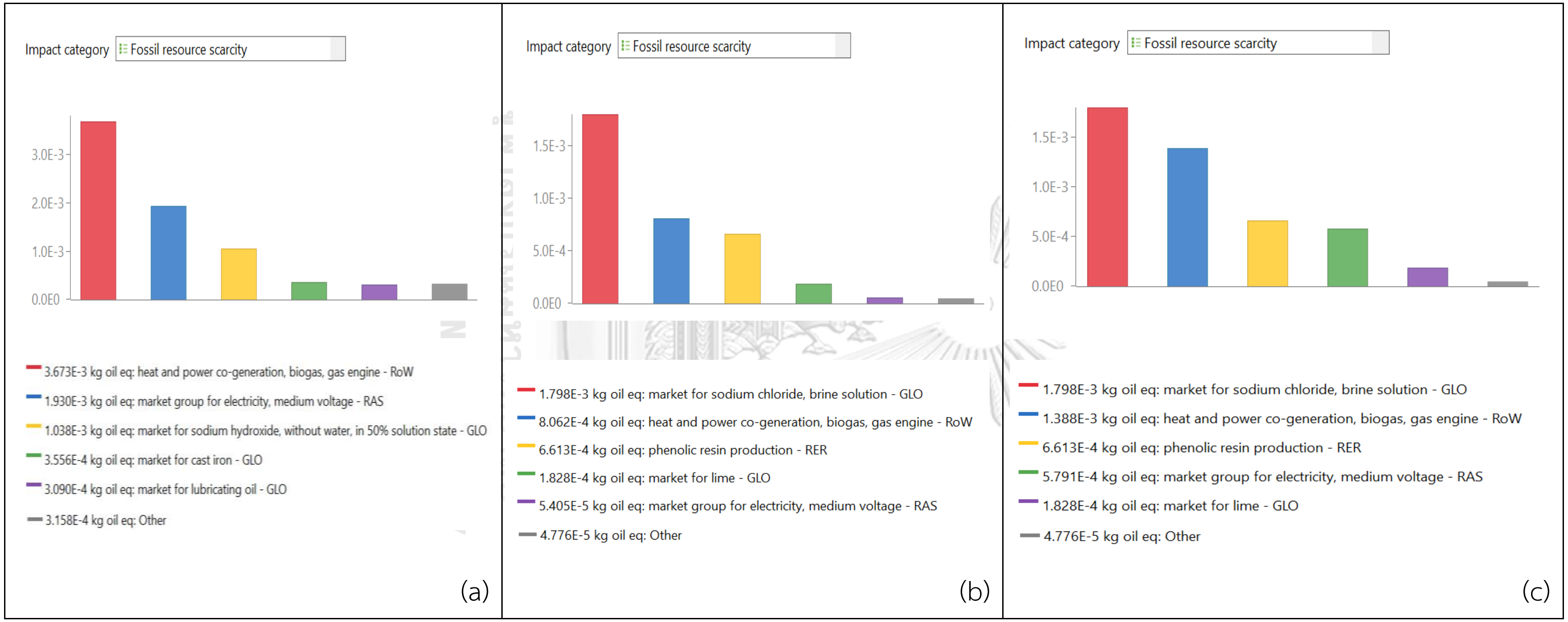


Figure 15 Contributors to fossil resource scarcity from the production of (a) raw sugar, (b) granulated sugar, and (c) refined sugar on a 1 kg functional unit

From Figure 11, the biggest contribution of the global warming in this study is electricity cogeneration in the production process for all sugar types. We estimated that heat and power co-generation contributed 82.36% of global warming in raw sugar product, 61.39% of global warming in granulated sugar, and 68.96% of global warming in refined sugar. (Meza-Palacios et al., 2019), on the other hand, determined that sugar milling contributed the biggest emission to the global warming (50.6%), followed by growing and harvesting (39.5%), transportation (9.2%), while electricity cogeneration was the minor contributor (0.7%).

Terrestrial ecotoxicity holds a notable impact in the top rank of the 18 categories (Figure 12). The results show that electricity consumption in production process contributed 55.97% and sodium hydroxide usage contributed 19.62% to terrestrial ecotoxicity for raw sugar product. On the contrary, sodium chloride played a major role in contributing to terrestrial ecotoxicity for granulated sugar and refined sugar by 89.52% and 84.26%, respectively.

Heat and power co-generation also contributed the largest portion to the terrestrial acidification between 97.23% and 99.32% for all three sugar types (Figure 14). (Meza-Palacios et al., 2019) estimated a total of 104 kg SO_2 eq per ton of raw sugar.

For human non-carcinogenic toxicity, heat and power co-generation contributed around 58.64% for raw sugar product. Whereas, sodium chloride occupied 81.57% and 88.40% for in the human non-carcinogenic toxicity category for making granulated sugar and refined sugar (Figure 13).

Heat and a group of electricity contributed 73.72% of fossil resource scarcity in raw sugar production, whereas sodium chloride and power co-generation shared quite a big portion in resource scarcity in granulated sugar and refined sugar (Figure 15).

4.2.3.2 Endpoint impacts

At the endpoint level, midpoint impact categories are multiplied by damage factors and grouped into three endpoint categories: human health, ecosystems, and resource scarcity. This study focuses on the impact on human health and the ecosystem.

Table 11 Damage to human health from production of raw sugar, granulated sugar and refined sugar

Impact category	Unit	Raw sugar (1 ton)	Granulated sugar (1 ton)	Refined sugar (1 ton)
Fine particulate matter formation	DALY	$6.48 x10^{-4}$	$7.28 x10^{-3}$	$7.38 x10^{-3}$
Global warming, Human health	DALY	$7.81 x10^{-5}$	$8.82 x10^{-4}$	$8.94 x10^{-4}$
Human carcinogenic toxicity	DALY	$9.21 x10^{-6}$	$1.05 x10^{-4}$	$1.06 x10^{-4}$
Human non-carcinogenic toxicity	DALY	$7.65 x10^{-6}$	$9.64 x10^{-5}$	$9.74 x10^{-5}$
Ionizing radiation	DALY	$1.17 x10^{-8}$	$1.38 x10^{-7}$	$1.40 x10^{-7}$
Ozone formation, Human health	DALY	$8.41 x10^{-8}$	$9.58 x10^{-7}$	$9.71 x10^{-7}$
Stratospheric ozone depletion	DALY	$3.20 x10^{-7}$	$3.59 x10^{-6}$	$3.64 x10^{-6}$
Water consumption, Human health	DALY	$1.06 x10^{-6}$	$1.17 x10^{-5}$	$1.17 x10^{-5}$
Total damage to human health	DALY	$7.45 x10^{-4}$	$8.38 x10^{-3}$	$8.50 x10^{-3}$

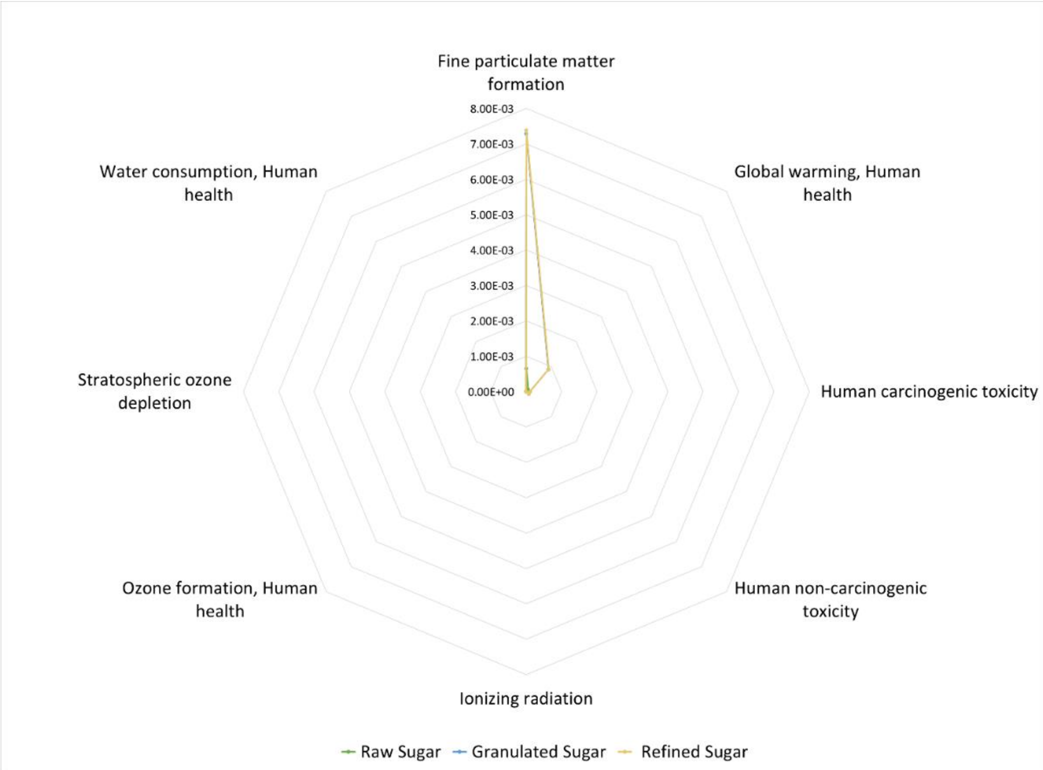


Figure 16 Damage to human health from production of raw sugar, granulated sugar and refined sugar

At endpoint level, for 1 ton of raw sugar product damaged to human health 7.45×10^{-4} DALY, 1 ton of granulated sugar production damage to human health 8.38×10^{-3} DALY and 1 ton of refined sugar production damage to human health 8.50×10^{-3} DALY. The impact category of fine matter formation contributed the most, with a value of 6.48×10^{-4}, $7.28 \times 10^{-3}$and 7.38×10^{-3} DALY, per 1 ton of raw, granulated, and refined sugar respectively. The generation of heat and power through co-generation has been found to be a contributing factor to the formation of fine particulate matter (Ibrahim & Workneh, 2022).

Table 12 Damage to ecosystems from production of raw sugar, granulated sugar and refined sugar

Impact category	Unit	Raw sugar (1 ton)	Granulated sugar (1 ton)	Refined sugar (1 ton)
Freshwater ecotoxicity	Species.yr	5.88×10^{-10}	7.30×10^{-9}	7.37×10^{-9}
Freshwater eutrophication	Species.yr	8.72×10^{-9}	1.03×10^{-7}	1.04×10^{-7}
Global warming, Freshwater ecosystems	Species.yr	6.43×10^{-12}	7.26×10^{-11}	7.36×10^{-11}
Global warming, Terrestrial ecosystems	Species.yr	2.35×10^{-7}	2.66×10^{-6}	2.69×10^{-6}
Land use	Species.yr	1.05×10^{-8}	1.21×10^{-7}	1.23×10^{-7}
Marine ecotoxicity	Species.yr	1.24×10^{-10}	1.54×10^{-9}	1.56×10^{-9}
Marine eutrophication	Species.yr	2.11×10^{-12}	2.43×10^{-11}	2.45×10^{-11}
Ozone formation, Terrestrial ecosystems	Species.yr	1.22×10^{-8}	1.39×10^{-7}	1.41×10^{-7}
Terrestrial acidification	Species.yr	1.69×10^{-6}	1.90×10^{-5}	1.92×10^{-5}
Terrestrial ecotoxicity	Species.yr	7.89×10^{-10}	1.01×10^{-8}	1.02×10^{-8}
Water consumption, Aquatic ecosystems	Species.yr	3.28×10^{-13}	3.63×10^{-12}	3.64×10^{-12}
Water consumption, Terrestrial ecosystem	Species.yr	6.49×10^{-9}	7.14×10^{-8}	7.16×10^{-8}
Total damage to ecosystems	Species.yr	1.96×10^{-6}	2.21×10^{-5}	2.24×10^{-5}

Figure 17 Damage to ecosystems from production of raw sugar, granulated sugar and refined sugar

At endpoint level, for 1ton raw sugar production damage to ecosystems 1.96×10^{-6} Species.yr, 1ton granulated sugar production damage to ecosystems 2.21×10^{-5} Species.yr and 1ton refined sugar production damage to ecosystems 8.50×10^{-3} Species.yr. The impact category of terrestrial acidification contributed the most, with a value of 1.69×10^{-6}, 1.90×10^{-5} and 1.92×10^{-5} Species.yr, per 1 ton of raw, granulated, and refined sugar respectively. Freshwater eutrophication has a greater impact on the environment than marine eutrophication, which these findings agree with (Ibrahim & Workneh, 2022).

4.3 Forecasting impacts to human health and ecosystem of cane sugar production, Tamaka Sugar Industry Co., Ltd.

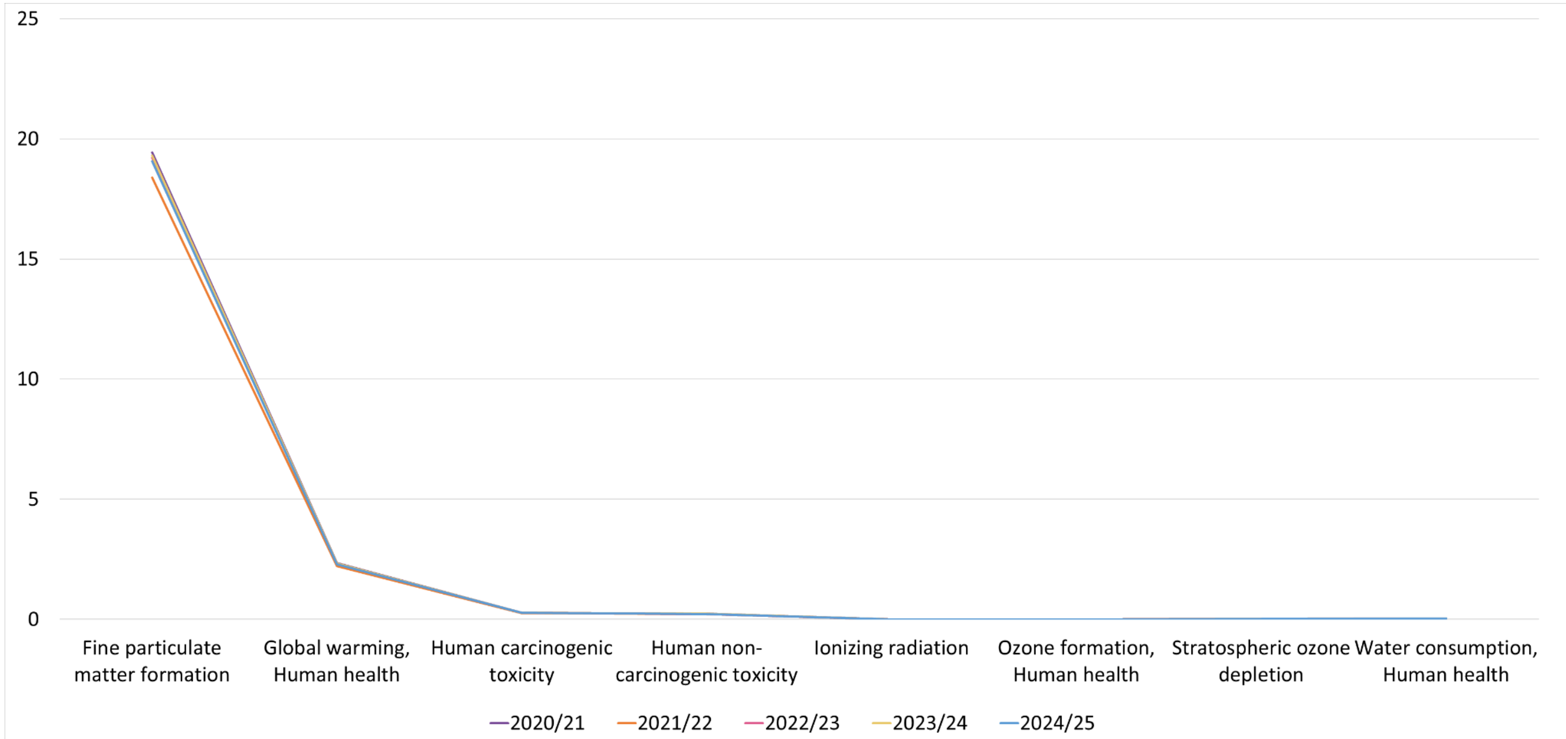
From cane sugar production in Tamaka Sugar Industry Co. Ltd., 100% of total raw sugar is divided into 29.26% of raw sugar for sale and the rest of 70.74% of total raw sugar for utilizing as raw material in the production of granulated and refined sugar. Raw sugar is used as a raw material of 42.79% granulated sugar and 57.21% refined sugar. Proportion of total sugar production can be divided into raw sugar 29.26%%, granulated sugar 42.79%, refined sugar 57.21%. Cane sugar production forecast was obtained by the predicted values of the amount of forecasted sugarcane received at Tamaka Sugar Industry Co., Ltd. To adjust the overestimation model performance the value of 0.5 was employed to estimate cane sugar production. The forecasted cane sugar production from years 2020/21 to 2024/25 classified by sugar types is shown in Table13.

Table 13 Cane sugar production forecast, Tamaka Sugar Industry Co., Ltd. classified by types of sugar

Production Year	Cane sugar production (ton)	Raw sugar (ton)	Granulated sugar (ton)	Refined sugar (ton)
2020/21	102,480	29,989.81	27,938.82	37,352.63
2021/22	96,967	28,376.34	26,435.69	35,343.03
2022/23	101,299	29,644.06	27,616.71	36,921.99
2023/24	101,828	29,799.01	27,761.06	37,114.98
2024/25	100,562	29,428.53	27,415.92	36,653.54

Using cane sugar production forecast, Tamaka Sugar Industry Co., Ltd. three sugar product multiplied by the impact value per 1 ton sugar raw sugar, granulated sugar, refined sugar at midpoint and endpoint. Forecasting impacts from production

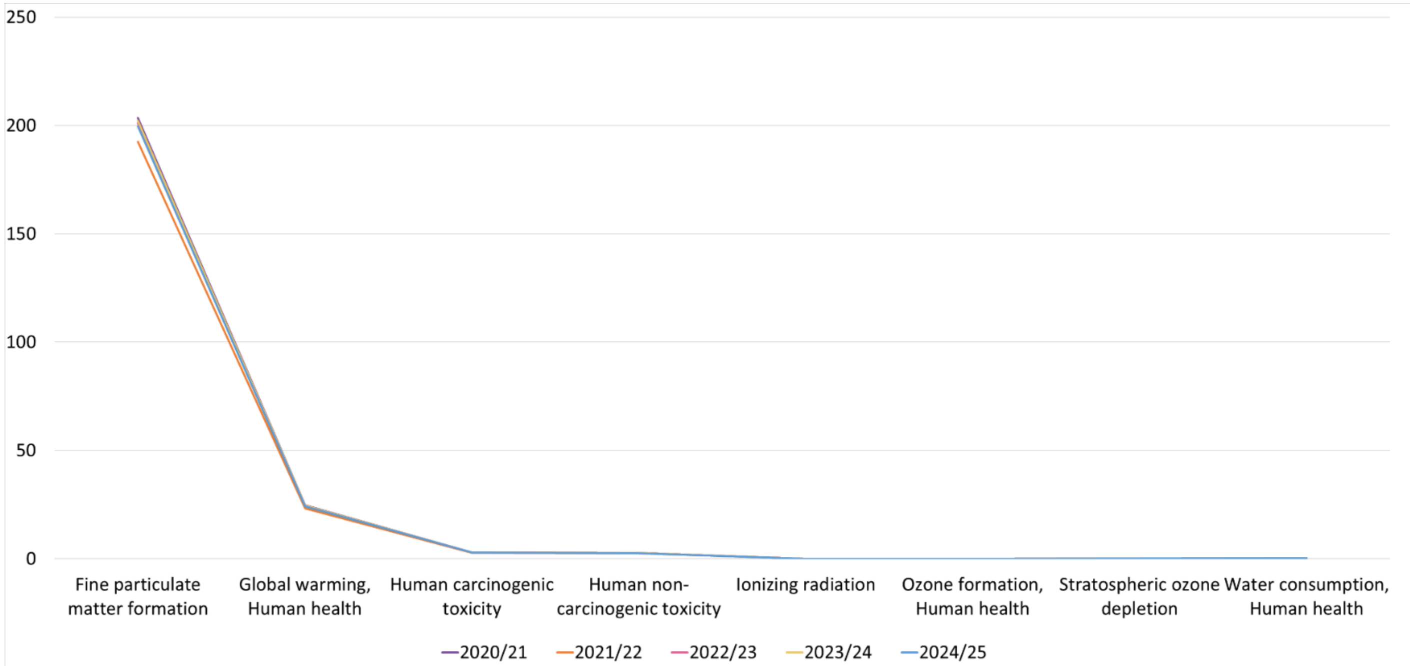
of raw sugar, granulated sugar, refined sugar production years 2020/21-2024/25 are displayed in Figures 18-23.



Note: Reference units = DALY

Figure 18 Forecasting damage to human health from raw sugar production year 2020/21-2024/25

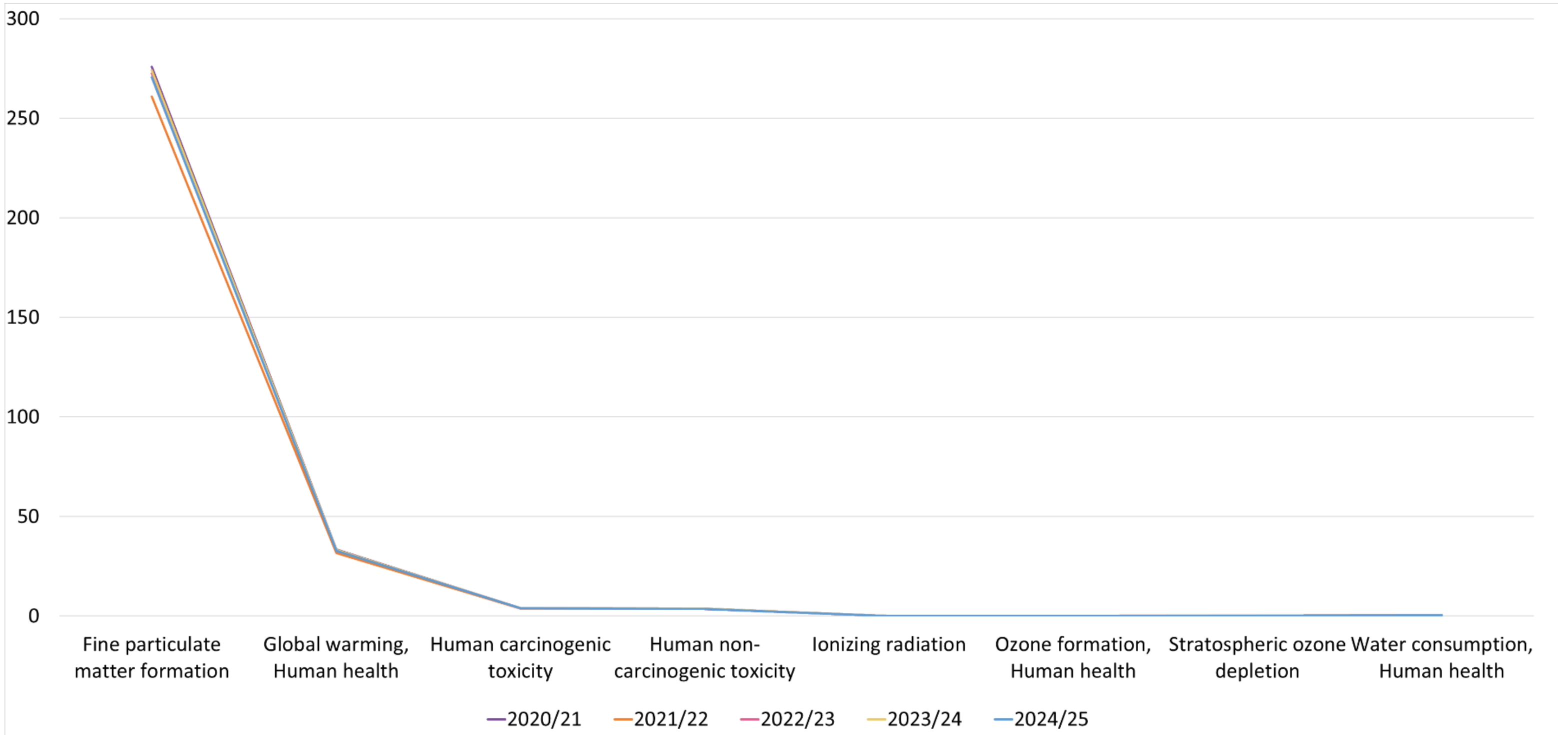
At the endpoint level, the total damage to human health for the production of 1 ton of raw sugar was measured at 22.33 DALY in 2020/21, 21.13 DALY in 2021/22, 22/07 DALY in 2022/23, 22.19 DALY in 2023/24 and 21.91 DALY in 2024/25 (Figure 15).



Note: Reference units = DALY

Figure 19 Forecasting damage to human health from granulated sugar production year 2020/21-2024/25

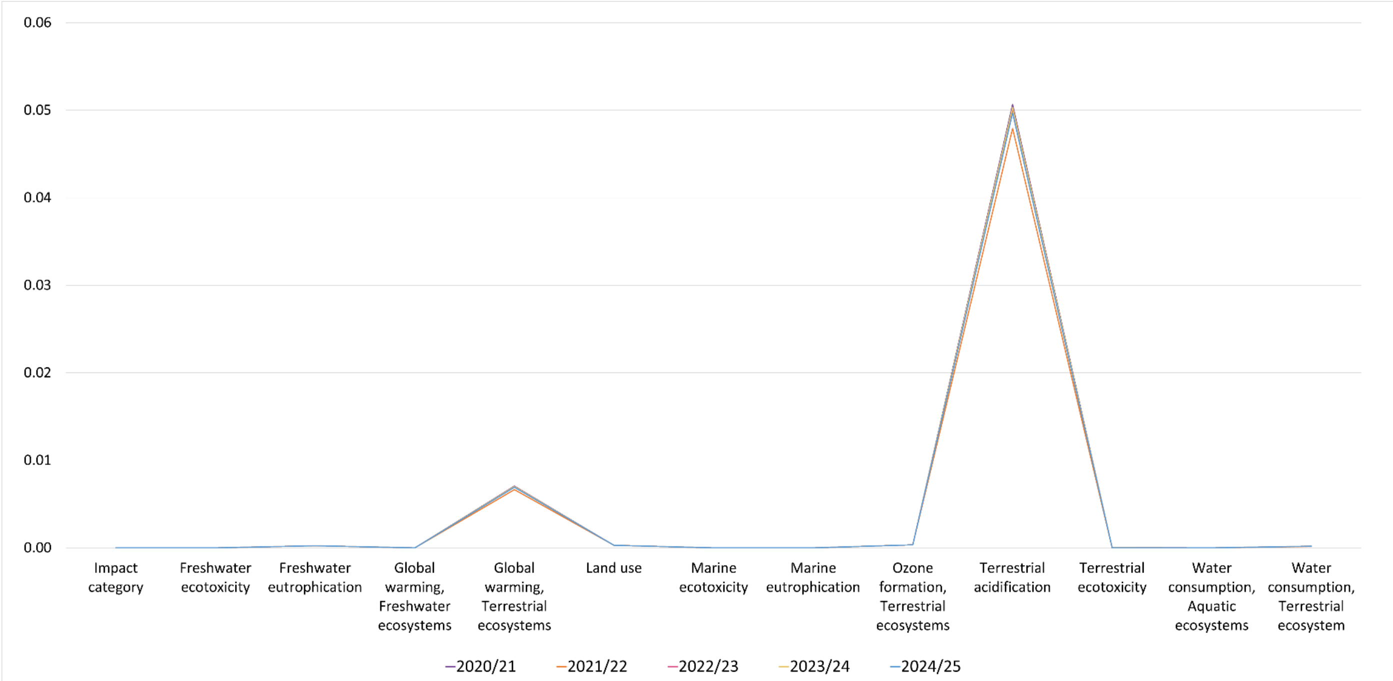
At the endpoint level, the total damage to human health for the production of 1 ton of granulated sugar was measured at 234.15 DALY in 2020/21, 221.56 DALY in 2021/22, 231.45 DALY in 2022/23, 232.66 DALY in 2023/24 and 229.77 DALY in 2024/25 (Figure 16).



Note: Reference units = DALY

Figure 20 Forecasting damage to human health from refined sugar production year 2020/21-2024/25

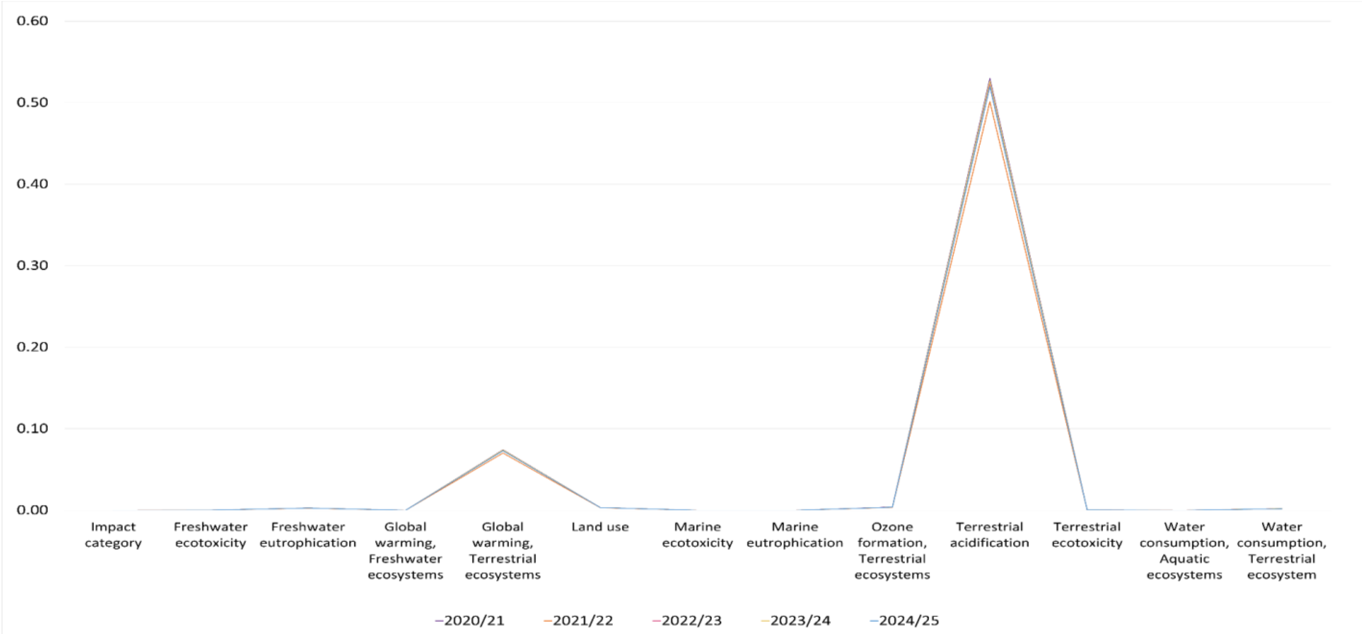
At the endpoint level, the total damage to human health for the production of 1 ton of refined sugar was measured at 317.40 DALY in 2020/21, 300.32 DALY in 2021/22, 313.74 DALY in 2022/23, 315.38 DALY in 2023/24 and 311.46 DALY in 2024/25 (Figure 17).



Note: Reference units = Species.yr

Figure 21 Damage to ecosystems from production of raw sugar production year 2020/21-2024/25

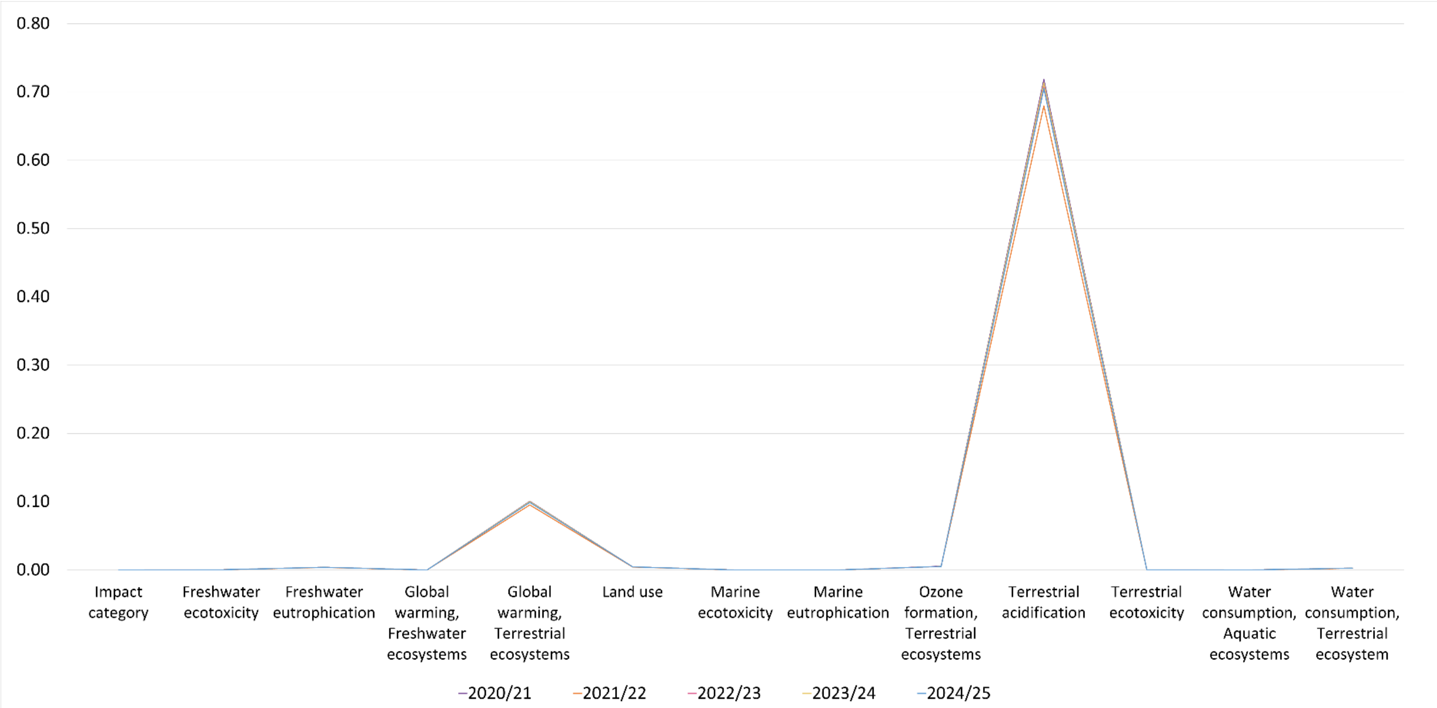
At the endpoint level, the total damage to ecosystems for the production of 1 ton of raw sugar was measured at 5.89 $x10^{-2}$ Species.yr in 2020/21, 5.57 $x10^{-2}$ Species.yr in 2021/22, 5.82 $x10^{-2}$ Species.yr in 2022/23, 5.85 $x10^{-2}$ Species.yr in 2023/24 and 5.78 $x10^{-}$ Species.yr in 2024/25 (Figure 18).



Note: Reference units = Species.yr

Figure 22 Damage to ecosystems from production of granulated sugar production year 2020/21-2024/25

At the endpoint level, the total damage to ecosystems for the production of 1 ton of granulated sugar was measured at 6.17 x10-1 Species.yr in 2020/21, 5.83 x10-1 Species.yr in 2021/22, 6.10 x10-1 Species.yr in 2022/23, 6.13 x10-1 Species.yr in 2023/24 and 6.05 x101Species.yr in 2024/25 (Figure 19).



Note: Reference units = Species.yr

Figure 23 Damage to ecosystems from production of refined sugar production year 2020/21-2024/25

At the endpoint level, the total damage to ecosystems for the production of 1 ton of refined sugar was measured at 8.36 $\times10^{-1}$ Species.yr in 2020/21, 7.91 $\times10^{-1}$ Species.yr in 2021/22, 8.26 $\times10^{-1}$ Species.yr in 2022/23, 8.31 $\times10^{-1}$ Species.yr in 2023/24 and 8.20 $\times10^{-1}$ Species.yr in 2024/25 (Figure 20).

In assessing the endpoint impact of raw sugar, granulated sugar, and refined sugar production from 2020/21 to 2024/25, it was found that fine particulate matter formation had the highest contribution to human health damage compared to other impacts, followed by global warming and human carcinogenic toxicity. The production's electricity cogeneration was identified as the main contributor to fine particulate matter formation. Regarding damage to ecosystems, terrestrial acidification was found to have the highest contribution to human health damage among other impacts, followed by global warming (terrestrial ecosystems). Our results align with previous findings by Meza-Palacios et al. (2019), highlighting that electricity cogeneration significantly contributes to dangerous effects on human health and ecosystem.

The impact of cane sugar production results was compared with studies assessing the impact of other productions, at the endpoint level; the total damage to human health for the production of 1 kg of raw sugar, granulated sugar, and refined sugar was 7.45×10^{-7}, 8.38×10^{-6}, and 8.50×10^{-6} DALY, respectively. The total damage to ecosystem for the production of 1 kg of raw sugar, granulated sugar, and refined sugar was 1.96×10^{-9}, 2.21×10^{-8}, and 2.24×10^{-8} Species.yr, respectively. Compared (Olagunju & Olanrewaju), the total damage to human health from the production of granulated sugar and refined sugar was higher than that from Portland cement production in South Africa, which was 1.22×10^{-6} DALY per 1 kg of Portland cement. The total damage to ecosystems from the production of granulated sugar and refined sugar was higher than the Portland cement production in South Africa, which was 3.1×10^{-9} Species.yr per 1 kg of Portland cement.

The production of refined sugar resulted in the greatest total damage to human health, followed by granulated and raw sugar production. Similarly, in terms of total damage to ecosystem, refined sugar production ranks the highest, followed by granulated ang raw sugar production. This discrepancy in rankings can be

attributed to the production process which involves several steps and the addition of various chemicals such as lime, sodium chloride, diatomite, phenolic resin, and ethanol for the production of granulated and refined sugar. Additionally, waste generated during production also contributes to the impacts. These variations in inputs can significantly influence the outcomes of the life cycle assessment. The impacts of cane sugar production on human health and ecosystems in this study can be a useful tool for identifying areas where improvements can be made to reduce the impacts.

The tendency of impacts from cane sugar production to increase or decrease depending on consumer demand by domestic and international purchasing power is gradually recovering in line with the economic direction, and industries tend to recover after the COVID-19 crisis subsides.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study aimed to forecast the sugarcane yield and cane sugar production and assessing human health and ecosystem caused by a cane sugar production. Forecasted sugarcane yield this study used stepwise multiple linear regression (MLR) and autoregressive integrated moving average (ARIMA) approach, to forecast sugarcane production from 2020/21 to 2024/25. Sugarcane yield in Kanchanaburi province was influenced by relative humidity at the Thong Pha Phum meteorological station, maximum temperature at the Kanchanaburi meteorological station, and the oceanic Niño Index (ONI). The forecasting models indicated that annual sugarcane yields during crop years 2020/21 to 2024/25 fluctuated from 1,978,907 to 2,091,432 tons.

At the midpoint impact level, the assessment of human health and ecosystems for the production of 1 ton of raw sugar, granulated sugar, and refined sugar revealed the top five impacts: global warming, terrestrial ecotoxicity, human non-carcinogenic toxicity, fossil resource scarcity, and terrestrial acidification. At endpoint level, the total damage to human health from the production of 1 ton of raw sugar, granulated sugar, and refined sugar was estimated at 6.48×10^{-4}, 7.28×10^{-3} and 7.38×10^{-3} DALY, respectively. In terms of damage to ecosystems, the production of 1 ton of raw sugar, granulated and refined sugar resulted in a total damage to ecosystems of 7.45×10^{-4}, 8.38×10^{-3} and 8.50×10^{-3} Species.yr, respectively.

In forecasting the impacts to human health and ecosystems from cane sugar production at Tamaka Sugar Industry Co., Ltd. For the production years 2020/21-2024/25, it was observed that at the endpoint level, the impact category with the highest contribution to damage to human health was caused by fine particulate matter formation, followed by global warming and human carcinogenic toxicity. In

terms of damage to ecosystems, the impact category with the greatest contribution was terrestrial acidification, followed by global warming (terrestrial ecosystems).

Sugarcane yield forecasting models established serve as essential instruments for projecting crop production pre-harvest, allowing for pricing import and export decisions, as well as formulating food procurement policies. The sugar factory can use the forecasted sugarcane values to plan their production and manage inventory. In addition, the human health and ecosystem impacts derived from this study can help identify avenues for improvement in cane sugar production, such as reduce the use of chemical products, water, and energy, in order to mitigate the impact on both human health and ecosystems. Despite the fact that the use of bagasse for energy production offers environmental advantages, it is imperative to implement robust policy measures to regulate and mitigate air emissions resulting from the combustion of bagasse. Furthermore, the installation of efficacious systems for the elimination of volatile ash This necessitates oversight and management by an environmental party.

5.2 Limitations

The study considers sugarcane production data specifically from Kanchanaburi province, Thailand, and the results may not be generalizable to other regions. In the forecasting step, only historical data up to 2010 is utilized, and the accuracy of the forecasts could be influenced by any changes in the sugarcane industry or external factors that occurred after 2010. Additionally, the study solely employs the Box-Jenkins seasonal ARIMA method for forecasting and does not compare it to other methods. Finally, the accuracy of the models for future years is uncertain and could vary due to factors such as climate change, disease outbreaks, and policy changes.

The assessment of the environmental impact focuses on sugar cane production at Tamaka Sugar Industry Co., Ltd. in Kanchanaburi Province, Thailand. It should be noted that the findings may not be representative of other sugar factory in the country or in different regions. Furthermore, the LCIA study exclusively examines the gate-to-gate life cycle of cane sugar production, meaning that it does not consider the cultivation, usage and disposal phases of sugar.

5.3 Recommendations

In order to forecast sugarcane yield more accurately in the future, it is important to consider various factors associated with yield. This may involve studying additional time series models or multivariate models to enhance forecasting accuracy. Incorporating exogenous variables that may affect sugarcane yield, utilizing more recent data to improve forecast precision, and applying the developed models to other regions or crops to test their generalizability and recommended approaches.

In terms of assessing the human and ecosystem impacts, it is imperative to proceed with a more comprehensive life cycle assessment that includes the cultivation, usage, and disposal phases of sugar. This holistic approach will yield a more accurate estimate of the overall environmental impact associated with sugar production.

Appendix

Table 14 Forecasting impact from production of raw sugar production year 2020/21-2024/25

Impact category	Unit	Raw sugar				
		2020/21	2021/22	2022/23	2023/24	2024/25
Fine particulate matter formation	kg $PM_{2.5}$ eq	3.09×10^4	9.99×10^4	1.04×10^5	3.07×10^4	3.03×10^4
Fossil resource scarcity	kg oil eq	2.29×10^5	7.39×10^5	7.72×10^5	2.27×10^5	2.24×10^5
Freshwater ecotoxicity	kg 1,4-DCB	2.55×10^4	8.23×10^4	8.60×10^4	2.53×10^4	2.50×10^4
Freshwater eutrophication	kg P eq	3.91×10^2	1.26×10^3	1.32×10^3	3.88×10^2	3.83×10^2
Global warming	kg CO_2 eq	2.52×10^6	8.15×10^6	8.51×10^6	2.50×10^6	2.47×10^6
Human carcinogenic toxicity	kg 1,4-DCB	8.32×10^4	2.69×10^5	2.81×10^5	8.27×10^4	8.16×10^4
Human non-carcinogenic toxicity	kg 1,4-DCB	1.01×10^6	3.26×10^6	3.40×10^6	1.00×10^6	9.88×10^5
Ionizing radiation	kBq Co-60 eq	4.14×10^4	1.34×10^5	1.40×10^5	4.11×10^4	4.06×10^4
Land use	m^2a crop eq	3.54×10^4	1.15×10^5	1.20×10^5	3.52×10^4	3.48×10^4
Marine ecotoxicity	kg 1,4-DCB	3.54×10^4	1.15×10^5	1.20×10^5	3.52×10^4	3.48×10^4
Marine eutrophication	kg N eq	3.71×10	1.20×10^2	1.25×10^2	3.69×10	3.64×10
Mineral resource scarcity	kg Cu eq	3.69×10^3	1.19×10^4	1.25×10^4	3.67×10^3	3.62×10^3
Ozone formation, Human health	kg NO_x eq	2.77×10^3	8.97×10^3	9.37×10^3	2.76×10^3	2.72×10^3

Table 14 (Cont.)

Ozone formation, Terrestrial ecosystems	kg NO_x eq	2.84 $\times 10^3$	9.19 $\times 10^3$	9.60 $\times 10^3$	2.83 $\times 10^3$	2.79 $\times 10^3$
Stratospheric ozone depletion	kg CFC-11 eq	1.81 x10	5.84 x10	6.11 x10	1.80 x10	1.77 x10
Terrestrial acidification	kg SO_2 eq	2.39 $\times 10^5$	7.72 $\times 10^5$	8.06 $\times 10^5$	2.37 $\times 10^5$	2.34 $\times 10^5$
Terrestrial ecotoxicity	kg 1,4-DCB	2.07 $\times 10^6$	6.71 $\times 10^6$	7.01 $\times 10^6$	2.06 $\times 10^6$	2.04 $\times 10^6$
Water consumption	m^3	1.55 $\times 10^4$	5.00 $\times 10^4$	5.23 $\times 10^4$	1.54 $\times 10^4$	1.52 $\times 10^4$

Table 15 Forecasting impact from production of granulated sugar production year 2020/21-2024/25

Impact category	Unit	Granulated sugar				
		2020/21	2021/22	2022/23	2023/24	2024/25
Fine particulate matter formation	kg $PM_{2.5}$ eq	3.87 $\times 10^4$	3.66 $\times 10^4$	3.83 $\times 10^4$	3.85 $\times 10^4$	3.80 $\times 10^4$
Fossil resource scarcity	kg oil eq	3.36 $\times 10^5$	3.18 $\times 10^5$	3.32 $\times 10^5$	3.33 $\times 10^5$	3.29 $\times 10^5$
Freshwater ecotoxicity	kg 1,4-DCB	5.98 $\times 10^4$	5.66 $\times 10^4$	5.91 $\times 10^4$	5.95 $\times 10^4$	5.87 $\times 10^4$
Freshwater eutrophication	kg P eq	6.91 $\times 10^2$	6.53 $\times 10^2$	6.83 $\times 10^2$	6.86 $\times 10^2$	6.78 $\times 10^2$
Global warming	kg CO_2 eq	3.30 $\times 10^6$	3.12 $\times 10^6$	3.26 $\times 10^6$	3.28 $\times 10^6$	3.24 $\times 10^6$
Human carcinogenic toxicity	kg 1,4-DCB	1.17 $\times 10^5$	1.11 $\times 10^5$	1.16 $\times 10^5$	1.16 $\times 10^5$	1.15 $\times 10^5$

Table 15 (Cont.)

Human non-carcinogenic toxicity	kg 1,4-DCB	2.54 x10^6	2.40 x10^6	2.51 x10^6	2.52 x10^6	2.49 x10^6
Ionizing radiation	kBq Co-60 eq	7.39E x10^4	7.00 x10^4	7.31 x10^4	7.35 x10^4	7.26 x10^4
Land use	m^2a crop eq	5.55 x10^4	5.25 x10^4	5.49 x10^4	5.51 x10^4	5.45 x10^4
Marine ecotoxicity	kg 1,4-DCB	8.43 x10^4	7.98 x10^4	8.33 x10^4	8.37 x10^4	8.27 x10^4
Marine eutrophication	kg N eq	5.64x10	5.33 x10	5.57 x10	5.60 x10	5.53 x10
Mineral resource scarcity	kg Cu eq	8.49 x10^3	8.03 x10^3	8.39 x10^3	8.44 x10^3	8.33 x10^3
Ozone formation, Human health	kg NO_x eq	3.87 x10^3	3.66 x10^3	3.82 x10^3	3.84 x10^3	3.79 x10^3
Ozone formation, Terrestrial ecosystems	kg NO_x eq	3.97x10^3	3.75 x10^3	3.92 x10^3	3.94E+03	3.89 x10^3
Stratospheric ozone depletion	kg CFC-11 eq	2.25 x10	2.12 x10	2.22 x10	2.23 x10	2.20 x10
Terrestrial acidification	kg SO_2 eq	2.97E x10^5	2.81E x10^5	2.93 x10^5	2.95 x10^5	2.91 x10^5
Terrestrial ecotoxicity	kg 1,4-DCB	5.66 x10^6	5.36 x10^6	5.60 x10^6	5.62 x10^6	5.55 x10^6
Water consumption	m^3	1.70 x10^4	1.61 x10^4	1.68 x10^4	1.69 x10^4	1.67 x10^4

Table 16 Forecasting impact from production of refined sugar production year 2020/21-2024/25

Impact category	Unit	Refined sugar				
		2020/21	2021/22	2022/23	2023/24	2024/25
Fine particulate matter formation	kg $PM_{2.5}$ eq	5.78 x10^4	5.47 x10^4	5.72 x10^4	5.75 x10^4	5.68 x10^4
Fossil resource scarcity	kg oil eq	4.90 x105	4.64 x10^5	4.84 x10^5	4.87 x10^5	4.81 x10^5
Freshwater ecotoxicity	kg 1,4-DCB	8.42 x10^4	7.97 x10^4	8.32 x10^4	8.37 x10^4	8.26 x10^4
Freshwater eutrophication	kg P eq	9.92 x10^2	9.38 x10^2	9.80 x10^2	9.85 x10^2	9.73 x10^2
Global warming	kg CO_2 eq	4.90 x10^6	4.64 x10^6	4.85 x10^6	4.87 x10^6	4.81 x10^6
Human carcinogenic toxicity	kg 1,4-DCB	1.64 x10^5	1.55 x10^5	1.62 x10^5	1.62 x10^5	1.60 x10^5
Human non-carcinogenic toxicity	kg 1,4-DCB	3.56 x10^6	3.37 x10^6	3.52 x10^6	3.54 x10^6	3.50 x10^6
Ionizing radiation	kBq Co-60 eq	1.05 x10^5	9.90 x10^6	1.03 x10^5	1.04 x10^5	1.03 x10^5
Land use	m^2a crop eq	8.08 x10^4	7.64 x10^4	7.99 x10^4	8.03 x10^4	7.93 x10^4
Marine ecotoxicity	kg 1,4-DCB	1.18 x10^5	1.12 x10^5	1.17 x10^5	1.18 x10^5	1.16 x10^5
Marine eutrophication	kg N eq	8.01 x10	7.57 x10	7.91 x10	7.95 x10	7.86 x10
Mineral resource scarcity	kg Cu eq	1.17 x10^4	1.11 x10^4	1.16 x10^4	1.17 x10^4	1.15 x10^4
Ozone formation, Human health	kg NO_x eq	5.70 x10^3	5.39 x10^3	5.63 x10^3	5.66 x10^3	5.59 x10^3

Table16 (Cont.)

Ozone formation, Terrestrial ecosystems	kg NO_x eq	5.84×10^3	5.53×10^3	5.77×10^3	5.80×10^3	5.73×10^3
Stratospheric ozone depletion	kg CFC-11 eq	3.36 x10	3.18 x10	3.32 x10	3.34 x10	3.29 x10
Terrestrial acidification	kg SO_2 eq	4.44×10^5	4.20×10^5	4.39×10^5	4.41×10^5	4.35×10^5
Terrestrial ecotoxicity	kg 1,4-DCB	7.86×10^6	7.44×10^6	7.77×10^6	7.81×10^6	7.71×10^6
Water consumption	m^3	2.33×10^4	2.20×10^4	2.30×10^4	2.31×10^4	2.28×10^4

Table 17 Forecasting damage to human health from raw sugar production year 2020/21-2024/25

Impact category	Unit	Raw sugar				
		2020/21	2021/22	2022/23	2023/24	2024/25
Fine particulate matter formation	DALY	1.94 x10	1.84 x10	1.92 x10	1.93 x10	1.91 x10
Global warming, Human health	DALY	2.34	2.22	2.31	2.33	2.30
Human carcinogenic toxicity	DALY	2.76×10^{-1}	2.61×10^{-1}	2.73×10^{-1}	2.74×10^{-1}	2.71×10^{-1}
Human non-carcinogenic toxicity	DALY	2.30×10^{-1}	2.17×10^{-1}	2.27×10^{-1}	2.28×10^{-1}	2.25×10^{-1}
Ionizing radiation	DALY	3.51×10^{-4}	3.32×10^{-4}	3.47×10^{-4}	3.49×10^{-4}	3.45×10^{-4}
Ozone formation, Human health	DALY	2.52×10^{-3}	2.39×10^{-3}	2.49×10^{-3}	2.51×10^{-3}	2.48×10^{-3}
Stratospheric ozone depletion	DALY	9.60×10^{-3}	9.08×10^{-3}	9.49×10^{-3}	9.54×10^{-3}	9.42×10^{-3}

Table17 (Cont.)

Water consumption, Human health	DALY	3.19×10^{-2}	3.01×10^{-2}	3.15×10^{-2}	3.17×10^{-2}	3.13×10^{-2}
Total damage to human health	DALY	22.33	21.13	22.07	22.19	21.91

Table 18 Forecasting damage to human health from production of granulated sugar production year 2020/21-2024/25

Impact category	Unit	Granulated sugar				
		2020/21	2021/22	2022/23	2023/24	2024/25
Fine particulate matter formation	DALY	2.03×10^{2}	1.92×10^{2}	2.01×10^{2}	2.02×10^{2}	2.00×10^{2}
Global warming, Human health	DALY	2.46 x10	2.33 x10	2.44 x10	2.45 x10	2.42 x10
Human carcinogenic toxicity	DALY	2.93	2.78	2.90	2.91	2.88
Human non-carcinogenic toxicity	DALY	2.69	2.55	2.66	2.68	2.64
Ionizing radiation	DALY	3.86×10^{-3}	3.66×10^{-3}	3.82×10^{-3}	3.84×10^{-3}	3.79×10^{-3}
Ozone formation, Human health	DALY	2.68×10^{-2}	2.53×10^{-2}	2.65×10^{-2}	2.66×10^{-2}	2.63×10^{-2}
Stratospheric ozone depletion	DALY	1.00×10^{-1}	9.49×10^{-2}	9.92×10^{-2}	9.97×10^{-2}	9.85×10^{-2}
Water consumption, Human health	DALY	3.27×10^{-1}	3.09×10^{-1}	3.23×10^{-1}	3.25×10^{-1}	3.21×10^{-1}
Total damage to human health	DALY	234.15	221.56	231.45	232.66	229.77

Table 19 Forecasting damage to human health from refined sugar production year 2020/21-2024/25

Impact category	Unit	Refined sugar				
		2020/21	2021/22	2022/23	2023/24	2024/25
Fine particulate matter formation	DALY	2.76×10^{2}	2.61×10^{2}	2.73×10^{2}	2.74×10^{2}	2.71×10^{2}
Global warming, Human health	DALY	3.34×10	3.16×10	3.30×10	3.32×10	3.28×10
Human carcinogenic toxicity	DALY	3.95	3.73	3.90	3.92	3.87
Human non-carcinogenic toxicity	DALY	3.64	3.44	3.60	3.62	3.57
Ionizing radiation	DALY	5.21×10^{-3}	4.93×10^{-3}	5.15×10^{-3}	5.18×10^{-3}	5.12×10^{-3}
Ozone formation, Human health	DALY	3.63×10^{-2}	3.43×10^{-2}	3.58×10^{-2}	3.60×10^{-2}	3.56×10^{-2}
Stratospheric ozone depletion	DALY	1.36×10^{-1}	1.29×10^{-1}	1.34×10^{-1}	1.35×10^{-1}	1.33×10^{-1}
Water consumption, Human health	DALY	4.38×10^{-1}	4.14×10^{-1}	4.33×10^{-1}	4.35×10^{-1}	4.30×10^{-1}
Total damage to human health	DALY	317.40	300.32	313.74	315.38	311.46

Table 20 Forecasting damage to ecosystems from raw sugar production year 2020/21-2024/25

Impact category	Unit	Raw sugar				
		2020/21	2021/22	2022/23	2023/24	2024/25
Freshwater ecotoxicity	Species.yr	1.76×10^{-5}	1.67×10^{-5}	1.74×10^{-5}	1.75×10^{-5}	1.73×10^{-5}
Freshwater eutrophication	Species.yr	2.62×10^{-4}	2.48×10^{-4}	2.59×10^{-4}	2.60×10^{-4}	2.57×10^{-4}
Global warming, Freshwater ecosystems	Species.yr	1.93×10^{-7}	1.82×10^{-7}	1.91×10^{-7}	1.92×10^{-7}	1.89×10^{-7}
Global warming, Terrestrial ecosystems	Species.yr	7.06×10^{-3}	6.68×10^{-3}	6.98×10^{-3}	7.01×10^{-3}	6.93×10^{-3}
Land use	Species.yr	3.14×10^{-4}	2.97×10^{-4}	3.11×10^{-4}	3.12×10^{-4}	3.08×10^{-4}
Marine ecotoxicity	Species.yr	3.72×10^{-6}	3.52×10^{-6}	3.68×10^{-6}	3.70×10^{-6}	3.65×10^{-6}
Marine eutrophication	Species.yr	6.32×10^{-8}	5.98×10^{-8}	6.24×10^{-8}	6.28×10^{-8}	6.20×10^{-8}
Ozone formation, Terrestrial ecosystems	Species.yr	3.67×10^{-4}	3.47×10^{-4}	3.63×10^{-4}	3.64×10^{-4}	3.60×10^{-4}
Terrestrial acidification	Species.yr	5.07×10^{-2}	4.79×10^{-2}	5.01×10^{-2}	5.03×10^{-2}	4.97×10^{-2}
Terrestrial ecotoxicity	Species.yr	2.37×10^{-5}	2.24×10^{-5}	2.34×10^{-5}	2.35×10^{-5}	2.32×10^{-5}
Water consumption, Aquatic ecosystems	Species.yr	9.84×10^{-9}	9.31×10^{-9}	9.73×10^{-9}	9.78×10^{-9}	9.65×10^{-9}
Water consumption, Terrestrial ecosystem	Species.yr	1.95×10^{-4}	1.84×10^{-4}	1.92×10^{-4}	1.93×10^{-4}	1.91×10^{-4}
Total damage to ecosystems	Species.yr	5.89×10^{-2}	5.57×10^{-2}	5.82×10^{-2}	5.85×10^{-2}	5.78×10^{-2}

Table 21 Forecasting damage to ecosystems from granulated sugar production year 2020/21-2024/25

Impact category	Unit	Granulated sugar				
		2020/21	2021/22	2022/23	2023/24	2024/25
Freshwater ecotoxicity	Species.yr	2.04×10^{-4}	1.93×10^{-4}	2.01×10^{-4}	2.03×10^{-4}	2.00×10^{-4}
Freshwater eutrophication	Species.yr	2.87×10^{-3}	2.72×10^{-3}	2.84×10^{-3}	2.85×10^{-3}	2.82×10^{-3}
Global warming, Freshwater ecosystems	Species.yr	2.03×10^{-6}	1.92×10^{-6}	2.00×10^{-6}	2.02×10^{-6}	1.99×10^{-6}
Global warming, Terrestrial ecosystems	Species.yr	7.43×10^{-2}	7.03×10^{-2}	7.34×10^{-2}	7.38×10^{-2}	7.29×10^{-2}
Land use	Species.yr	3.39×10^{-3}	3.20×10^{-3}	3.35×10^{-3}	3.36×10^{-3}	3.32×10^{-3}
Marine ecotoxicity	Species.yr	4.31×10^{-5}	4.08×10^{-5}	4.26×10^{-5}	4.29×10^{-5}	4.23×10^{-5}
Marine eutrophication	Species.yr	6.78×10^{-7}	6.41×10^{-7}	6.70×10^{-7}	6.73×10^{-7}	6.65×10^{-7}
Ozone formation, Terrestrial ecosystems	Species.yr	3.89×10^{-3}	3.68×10^{-3}	3.85×10^{-3}	3.87×10^{-3}	3.82×10^{-3}
Terrestrial acidification	Species.yr	5.30×10^{-1}	5.01×10^{-1}	5.24×10^{-1}	5.26×10^{-1}	5.20×10^{-1}
Terrestrial ecotoxicity	Species.yr	2.83×10^{-4}	2.67×10^{-4}	2.79×10^{-4}	2.81×10^{-4}	2.77×10^{-4}
Water consumption, Aquatic ecosystems	Species.yr	1.01×10^{-7}	9.59×10^{-8}	1.00×10^{-7}	1.01×10^{-7}	9.95×10^{-8}
Water consumption, Terrestrial ecosystem	Species.yr	2.00×10^{-3}	1.89×10^{-3}	1.97×10^{-3}	1.98×10^{-3}	1.96×10^{-3}
Total damage to ecosystems	Species.yr	6.17×10^{-1}	5.83×10^{-1}	6.10×10^{-1}	6.13×10^{-1}	6.05×10^{-1}

Table 22 Forecasting damage to ecosystems from refined sugar production year 2020/21-2024/25

Impact category	Unit	Refined sugar				
		2020/21	2021/22	2022/23	2023/24	2024/25
Freshwater ecotoxicity	Species.yr	2.75×10^{-4}	2.61×10^{-4}	2.72×10^{-4}	2.74×10^{-4}	2.70×10^{-4}
Freshwater eutrophication	Species.yr	3.89×10^{-3}	3.68×10^{-3}	3.84×10^{-3}	3.86×10^{-3}	3.81×10^{-3}
Global warming, Freshwater ecosystems	Species.yr	2.75×10^{-6}	2.60×10^{-6}	2.72×10^{-6}	2.73×10^{-6}	2.70×10^{-6}
Global warming, Terrestrial ecosystems	Species.yr	1.01×10^{-1}	9.52×10^{-2}	9.95×10^{-2}	1.00×10^{-1}	9.88×10^{-2}
Land use	Species.yr	4.59×10^{-3}	4.34×10^{-3}	4.53×10^{-3}	4.56×10^{-3}	4.50×10^{-3}
Marine ecotoxicity	Species.yr	5.83×10^{-5}	5.52×10^{-5}	5.76×10^{-5}	5.79×10^{-5}	5.72×10^{-5}
Marine eutrophication	Species.yr	9.14×10^{-7}	8.65×10^{-7}	9.04×10^{-7}	9.08×10^{-7}	8.97×10^{-7}
Ozone formation, Terrestrial ecosystems	Species.yr	5.27×10^{-3}	4.99×10^{-3}	5.21×10^{-3}	5.24×10^{-3}	5.17×10^{-3}
Terrestrial acidification	Species.yr	7.18×10^{-1}	6.80×10^{-1}	7.10×10^{-1}	7.14×10^{-1}	7.05×10^{-1}
Terrestrial ecotoxicity	Species.yr	3.81×10^{-4}	3.61×10^{-4}	3.77×10^{-4}	3.79×10^{-4}	3.74×10^{-4}
Water consumption, Aquatic ecosystems	Species.yr	1.36×10^{-7}	1.29×10^{-7}	1.34×10^{-7}	1.35×10^{-7}	1.33×10^{-7}
Water consumption, Terrestrial ecosystem	Species.yr	2.67×10^{-3}	2.53×10^{-3}	2.64×10^{-3}	2.66×10^{-3}	2.62×10^{-3}
Total damage to ecosystems	Species.yr	8.36×10^{-1}	7.91×10^{-1}	8.26×10^{-1}	8.31×10^{-1}	8.20×10^{-1}

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