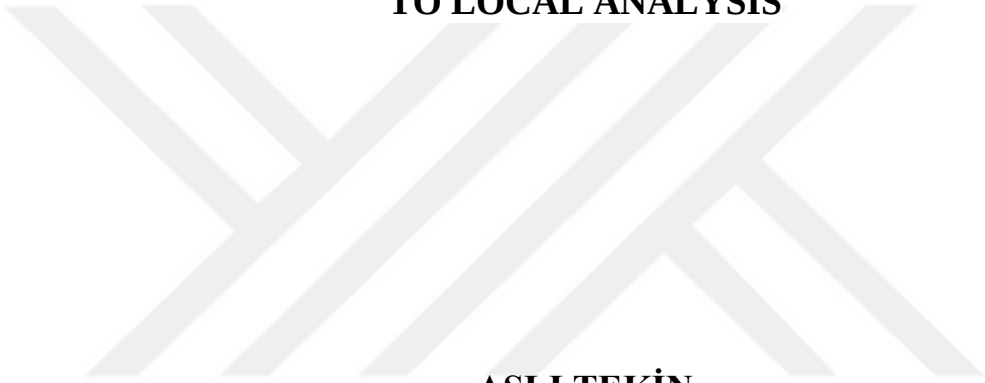


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**FEASIBILITY ANALYSIS OF BIOHYDROGEN GENERATION
FROM DIFFERENT FOOD WASTES IN TURKEY: A GLOBAL
TO LOCAL ANALYSIS**



ASLI TEKİN

**A THESIS SUBMITTED FOR THE DEGREE OF
MASTER OF SCIENCE
DEPARTMENT OF CHEMICAL ENGINEERING**

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T.C.
GEBZE TEKNİK ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ

TÜRKİYE'DEKİ FARKLI GIDA
ATIKLARINDAN BİOHİDROJEN ÜRETİMİ
FİZİBİLİTE ANALİZİ: KÜRESELDEN
YERELE ANALİZLER

ASLI TEKİN
YÜKSEK LİSANS TEZİ
KİMYA MÜHENDİSLİĞİ ANABİLİM DALI

DANIŞMANI
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GEBZE

2022



YÜKSEK LİSANS JÜRİ ONAY FORMU

GTÜ Fen Bilimleri Enstitüsü Yönetim Kurulu'nun 16/06/22 tarih ve 2022/29 sayılı kararıyla oluşturulan jüri tarafından 29/06/2022. tarihinde tez savunma sınavı yapılan Aslı TEKİN'in tez çalışması Kimya Mühendisliği Anabilim Dalında YÜKSEK LİSANS tezi olarak kabul edilmiştir.

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İMZA/MÜHÜR

SUMMARY

In this thesis study, Turkey's wheat, corn, barley, rice and potato production, consumption, associated losses and food waste generation till 2030 were forecasted based on semi-empirical models. Biohydrogen generation potentials from these wastes streams were estimated based on different scenarios using the models developed in this study. It is found that Turkey's corn, coarse grains and rice production do not meet the country's demand for consumption, which is important for Turkey's food safety and strategy. It was estimated that biohydrogen worth 1.1 billion US\$ could be produced from Turkey's household food wastes in 2030 and utilization of these wastes for biohydrogen generation could provide a synergistic solution to associated environmental problems. The analysis given in this study clearly showed that there is a great potential for economic and environmental gain from agricultural and food waste based biohydrogen generation in Turkey. Therefore, the methodology given in this study could be used by researchers around the globe to forecast local and national biohydrogen production potentials from agricultural and food wastes.

Key Words: agricultural waste, biohydrogen, food waste, sustainability, techno-economic analysis.

ÖZET

Bu tez çalışmasında, Türkiye'nin buğday, mısır, arpa, pirinç ve patates üretim, tüketim, üretim ve tüketim kayıpları ve gıda atığı üretim potansiyelleri 2030 yılına kadar yarı-ampirik modeller ile tahmin edilmiştir. Bu modeller kullanılarak daha sonrasında atık akımlarından biyohidrojen üretim potansiyelleri farklı senaryolara göre hesaplanmıştır. Yapılan detaylı analiz neticesinde Türkiye'nin mısır, kaba tahıl ve pirinç üretimlerinin ülkedeki tüketimi karşılamaya yetmediği tespit edilmiştir. Bu bulgu Türkiye'nin gıda güvenliği ve stratejisi açısından oldukça önemlidir. Yapılan modelleme çalışmaları neticesinde Türkiye'nin gıda atıklarından 2030 yılında yaklaşık 1.1 milyar dolar değerinde biyohidrojen üretilebileceği hesaplanmıştır. Bu üretim sayesinde Türkiye'nin ilgili çevresel problemlere sinerjik bir çözüm sağlanabilecektir. Yapılan tez çalışması Türkiye'nin tarımsal ve gıda atıklarından biyohidrojen üretimi konusunda oldukça iyi bir potansiyeli olduğunu net bir şekilde ortaya koymuştur. Sonuç olarak, bu çalışmada verilen metodoloji dünyadaki başka araştırmacılar tarafından tarımsal ve gıda atıklarından yerel ve ülkesel seviyede biyohidrojen üretim potansiyellerinin hesaplanmasında kullanılabilecektir.

Anahtar Kelimeler: biyohidrojen, gıda atığı, sürdürülebilirlik, tarımsal atık, teknik-ekonomik analiz.

ACKNOWLEDGEMENTS

I would like to express my deep and sincere gratitude to my supervisor, Prof. Dr. Mehmet MELİKOĞLU, who not only shared his profound scientific knowledge with me but also shared his valuable knowledge and experience with me. His support, suggestions and encouragement gave me the drive and will to complete this work.

I am highly grateful to my precious family for their love and support.



TABLE of CONTENTS

	<u>Page</u>
SUMMARY	v
ÖZET	vi
ACKNOWLEDGMENTS	vii
TABLE of CONTENTS	viii
LIST of ABBREVIATIONS and ACRONYMS	x
LIST of FIGURES	xii
LIST of TABLES	xvi
1. INTRODUCTION	1
2. LITERATURE REVIEW and DATA	11
2.1. Data for Biohydrogen Generation from Different Food Wastes	11
2.1.1. Biohydrogen Yield from Different Crop and Cereal Wastes	11
2.1.2. Production of Biohydrogen	14
2.1.3. Biohydrogen Yield from Different Crop and Cereal Wastes	15
2.2. Data for Agricultural Wastes in Turkey and Associated Biohydrogen Yields	15
2.2.1. Major Food Wastes Generated in Turkey	16
2.2.2. Data Used for Estimating Biohydrogen Generation from Agricultural Wastes in Turkey	16
2.3. Data for Wheat, Corn, Barley, Rice and Potato Production, Consumption and Associated Losses in Turkey	18
3. METHODOLOGY	22
3.1. Methodology for Forecasting Turkey's Wheat, Corn, Barley, Rice and Potato Production, Consumption and Associated Losses between 2010 and 2030	22
3.2. Biohydrogen Generation Potentials from Wheat, Barley, Corn, Rice and Potato Production and Consumption Losses in Turkey between 2010 and 2030 with Different Scenarios	25
4. RESULTS and DISCUSSION	27

4.1. Forecasting Turkey's Wheat, Barley, Corn, Rice and Potato Production, Consumption and Associated Losses between 2010 and 2030	27
4.2. Forecasting Turkey's Biohydrogen Generation Potential from Wheat, Barley, Corn, Rice and Potato Production and Consumption Losses between 2010 and 2030 and Calculating Biohydrogen Yield from Generic Food Waste	32
4.3. From Global to Local: Waste Analysis for Wheat, Barley, Corn, Rice and Potato Production around the World and Estimating Biohydrogen Yield from Food Waste in Turkey	39
4.4. Techno-economic Evaluation	47
5. CONCLUSION	57
REFERENCES	58
BIOGRAPHY	63

LIST OF ABBREVIATIONS AND ACRONYMS

<u>Abbreviations and Acronyms</u>	<u>Explanations</u>
ε_t	: "Random" error term
%	: Percentage
A	: Availability factor of the crop and cereal losses, %
Bcl(t)	: Biyohydrogen yield from crop and cereal production loss in year t in liters
Bfw(t)	: Biohydrogen generation forecast from food waste in year t in liters
Bpl(t)	: Biyohydrogen yield from crop and cereal production loss in year t in liters
By	: Biyohydrogen yield from crop and cereal in litres per ton
Cc(t)	: Crop and cereal consumption in year t in tons
Ccl(t)	: Crop and cereal consumption loss in year t in tons
Ccpc	: Average crop and cereal consumption per capita in kg
CCSU	: Carbon capture storage and use
CO ₂	: Carbon dioxide
Cp(t)	: Crop and cereal production in year t in tonnes
Cpl(t)	: Crop and cereal production loss in year t in tons
Cppc	: Average crop and cereal production per capita in kg
FAO	: Food and Agriculture Organization
Fclf	: Average crop and cereal consumption loss factor
Fplf	: Average crop and cereal production loss factor
Fw(t)	: Food waste generation forecast in year t in tons
Fwpc	: Annual household food waste per capita in tons
g	: Gram
GDP	: Gross domestic product
H ₂	: Hydrogen
HRES	: Hybrid Renewable Energy Systems
IEA	: International Energy Agency

kg	: Kilogram
kW	: Kilowatt
kWh	: Kilowatt-hour
L	: Liter
m ³	: Cubic meter
MJ	: Mega joule
mL	: Mililiter
MSW	: Municipal solid waste
Mt	: Milltion tonnes
Mtoe	: Million tons of oil equivalent
N/A	: Not applicable or not available
OECD	: Organization for Economic Co-Operation and Development
P(t)	: Population
SMR	: Steam methane reforming
t	: Year
toe	: Tons of oil equivalent
TurkStat	: Turkish Statistical Institute
TWh	: Terawatt-hour
U.S	: United States Of America
UN	: United Nations
UNEP	: United Nations Environment Programme
US\$	: United States Dollar

LIST OF FIGURES

<u>Figure No:</u>	<u>Page</u>
1.1: Biyohydrogen production ways.	6
2.3: (a) Wheat, corn, barley, rice and potato production in Turkey, in tons, (b) Wheat, corn, barley, rice and potato production losses in Turkey, in tons, (c) Wheat, corn, barley, rice and potato production losses/production in Turkey, %, (d) Wheat, corn, barley, rice and potato consumption in Turkey, in tons.	19
4.1.1: (a) Production of wheat, barley, corn, rice and potato in Turkey, kg, (b) Consumption per capita of wheat, barley, corn, rice and potato in Turkey, kg, (c) Wheat, barley, corn, rice and potato production forecasts in Turkey between 2010 and 2030, tons, (d) Wheat, barley, corn, rice and potato consumption forecasts in Turkey between 2010 and 2030, tons.	28
4.1.2: (a) Forecasts for production losses of wheat, barley, corn, rice and potato in Turkey between 2010 and 2030, tons, (b) Forecasts for consumption losses of wheat, barley, corn, rice and potato in Turkey between 2010 and 2030, tons.	31
4.2.1: (a) Forecasted theoretical maximum biohydrogen generation from wheat, barley, corn, rice and potato production losses, m ³ H ₂ , (b) Forecasted theoretical maximum biohydrogen generation potential from wheat, barley, corn, rice and potato consumption losses, m ³ H ₂ , (c) Forecasted theoretical maximum biohydrogen generation potential if 1.0% of wheat, barley, corn, rice and potato production losses are recovered, m ³ H ₂ , (d) Forecasted theoretical maximum biohydrogen generation potential if 1.0% of wheat, barley, corn, rice and potato consumption losses are recovered, m ³ H ₂ .	34
4.2.2: (a) Average maximum biohydrogen production yield for wheat, barley, corn, rice, potato and food waste, (b) Average maximum biohydrogen production yield for vegetable waste, fruit waste, bread waste, meat/meat product wastes and food (generic).	38

4.3.1:	(a): Wheat, barley, corn, rice and potato production in South Korea between 2010 and 2019, (b): Wheat, barley, corn, rice and potato production in the U.S. between 2010 and 2019, (c): Wheat, barley, corn, rice and potato production in Italy between 2010 and 2019.	39
4.3.2:	Annual per capita household food waste of Italy, the U.S. and South Korea in 2020, kg.	42
4.3.3:	Global data on food loss from post-harvest to distribution in 2019	43
4.3.4:	(a): Household food waste calculated forecast for Turkey by using forecast population between 2010 and 2030, tons, (b): 0.1%, 0.5%, 1.0%, 3.0% and 5.0% of the food waste generated in Turkey between 2010 and 2030, tons, (c): Generation of maximum assessed H2 for the amount of food waste that generated after the recycling at the rates of 0.1%, 0.5%, 1.0%, 3.0% and 5.0% between 2010 and 2030 in Turkey, L H2.	44

LIST OF TABLES

<u>Table No:</u>	<u>Page</u>
1.1: Socio-economic, energy and greenhouse gas emission related parameters of Turkey.	2
1.2: Comparison of the electricity generation by sources around the world.	4
1.3: Food loss and waste percentages in different region.	7
1.4: Municipal waste distribution of Turkey.	8
1.5: High energy agricultural crop residues energy content and production values in Turkey.	9
2.1.1: Biohydrogen potential from different agricultural residues in batch type process.	13
2.1.2: Biohydrogen yields from different processes.	14
2.1.3: H ₂ production yields of agricultural wastes via anaerobic fermentation in batch reactors.	15
2.2.2.1: Total utilized agricultural land between 2015 and 2020.	17
2.2.2.2: Statistical data about crops and cereals in Turkey.	17
3.1.1: Average values and OECD-FAO estimates for per capita for Turkey's per capita wheat, barley, corn, rice and potato production and consumption values.	23
3.1.2: Turkey's population forecast between 2010 and 2030.	24
3.1.3: Average values for Turkey's wheat, barley, corn, rice and potato production losses/production and consumption losses/consumption between 2010 and 2030.	25
4.2.1: An average of maximum hydrogen production yield value for wheat, barley, corn, rice, potato and food waste.	33
4.2.2: Maximum H ₂ production yields for vegetable waste, fruit waste, bread waste and meat/meat products wastes.	37
4.4.1: Value chain steps in the projected costs for hydrogen in Europe in 2030.	48

4.4.2: Forecasts for food waste generation, biohydrogen production both in 50
litres and kg, production cost and sale costs, and net return (a) when
the recovery rate is 100%, (b) when the recovery rate is 0.1%, (c)
when the recovery rate is 0.5%, (d) when the recovery rate is 1.0%,
(e) when the recovery rate is 3.0%, (f) when the recovery rate is
5.0%.



1. INTRODUCTION

Turkey is located in a unique geographical location that acts as a bridge between the Europe, Asia and North Africa. This unique location makes Turkey an economic hub for the Middle East and Northern Africa (MENA) region. As of 2019, Turkey is considered as a developing country with a population greater than 84 million people [Web 14]. In the same year, the annual population growth rate of Turkey was estimated as nearly 1.3% [Web 14]. Turkey has a vast economy that is powered by its agricultural, industrial and service sectors. Out of these three, agriculture has been an important component of Turkey's economy since its foundation in 1923. Turkey has vast amounts of suitable land for agriculture due to its geographic location and climatic conditions. These agricultural lands are dispersed throughout the country. Favorable and mild climatic conditions are found in different locations of Turkey, which supports annual production of different types of vegetables and fruits together with different type of crops such as wheat, barley, corn (also known as maize) and etc. Turkey's agricultural and food production sustains most of the local demand and excess food is exported to many countries around the world.

In the last 20 years, Turkey's gross domestic product (GDP) has been increasing almost continuously [Web 14]. In 2019, Turkey's GDP reached to US\$ 761,425 million [Web 14]. Turkey's population and life expectancy also increased in the last couple of decades due to increasing public welfare and economic status. In 2019, the average life expectancy in Turkey was recorded as 78 years [Web 14]. Details about Turkey's economic and energy related indicators are given in Table 1.1 [Web 5]; [Web 10]; [Web 13]; [Web 14].

Table 1.1: Socio-economic, energy production and gas emission indices about Turkey.

Parameters	Unit/Factor	Publication Year	Data	Reference
Social parameters				
Population, total	Million	2019	83,429,615	[Web 14]
Population growth rate	%	2019	1.34	[Web 14]
Agriculture sector/Total sectors	%	2017	6.80	[Web 10]
Industrial sector/Total sectors	%	2017	32.30	[Web 10]
Services sector/Total sectors	%	2017	60.70	[Web 10]
GDP real growth rate	%	2019	0.98	[Web 14]
GDP annual	%	2019	0.92	[Web 14]
Energy parameters				
Energy production	Mtoe	2019	40.40	[Web 5]
Total energy supply [TES]	Mtoe	2019	144.20	[Web 5]
Net energy imports	Mtoe	2019	109.30	[Web 5]
TES/population	toe/capita	2019	1.77	[Web 5]
Total electricity [power] generation	TWh	2019	272.50	[Web 5]
Coal power/Total power	%	2019	37.10	[Web 13]
Natural gas power/Total power	%	2019	18.90	[Web 13]
Liquid fuels/Total power	%	2019	0.10	[Web 13]
Hydropower/Total power	%	2019	29.20	[Web 13]
Renewable energy and wastes power/Total power	%	2019	14.70	[Web 13]
Greenhouse gas emissions parameters				
Carbon dioxide emissions [emissions from fuel combustion only]	Mt of CO ₂	2019	374.10	[Web 5]
Carbon dioxide emissions/TES	t CO ₂ /toe	2019	2.59	[Web 5]
Carbon dioxide emissions /Population	t CO ₂ /capita	2019	4.60	[Web 5]

Energy is essential for sustaining our daily life. Mankind needs continuous supply of energy 7/24. In the 21st century, global economy is powered by energy. Agriculture, manufacturing, telecommunication, internet technologies, food industry, and etc. all require continuous supply of energy for delivering products and services.

As a result, energy security is a key component of the worldwide economic and social system.

Unstopping global population growth continuously increases the demand for energy. Energy consumption has been continuously increasing since the beginning of the 21st century. In 2014, global energy consumption was nearly 1,920 kg oil per capita [Web 14]. In line with the continuous increasing trend, countries around the globe are in search of finding new energy sources for supplying their demand and fulfilling the environmental constraints. From global to local, energy is an important parameter for the Turkish economy. Details of this can be found in able 1.1.

The global demand for fossil fuels [coal, natural gas, petroleum] has been continuously increasing due to increasing worldwide economic activity [Callegari et al., 2019]. The consumption of fossil fuels for supplying global energy demand skyrocketed greenhouse gas emissions and speeded global warming [Osman et al., 2020]. Finding alternative energy sources to reduce our global dependence on fossil fuels is a must [Rincon et al., 2019]. Therefore, there is global will to utilize renewable energy sources instead of fossil fuels to save the environment and provide a sustainable future for next generations.

Renewable energy sources and nuclear could pave the way for a sustainable future. Increasing industrial and economic activity must be facilitated with increased utilization of cleaner energy sources. There is a global demand for the utilization of solar, wind, geothermal, ocean and biomass energy [Melikoglu, 2018a]. Whereas, there is still global concern about the sustainability and safety of nuclear energy [Melikoglu, 2016].

Global electricity consumption is continuously increasing. In 2014, worldwide electricity consumption per capita was recorded as 3,100 kW [Web 14]. Moreover, electricity consumption is expected to increase in the years to come since the global population is continuously increasing and electricity is the backbone of global economy [Melikoglu, 2018b].

Most of the global electricity demand is supplied from fossil fuels. Yet, the environmental constraints are forcing the governments to shift from a fossil based power generation into a renewable dominated system. The beginning of this shift is nowadays seen in energy markets. The use of fossil fuels is gradually decreasing around the world and the tendency towards renewable energy sources for electricity generation is

increasing [Web 14]. Table 1.2 clearly shows the worldwide change in the composition of energy sources for electricity generation between 1973 and 2018 [Web 5].

Table 1.2: Comparison of the electricity generation by sources around the world.

Electricity Source	
Year 2018	Percentage, %
Coal	38.2%
Oil	2.9%
Natural gas	23.1%
Nuclear	10.2%
Hydro	15.8%
Non-hydro renewables and waste	9.8%
Total	100%
Year 1973	Percentage, %
Coal	38.3%
Oil	24.8%
Natural gas	12.1%
Nuclear	3.3%
Hydro	20.9%
Non-hydro renewables and waste	0.6%
Total	100%

In 2015, worldwide electricity generation from renewable energy sources was 1.645 trillion kWh [Web 14]. Among different renewable energy sources biomass is the only combustible energy source. All biomass can be used as a fuel. Thus, different types of biomass can be used alongside with fossil fuels in hybrid systems. Biomass and biofuels can be used as alternative energy sources to meet the energy demand of the developing and developed world. Hybrid renewable energy systems (HRES) design incorporating biomass is a new and developing research and industrial area with vast applications in many different sectors [Kirim et al., 2021]. It is envisaged that HRES will be used in many sectors in the near future.

The growing gap between increasing energy demand and energy supply has sparked a great interest in biofuel production, which also promoted extensive research in biomass process engineering [Osman et al., 2020]. Biofuels are fuel products that derived from different types of biomass [Callegari et al., 2019]. Biogas, biohydrogen, biodiesel, bioethanol, biomethane, bio-oils are some of the most important types of biofuels [Callegari et al., 2019].

Biomass have different advantages when compared to other renewable energy sources because of its different types. No other renewable energy source has such a spectrum for energy diversity. Solar energy is solar, wind energy is wind, etc. This makes biomass unique. As of today, most of the research focuses on generating new types of biofuels but one of the most common type of biomass is forestry and agro products. Biomass from forestry, agricultural products, and agro-industrial-domestic waste [municipal and solid] streams are the most common types of biomass based energy sources [Toklu, 2017].

Biomass resources can be divided into three groups: a) Forestry products, such as wood, trees, shrubs, wood residues, logging residues, etc., b) energy crops, such as starch (barley, corn, and wheat) and sugar crops (sugar beet and sugar cane), oilseed crops (safflower, sunflower, and soybean), c) wastes, such as agricultural production wastes, crop residues, agricultural processing wastes, urban wastes, wood wastes and food wastes [Melikoglu, 2020c; Ozturk et al., 2017]. Energy production from food wastes is a global hot research topic. Energy generation from food wastes via different bioprocessing routes is a novel research idea [Melikoglu, 2020a].

Today, biogas, bioethanol and biodiesel have a great role in the global liquid and gaseous transportation fuels market. The goal for establishing a circular economy and reducing global greenhouse gas emissions made biofuels key components of today's and tomorrow's energy systems. Amongst different biofuels biohydrogen has an increasing popularity in terms of research and market domination. Global energy companies are building biohydrogen based systems and their future projections include a hydrogen based economy [Web 9].

Biohydrogen is hydrogen that is produced from biomass via chemical or bioprocess engineering routes. Biohydrogen can be used directly in combustion engines for transportation [Guo et al., 2010]. After purification, it can also be used in fuel cells to generate electricity [Guo et al., 2010]. The energy content of [bio]hydrogen is 142 MJ/kg [Jarunglumlert et al., 2018]. This is quite large when compared to the other biofuels. The energy content of biomethane and gasoline are 55.0 MJ/kg and 47.3 MJ/kg, respectively [Jarunglumlert et al., 2018].

Biohydrogen is a unique and environmentally friendly fuel, which is considered as a sustainable alternative to fossil based fuels [Chai et al., 2021; Oruc & Dincer, 2021]. The outcome of pure biohydrogen combustion is water [Rajagopal et

al., 2021]. There are different routes for biohydrogen production as shown in Figure 1.1.

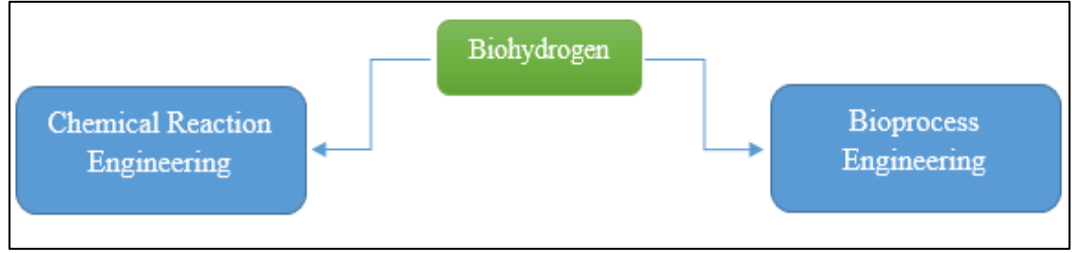
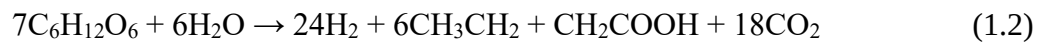
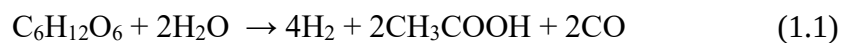
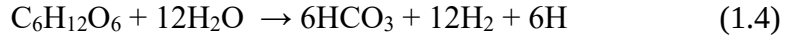
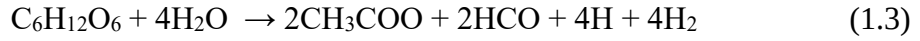


Figure 1.1: Biohydrogen production ways.

Chemical processes (conventional) such as gasification of hydrocarbons and steam reforming are considered as unsustainable and not environmentally benign for biohydrogen generation because fossil fuels are used as raw materials. On the contrary, biohydrogen generated via bioprocess engineering routes are considered as more environmentally friendly and if the process routes are optimized they could also be considered as sustainable. The current novel research on biohydrogen focuses on production routes dealing with the utilization of organic wastes [W. Han et al., 2016]. In that context biohydrogen generation from wastes is a hot research topic.

Biohydrogen can be produced via the following four routes: (a) Biofermentation (dark and photofermentation), (b) biophotolysis (direct and indirect), (c) bioelectrochemical, and (d) gasification [Osman et al., 2020]. Biohydrogen production with dark fermentation is a very complex process and it is affected by many factors such as inoculum type, temperature, pH, hydraulic retention time (HRT), gas partial pressure, fermentation medium, and fermentation end-products [Soares et al., 2020]. The carbon in organic wastes is the primary source for hydrogen generation via biological routes. Routes of biohydrogen production from different organic waste materials via dark fermentation are explained in equations (1.1), (1.2), (1.3) and (1.4) [Sarangi & Nanda, 2020].





Agriculture and food production is key global economic activity [Chatellard et al. 2016]. The main problem with food generation is waste production. Nearly 1.3 billion tons of food is wasted each year [Web 4]. The rate of global food loss is estimated as 13.8% [Web 3]. The percentage of food loss/waste in different global regions are summarized in Table 1.3 [Web 3]. In 2018, Environmental Protection Agency (US EPA) estimated that in the United States (U.S.) nearly 63.1 million tons of food waste was generated from commercial, institutional, and residential sectors [Web 13]. This amount of waste was equal to nearly 21.6% of the municipal solid waste (MSW) generated in the same year [Web 13]. When food waste is not disposed of properly, it causes significant environmental problems. For this reason, it is vital to turn food waste into useful products [Melikoglu et al., 2013].

Table 1.3: Food loss and waste percentages in different region of the world.

Region or country	Percentage, %
Western Asia and Northern Africa	10.8%
Australia and New Zealand	5.8%
Central and Southern Asia	20.7%
Eastern and South-Eastern Asia	7.8%
Latin America and The Caribbean	11.6%
Northern America and Europe	15.7%
Oceania [Not Australia and New Zealand]	8.9%
Sub-Saharan Africa	14.0%

From global to local, agricultural sector provides nearly one fifth [18.1% precisely] of Turkey's employment in 2020 [Web 14]. In the 21st century, Turkey's economy is mostly based on service and industrial sectors. Yet, agriculture still has an important share in the country's economy. In 2019, agriculture had a 6% GDP contribution to the economy [Web 14]. In Turkey, annual per capita food waste generation is nearly 425 kg [or 1.13 kg per day per person] [Web 11]. Majority of food waste in Turkey is generated from agricultural and food processing sectors, which is followed by food waste coming as a part of municipal waste. Municipal waste distribution in Turkey is given in Table 1.4 [Web 11].

Table 1.4: Municipal waste distribution of Turkey.

Title	Unit	Year	Amount
Total waste [collected]	thousand tons per year	2018	32,209
Population	people	2018	82,003,882
Number of municipalities	-	2018	1,399
Waste composted	thousand tons per year	2018	38
Average municipal waste	kg per capita per day	2018	1.16

There are three distinct groups of agricultural waste: First group comprises waste generated from agricultural production, such as crop residues, second group includes livestock waste, and the third group covers food waste, which are end products of agricultural production [Guo et al. 2010]. As can be seen in Table 1.4, the population of Turkey was 82,003,882 people in 2018 and an average of 32,209,000 tons of waste was collected by local authorities. In the same year, the average amount of municipal waste per capita was 1.16 kg per day. As a reminder, these average values will be used as base figures in the forecasting part of this thesis.

Food waste is an important environmental, economic and social problem. Management and disposal of food waste must provide sustainable solutions to the environmental, economic and social problems associated with its disposal. Food waste is generated at any stage of production, processing and consumption [Rao & Rathod, 2019]. In addition, during processing some parts of the foods cannot be recovered and these parts inevitably fall into the waste class [Rao & Rathod, 2019]. Many countries have problems in disposal/treatment of food waste due to inappropriate waste management systems. These problems can be solved by using food wastes as raw materials for alternative purposes.

Utilization of agricultural/food wastes for hydrogen production is a novel research topic and it can provide promising sustainable solutions to the problems in hand. The problem covers energy, food and environmental aspects. Agricultural crop residues can be used as raw materials for hydrogen production. All crops are biodegradable and to altering degrees, possibly can be biologically converted to hydrogen and methane via anaerobic digestion processes [Guo et al., 2010]. The carbon content of crops is the most important factor that affects the amount of hydrogen to be produced [Melikoglu, 2020a].

Energy content of agricultural/food wastes are connected to their calorific value (heat released during combustion in the presence of excess oxygen). Energy or

calorific value is also known as heat value, which is the measurement of a fuel's energy density, and it is expressed in energy (joules) per specified amount (e.g. kilograms) [Melikoglu, 2020a]. Main high energy crop residues produced in Turkey, their energy content and production values are given in Table 1.5 [Ozturk et al., 2017].

Table 1.5: High energy agricultural crop residues energy content and production values in Turkey.

Product	Annual Production [tons]	Energy content [MJ/kg]
Wheat residues	30,000-40,000	18.40
Barley residues	12,000-16,000	17.10
Oats residues	400-600	17.70
Rye residues	350-450	17.60
Rice residues	250-350	15.40
Corn residues	4,000-5,000	16.80
Sun flower residues	2,500-3,000	14.28
Cotton seed residues	2,600-3,100	17.07
Sugar beet residues	1,500-2,000	16.72
Wood and woody materials	12,000,000	224.28

As can be seen from Table 1.5, the most common agricultural residue in Turkey is wood and woody materials, which is expected because wood and woody materials are found abundantly in the nature. Wood has always been a fuel due to its high energy content. Wood and woody materials have the highest energy content amongst all agricultural/food wastes listed in Table 1.5. The average energy content of crops and cereals listed in Table 1.5 is estimated as nearly 16.8 MJ/kg. As a reminder, the values given in this table will be used in the estimation part of this thesis.

Research in biohydrogen is a new topic when compared to the research in the fields of bioethanol, biodiesel and biogas generation. This is beneficial for research and development studies conditional that the research could lead to a sustainable and feasible path. This is one of the reasons of focusing biohydrogen in this thesis. The primary aim of this thesis study can be summarized as technical and economic feasibility analysis of biohydrogen production from different food wastes in Turkey till 2030 based on different scenarios.

In this thesis study, focus is given on biohydrogen production from five different crop/cereal wastes: (i) wheat, (ii) barley, (iii) corn, (iv) rice, and (v) potato and food wastes. A nationwide analysis is carried out for Turkey. The novelty of this

research is estimation (forecasting) of crop production/consumption and production/consumption losses rather than direct calculation of yields from current or past production/consumption data and estimating the food wastes. The source production/consumption data are taken from the literature. In this thesis study, Turkey's wheat, corn, rice, barley and potato production, consumption and associated losses and food waste generation potentials are estimated and related biohydrogen yields are calculated for the first time in the literature.

This thesis is structured as follows: In section 2, results from a detailed literature review about biohydrogen production from different agricultural and food wastes are given based on a global to local perspective. Then, in section 3, data and methodology about wheat, corn, rice and potato production, consumption and associated losses in Turkey are given, and methodology for forecasting Turkey's wheat, corn, rice and potato production, consumption and associated losses between 2010 and 2030 is explained. In section 4, forecasting results about wheat, corn, rice and potato production, consumption, associated losses and food waste generation in Turkey between 2010 and 2030 are given. Then using these forecasting results Turkey's potential biohydrogen production yields from wheat, corn, rice and potato production and consumption losses and food wastes are given based on different scenarios. This section is concluded with a detailed techno-economic analysis of biohydrogen generation from Turkey's food wastes between 2010 and 2030. Finally, conclusions driven from this study are given in the last section of this thesis.

2. LITERATURE REVIEW and DATA

2.1. Data for Biohydrogen Generation from Different Food Wastes

According to the Food and Agriculture Organization of the United Nations [FAO], each year almost 33% of the food [or nearly 1.3 billion tons] edible is lost [or wasted] around the globe [Web 3]. Production of sustainable alternatives to fuels and chemicals from food waste is hot research topic. Food wastes can be converted into alternative fuels such as bioethanol or biohydrogen via different bioprocessing routes [Melikoglu & Menekse, 2020; Melikoglu & Turkmen, 2019]. Hydrogen (H_2) production is positively affected by the processable carbohydrate concentration and adversely affected by the cellulosic material concentration [Kobayashi et al., 2012]. Processing method, temperature, pH, microbial consortium are some of the important factors that affect H_2 production efficiency [Jarunglumlert et al., 2018].

The novel research dealing with H_2 production from food wastes focuses on microorganism community and waste diversity [Melikoglu, 2020a]. Integration of multiple different production processes and different biomass waste streams will be required, alongside with process modeling and optimization for enhanced biohydrogen production [Osman et al., 2020]. Production of biohydrogen from wastes will help alleviating environmental problems associated with the utilization of fossil fuels for power generation by bringing significant environmental benefits, and ultimately leading us to a path that will deliver us to a net-zero (carbon) economy [Melikoglu, 2020a; Osman et al., 2020].

2.1.1. Biohydrogen Yield from Different Crop and Cereal Wastes

Hydrogen has an energy yield of 122 KJ/g [W. Han et al., 2016]. Food and agricultural wastes can be used as a promising carbon source for hydrogen production, as it can lower the cost of generation via dark fermentation using recycled organic urban solid waste [W. Han et al., 2016].

The agricultural residue category can be divided into three groups: (i) Direct agricultural production waste such as crops left on field and crop residues, (ii) livestock

waste (manure), and (iii) different types of food waste [Guo et al., 2010]. Agricultural wastes from harvested crops are considered amongst the most abundant, cheapest and readily available biologically recycled organic wastes. They contain straw, sedge, peels, cobs, stems, pulp and other lignocellulosic residues [Guo et al., 2010].

Food wastes have relatively high energy contents and they are highly biodegradable [Guo et al., 2010]. Food wastes generally contain 85-95% volatile solids and 75-85% moisture, which is highly beneficial for microbial [Guo et al., 2010; Melikoglu, 2020c]. Food wastes can also be used to produce fuels and other value added products but collection and treatment of food wastes should be optimized in order to increase process efficiency. Energy that is stored in food waste are generally in the form of starch, which must be converted into glucose before being utilized by hydrogen-producing microorganisms [W. Han et al., 2016]. Enzymatic hydrolysis is a promising way of converting starch stored in food waste to glucose with the advantage of common conditions and without inhibitor production [W. Han et al., 2016; Melikoglu, 2020a].

Animal waste is readily available in animal husbandry and farmers tend to find alternative solutions to dispose huge amounts of waste that is generated. Biohydrogen production from animal wastes could provide a synergistic solution to this problem. Detailed literature review showed that food waste gives the highest hydrogen yield, followed by crop residues and manure for biohydrogen production [W. Han et al., 2016]; [Melikoglu, 2020b, 2020c].

There are many researches about hydrogen production by dark fermentation, which use simple sugars such as glucose, sucrose or lactose as substrates. However, fewer studies have investigated solid substrate conversion [Guo et al., 2010]. Organic waste materials that are abundant and readily available must also be cheap and highly biodegradable for sustainable biohydrogen production generation [Chatellard et al., 2016]. It is believed that significant amounts of biohydrogen could be produced from agricultural, food and animal wastes in the near future but as of today the technological development is still limited. Biohydrogen production yields of different agricultural wastes and associated process parameters are summarized in Table 2.1.1 [Chatellard et al., 2016].

Table 2.1.1: Biohydrogen potential from different agricultural residues in batch type process.

Substrate	Type of inoculum/ pretreatment	Process conditions [g·l ⁻¹ °C/pH]	H ₂ production yield [ml H ₂ ·g ⁻¹]	References
Beet pulp	Seed sludge	20/35/6.0	90.10	[Ozkan et al., 2011]
Lettuce	Heat-treated anaerobic sludge	20/37/5.5	48.00	[Dong et al., 2009]
Potato	Heat-treated anaerobic sludge	20/37/5.5	102.00	[Dong et al., 2009]
Rice straw	Anaerobic sludge	90/55/6.5	24.80	[Chen et al., 2012]
Soybean straw	Cracked cereal acclimated in continuous stirred tank reactor [CSTR]	-/35/70	5.46	[H. Han et al., 2012]
Sunflower stalk	Anaerobic digested sludge	5/35/5.5	2.30	[Monlau et al., 2013]
Wheat bran	Activated sludge paper mill	100/36/7.0	50.60	[Pan et al., 2008]
Wheat bran	Digested sludge paper	100/36/7.0	28.60	[Pan et al., 2008]
Wheat bran	Mill cornstalk compost	100/36/7.0	22.60	[Pan et al., 2008]
Wheat bran	Wheat straw compost	100/36/7.0	17.70	[Pan et al., 2008]
Wheat stalks	Anaerobic digested activated sludge	60/35/6.5	23.00	[Chu et al., 2011]
Wheat straw	Seed sludge from H ₂ producing CSTR	6/35/-	5.69	[Nasirian et al., 2011]
Wheat straw	Mesophilic anaerobically digested sludge	4/37/5.5	10.52	[Quéméneur et al., 2012]
Wheat straw	<i>Clostridium butyricum</i>	40/35/7.2	9.00	[Li & Chen, 2007]
Wheat stalk	Anaerobic digested dairy manure	60/35/6.5	37.00	[Chu et al., 2011]
Wheat straw	Cow dung compost	25/36/7.0	0.50	[Fan et al., 2006]

In Table 2.1.1, the potential biohydrogen production yields of corn, potato, rice, wheat, other crops and some plant-derived substrates are given based on a detailed literature review. The productions differ from each other in that they require various pre-treatments. Generally, the operation method is batch and the temperatures vary. As a result, the biohydrogen production yields depending on the temperature and operation requirements given in this table are amongst the data to be used in the estimation parts of this thesis.

2.1.2. Production of Biohydrogen

There are various bioprocesses for biohydrogen production including dark fermentation, photofermentation, biophotolysis, microbial electrolysis, gasification [Osman et al., 2020]. Some of these bioprocesses take long time, some require biological improvements, and others require different factors that must all be optimized for increasing process efficiency and biohydrogen yield. Various parameters such as type of raw material, carbon content, need for pre-treatment, temperature, hydraulic retention time [HRT] and pH can all change the efficiency of hydrogen production in these processes [Osman et al., 2020]. Therefore, systems optimization must be carefully made beforehand. Biohydrogen production yields from these different processes are summarized in Table 2.1.2 [Osman et al., 2020].

Table 2.1.2: Biohydrogen yields from different processes.

Production process	Feedstock	Maturity	Energy conversion [%]
Dark fermentation	Biomass	Long Term	4.3
Photofermentation	Biomass + sunlight	Long Term	5.1
Biophotolysis	Biomass + water	Long Term	2.7-4.0
Microbial electrolysis	Biomass + electricity	Long Term	11.3
Biomass gasification	Biomass	Commercial	88.1

Wastewater, wood and agricultural residues, food wastes, municipal and sewerage wastes could all be used in biohydrogen production. Yet, when the concern is high H₂ yield dark fermentation, photo-fermentation and gasification shows promising results [Osman et al., 2020]. Gasification is used for biohydrogen generation but this method is energy intensive and requires expensive equipment.

2.1.3. Biohydrogen Production Yields of Different Agricultural Wastes

Crop residues, livestock and food waste are suitable substrates for biohydrogen production through different bioprocess routes. Table 2.1.3 summarizes estimated H₂ production yields from various agricultural wastes [Guo et al., 2010].

Table 2.1.3: H₂ production yields of agricultural wastes via anaerobic fermentation in batch reactors.

Substrate	Maximum assessed production yield [mL H ₂ ·g ⁻¹]	References
Corn straw	9.0	[Li and Chen 2007]
Corn straw	68.0	[Li and Chen 2007]
Corn stover	49.0	[Datar et al., 2007]
Corn stover	66.0	[Datar et al., 2007]
Corn stalk	57.0	[Zhang et al., 2007]
Corn stalk	150.0	[Zhang et al., 2007]
Corn leaves	42.0	[Ivanova et al., 2009]
Rice bran	61.0	[Noike & Mizuno, 2000]
Wheat straw	68.0	[Ivanova et al., 2009]
Wheat bran	43.0	[Noike & Mizuno, 2000]
Rice	96.0	[Okamoto et al., 2000]

2.2. Data for Agricultural Wastes in Turkey and Associated Biohydrogen Yields

In 2020, cereal production in Turkey was approximately 37.2 million tons, which was 8.1% higher than the production in 2019 [TurkStat, 2020c]. In 2020, wheat production increased by 7.9% and reached to 20.5 million tons, barley production increased by 9.2% and reached to 8.3 million tons, corn production increased by 8.3% and reached to 6.5 million tons, and potato production increased by 4.4% and reached to 5.2 million tons [TurkStat, 2020c].

In 2020, nearly 69.3 million tons of cereals and herbal products, 31.2 million tons of vegetables, and 23.6 million tons of fruits, beverages and spice plants were produced in Turkey [TurkStat, 2020c]. This mean that, production quantities increased by 8.7% in cereals and other herbal products, 0.3% in vegetables, 5.8% in fruits,

beverages and spice crops when compared to the previous year, 2019 [TurkStat, 2020c].

2.2.1. Major Food Wastes Generated in Turkey

According to a recent report, the amount of wasted fruits and vegetables in Turkey was 12 million tons in 2019, which had an estimated worth of 25 million Turkish Liras [$\approx$ US\$ 4.4 billion] [Web 1]. Food waste is a type of biomass, which can be processed to produce value added goods via biorefineries. A partial solution to Turkey's food and/or agricultural waste problem could be found by producing biohydrogen from these different wastes. Detailed literature review given above showed that when food and/or agricultural waste was collected and processed properly significant amounts of biohydrogen could be generated.

The major parameters that could be used for the selection of food and agricultural wastes for biohydrogen generation are easy access, availability, cost, carbohydrate content, carbon to nitrogen [C/N] ratio, and eco-friendliness [Melikoglu, 2020c]. Simple sugars such as glucose, sucrose and lactose are easily biodegradable and preferred raw materials for biofuel production [Melikoglu, 2020c]. Major food and agricultural wastes in Turkey, which could be used for biohydrogen generation are [Melikoglu & Turkmen, 2019]:

- Corn
- Potato
- Rice
- Wheat
- Some vegetables and fruits

2.2.2. Data Used for Estimating Biohydrogen Generation from Agricultural Wastes in Turkey

In 2020, the land used for producing cereals and other crops was reached to 15,615 thousand hectares of sown area and 19,572 thousand hectares total cultivated agricultural area [TurkStat, 2020c]. Total utilized agricultural land in Turkey between 2015 and 2020 are summarized in Table 2.2.2.1 [Web 11].

Table 2.2.2.1: Total utilized agricultural land between 2015 and 2020.

Years	Area [1000 hectare]
2015	38,551
2016	38,328
2017	37,964
2018	37,797
2019	37,716
2020	37,753

Key statistical data about crops and cereals in Turkey including production, harvest losses, domestic use, human consumption, losses, and human consumption per capita [kg] are given in Table 2.2.2.2 [Web 11].

Table 2.2.2.2: Statistical data about crops and cereals in Turkey.

Product	Rice	Potato	Corn	Wheat	Barley
Production	600,000	4,979,824	6,000,000	19,000,000	7,600,000
Harvest Losses	6,000	84,657	180,000	1,045,000	456,000
Domestic Use	699,863	4,703,722	7,705,690	20,069,822	7,536,139
Human Consumption	665,387	4,210,367.8	1,087,401.3	16,034,510.9	71,440
Losses	19,305	141,111.7	174,600	535,673.3	178,600
Human Consumption per capita [kg]	8.0	50.6	13.1	192.8	0.9

In Table 2.2.2.2, production, consumption amounts and production losses are given for rice, potato, corn, wheat and barley, which are amongst the main crops and cereals produced in Turkey. These values are used in the estimation sections in the later parts of this thesis. In a country with high production and consumption rates, waste generation is inevitable. Chemical engineering material balances dicatate waste generation will be colossal if production and consumption rates are high. Finally, It is estimated that nearly 1.13 kg of food and agricultural waste was generated per person per day [Web 11].

2.3. Data for Wheat, Corn, Barley, Rice and Potato Production, Consumption and Associated Losses in Turkey

Turkey's social and economic life is changing alongside with shifts in eating habits and increasing consumption of foods. Food consumption in Turkey is continuously increasing. Increased food consumption must be sustained from increased agricultural production. Thus, huge amounts of wheat, corn, barley, rice and potato waste are generated in Turkey [Melikoglu & Turkmen, 2019]. Any significant loss or wastes in these feedstock streams become major economic and environmental problems. These crops and cereals can also be used as raw materials for biohydrogen production [Avcioğlu et al., 2019]; [Guo et al., 2010]; [Osman et al., 2020]. Thus a win-win situation could be attained if these agricultural wastes are converted into biohydrogen.

In order to estimate biohydrogen production potentials in Turkey from wasted cereals and crops, first, the appropriate production and consumption data must be found from the literature. In this study, the official data from Turkish Statistical Institute [TurkStat] are used for associated calculations. Turkey's wheat, corn, barley, rice and potato production, production losses, consumption and consumption losses between 2010 and 2020 are shown in Figure 2.3 [Web 11] . Here, it must be emphasised that the consumption values given in Figure 2.3 are related to Turkey's population. Novel to this study, ratios of production losses to production and consumption losses to consumption are estimated for the first time in the literature and shown in Figure 2.3.

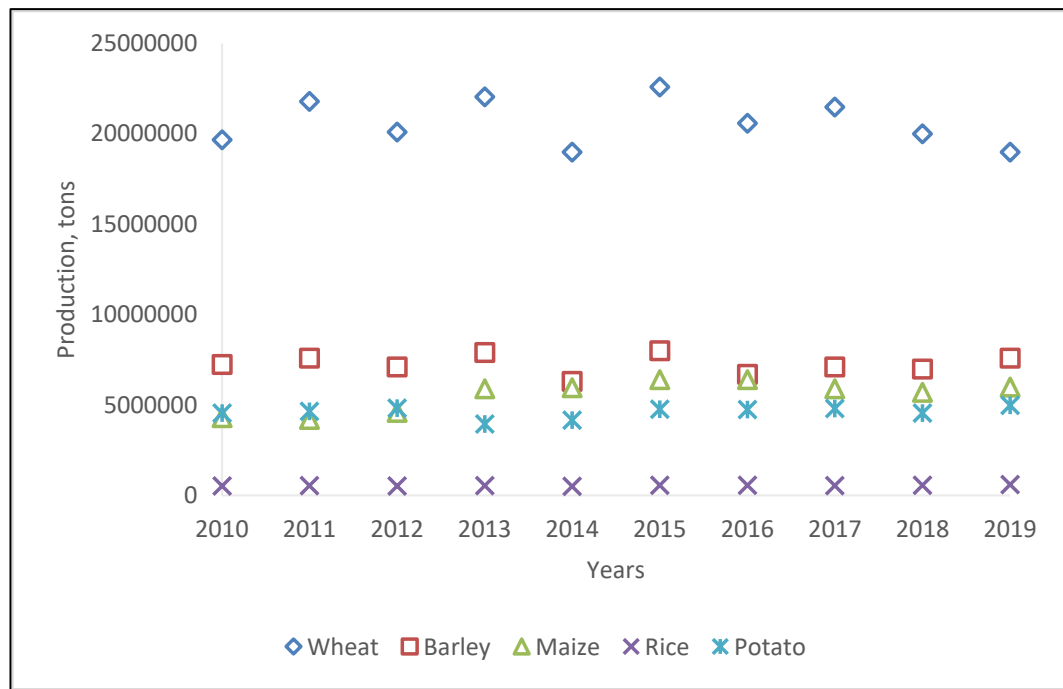


Figure 2.3 (a): Wheat, corn, barley, rice and potato production in Turkey, in tons.

As can be seen from Figure 2.3 (a), wheat production is highest amongst all selected cereals and crops. This is followed by barley, corn, potato and rice production. In terms of consumption, wheat is followed by potato, corn, rice and barley. Since the production and consumption of these five cereals and crops are in million tons range; consequently, associated losses is expected to be in multiple thousand tons range. This estimate for associated losses is validated by checking Figure 2.3 (b) and (c), therefore if recovered and bioprocessed properly then considerable amounts of biohydrogen can be generated from these agricultural waste streams. In order to achieve this goal first Turkey's wheat, corn, barley, rice and potato production and consumption must be accurately forecasted till 2030. When this data is calculated then associated losses from those agricultural waste streams could be estimated.

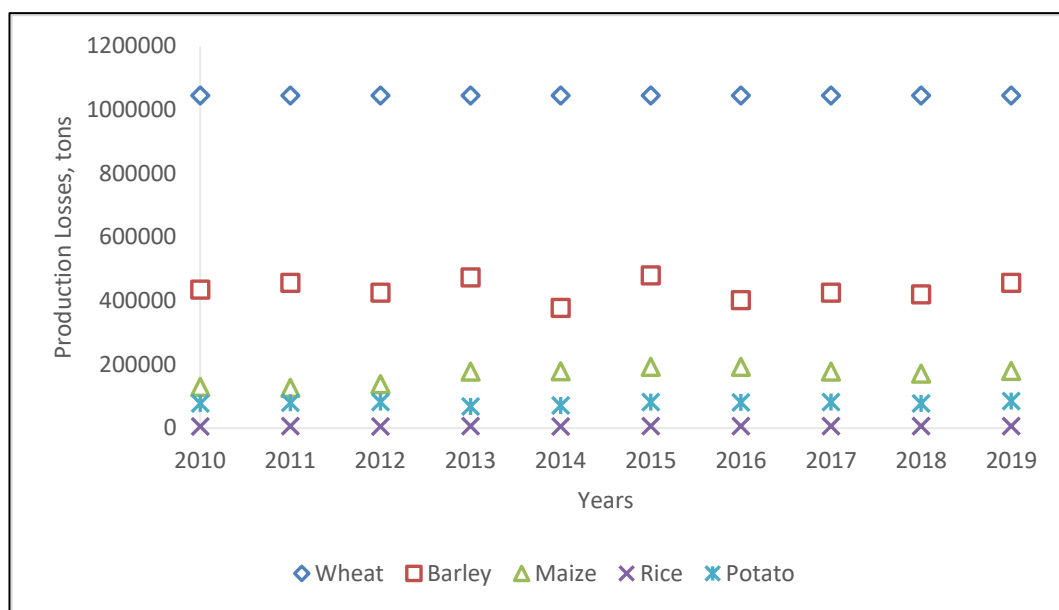


Figure 2.3 (b): Wheat, corn, barley, rice and potato production losses in Turkey, in tons.

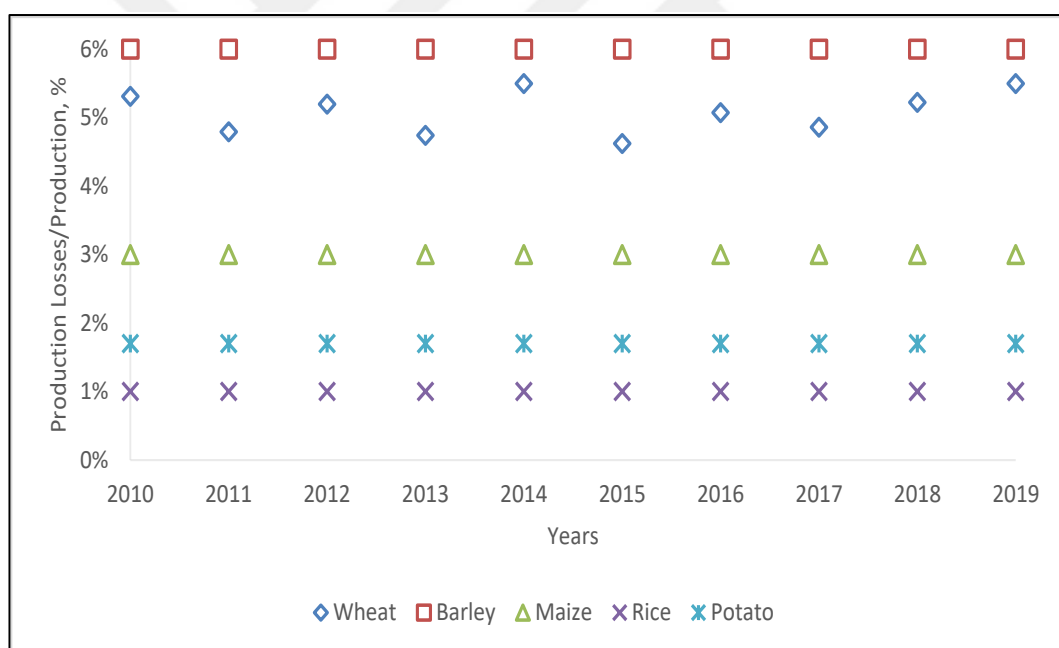


Figure 2.3 (c): Wheat, corn, barley, rice and potato production losses/production in Turkey, %.

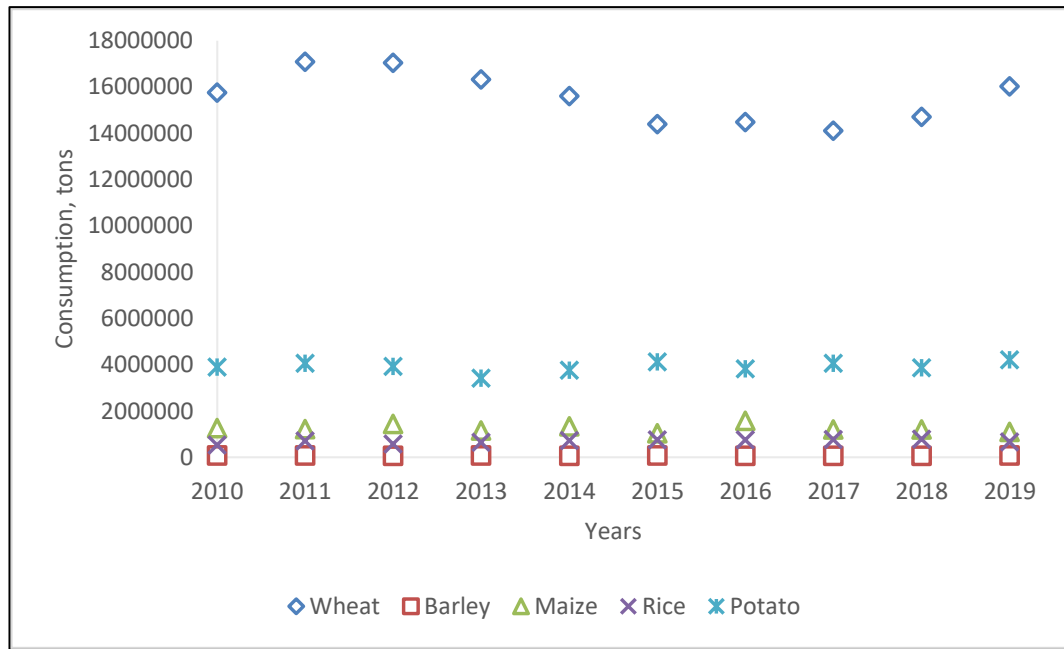


Figure 2.3 (d): Wheat, corn, barley, rice and potato consumption in Turkey, in tons.

Finally, using this data and average yield values given in Table 2.1 and energy content values in Table 1.3, Turkey's potential biohydrogen generation from these waste streams could be estimated. The methodology to do all of this is explained in the following section.

3. METHODOLOGY

3.1. Methodology for Forecasting Turkey's Wheat, Corn, Barley, Rice and Potato Production, Consumption and Associated Losses between 2010 and 2030

The methodology for estimating Turkey's wheat, corn, barley, rice and potato production, consumption and associated losses are as follows: First, Turkey's wheat, corn, barley, rice and potato production and consumption per capita values were calculated and cross-checked with the data from TurkStat. Then, Turkey's wheat, corn, barley, rice and potato production and consumption estimates were calculated using equations (3.1.1) and (3.1.2). Equations were modified from the previous study of our research group [Melikoglu & Turkmen, 2019].

$$C_p(t) = C_{ppc} \times P(t) + \varepsilon_t \quad (3.1.1)$$

$$C_c(t) = C_{cpc} \times P(t) + \varepsilon_t \quad (3.1.2)$$

In equations (3.1.1) and (3.1.2), t represents the year, which is ≥ 2010 , $C_p(t)$ represents the crop or cereal production in year t in tons, and $C_c(t)$ represents the consumption of crop or cereal in year t in tons, C_{ppc} average crop or cereal production per capita, in kg, C_{cpc} average crop or cereal consumption per capita in kg, and $P(t)$ is Turkey's population in year t , and ε_t the "random" error term [Melikoglu and Turkmen 2019]. It is assumed that average per capita production and consumption values between 2010 and 2019 could be used as a solid basis in order to estimate data for the time period between 2010 and 2030.

Average per capita values of Turkey's wheat, barley, corn, rice and potato production and consumption values are given in Table 3.1.1, which was acquired from the United Nations (UN) Food and Agriculture Organization (FAO) and the Organization for Economic Co-operation and Development (OECD) [OECD-FAO Agricultural Outlook 2020-2029]. Turkey's population forecast between 2010 and 2030 are also given in Table 3.1.2 [Web 11].

Table 3.1.1: Average values and OECD-FAO estimates for per capita for Turkey's per capita wheat, barley, corn, rice and potato production and consumption values.

Cereal or Crop	Average per capita production values for 2010 and 2030 in kg, current study, C_{ppc} values calculated from [Web 11]	Average per capita consumption values for 2010 and 2030 in kg, current study, C_{cpc} values calculated from [Web 11]	OECD-FAO estimate for per capita production in 2028 [Web 8]	OECD-FAO estimate for per capita consumption in 2028 [Web 8]	% difference with the per capita consumption estimate found in the current study and OECD-FAO values
Wheat	264.01	199.3	N/A	209.75	4.98% smaller than the OECD-FAO estimate [match 95.02%]
Barley	92.82	0.87	N/A	N/A	N/A
Corn	70.52	16.01		15.99	0.08% greater than the OECD-FAO estimate [match 100.08%]
Potato	58.78	50.01	N/A	N/A	N/A
Rice	6.94	8.75	N/A	9.43	7.21% smaller than the OECD-FAO estimate [match 92.79%]

Table 3.1.2: Turkey's population forecast between 2010 and 2030.

Year	Population
2010	73,722,988
2011	74,724,269
2012	75,627,384
2013	76,667,864
2014	77,695,904
2015	78,741,053
2016	79,814,871
2017	80,810,525
2018	82,003,882
2019	83,154,997
2020	83,614,362
2021	85,042,738
2022	85,561,876
2023	85,957,253
2024	87,396,000
2025	88,844,934
2026	89,698,582
2027	90,560,432
2028	91,430,563
2029	92,309,054
2030	93,328,574

When the annual estimates for production and consumption are available, the relevant losses could be estimated. As a result, the following methodology based on equations (3.1.3) and (3.1.4) are used to estimate Turkey's wheat, corn, rice and potato production-consumption losses between 2010 and 2030. Equations were modified from the previous study of our research group [Melikoglu & Turkmen, 2019].

$$C_{pl}(t) = C_p(t) \times F_{plf} + \varepsilon_t \quad (3.1.3)$$

$$C_{cl}(t) = C_c(t) \times F_{clf} + \varepsilon_t \quad (3.1.4)$$

In equations (3.1.3) and (3.1.4), t represents the year, which is ≥ 2010 , $C_{pl}(t)$ represents the loss of crop or cereal production in year t in tons, and $C_{cl}(t)$ represents loss of crop or cereal consumption in year t in tons. Likewise, $C_p(t)$ and $C_c(t)$ in the equations are represent the production and consumption of crop or cereal in tons. F_{plf} is the average crop or cereal production. The loss factor, F_{clf} , is the average crop or cereal consumption loss factor, and ε_t is a "random" error term.

It is assumed that the average F_{plf} and F_{clf} values of each crop or cereal between 2010 and 2020 could be used as a solid basis in order to estimate data for the time period between 2010 and 2030. As a result, the average F_{plf} and F_{clf} values were calculated and given in Table 3.1.3. As a novelty, these calculations were made for the first time in the literature.

Table 3.1.3: Average values for Turkey's wheat, barley, corn, rice and potato production losses/production and consumption losses/consumption between 2010 and 2030.

Cereal or Crop	Average value for production losses/production, %, values for 2010 and 2030, current study, F_{plf} values calculated from [TurkStat, 2020c]	Average value for consumption losses/consumption, %, values for 2010 and 2030, current study, F_{clf} values calculated from [TurkStat, 2020c]
Wheat	5.1%	3.7%
Barley	6.0%	250%
Corn	3.0%	12.9%
Rice	1.0%	2.5%
Potato	1.7%	3.4%

3.2. Biohydrogen Generation Potentials from Wheat, Barley, Corn, Rice and Potato Production and Consumption Losses in Turkey between 2010 and 2030 with Different Scenarios

When agricultural production and consumption losses were estimated then biohydrogen production potentials from these wastes were estimated using equations (3.2.1) and (3.2.2).

$$B_{pl}(t) = C_{pl}(t) \times B_y \times A + \varepsilon_t \quad (3.2.1)$$

$$B_{cl}(t) = C_{cl}(t) \times B_y \times A + \varepsilon_t \quad (3.2.2)$$

In equations (3.2.1) and (3.2.2), t represents the year, which is ≥ 2010 , $B_{pl}(t)$ is the biohydrogen production potentials from loss of crop or cereal production in year t in liters, $B_{cl}(t)$ is biohydrogen production potentials from the loss of crop or cereal consumption in year t in liters, $C_{pl}(t)$ and $C_{cl}(t)$ are represent the production and

consumption losses of the crop or cereal in year t , and B_y is the biohydrogen yield from crop or cereals in milliliters per g, A is the availability factor of production and consumption losses of crop or cereal to be used for biohydrogen production, and ε_t is a "random" error term.

In this thesis study, A was taken as 100% or 1.0 in order to calculate the maximum biohydrogen potential. Also, B_y values of crop or cereals given in Table 2.1.1 were used for associated calculation. For the data used in the forecasting calculations, the bioprocess type was accepted as batch in the light of literature studies.

For other scenarios, estimated calculations were made by using the energy conversion values given in Table 2.1.2. In order to calculate the energy obtained from production and consumption losses, the energy content data of the crops and cereals products given in Table 1.6 were used.

As a result, in this section, the methodology used in estimating Turkey's wheat, barley, corn, rice and potato production, consumption, losses in production and consumption between 2010 and 2030 and the potential maximum biohydrogen yield from these losses are explained in detail. The data used for associated calculations were estimated using equations (3.1.1) to (3.2.2), and data from Table 2.1.1 and Table 2.1.2. Finally, the results attained using this methodology are given in chapter 4 with appropriate scientific discussion.

4. RESULTS and DISCUSSION

4.1. Forecasting Turkey's Wheat, Barley, Corn, Rice and Potato Production, Consumption and Associated Losses between 2010 and 2030

The results obtained in this thesis study on per capita production and consumption of wheat, barley, corn, rice and potato in Turkey between 2010 and 2019 are given in Figure 4.1. As can be seen from the data given in this figure, the average values of wheat, barley, corn, rice and potato production and consumption per capita in Turkey vary between 5-270 and 1-200 kg, respectively. Thus, the average values of wheat, barley, corn, rice and potato production and consumption per capita in Turkey between 2010 and 2030 were calculated on the basis of production and consumption between 2010 and 2019, and were reported in Figure 2.3.

As explained in section 3, it is assumed that Turkey's per capita production and consumption of wheat, barley, corn, rice and potatoes between 2010 and 2030 will be the same as the estimated average values calculated between 2010 and 2019. Wheat, barley, corn, rice and potato production and consumption estimates for the years between 2010 and 2030 were calculated using the average per capita values given in Table 3.1.1, the population forecasts given in Table 3.1.2, and by using equations [3.1.1] and [3.1.2]. The results of this analysis are shown in Figure 4.1.1.

As can be seen from Table 3.1.1, in this thesis study, the estimated per capita consumption of wheat, corn and rice in Turkey between 2010 and 2030 are 92% or higher agreement with FAO and OECD data.

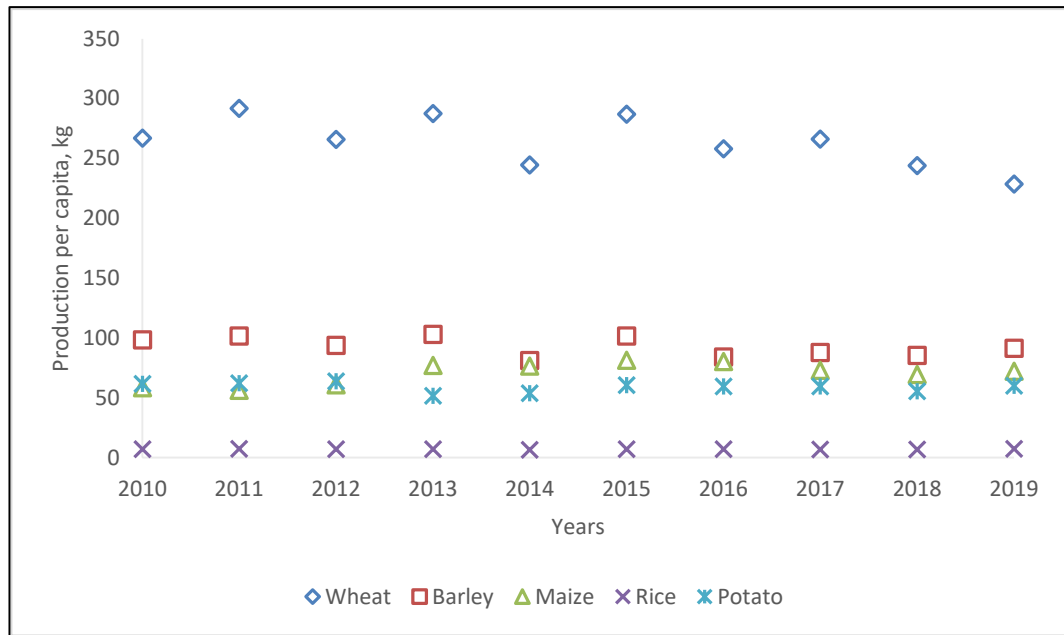


Figure 4.1.1 (a): Production of wheat, barley, corn, rice and potato in Turkey, kg.

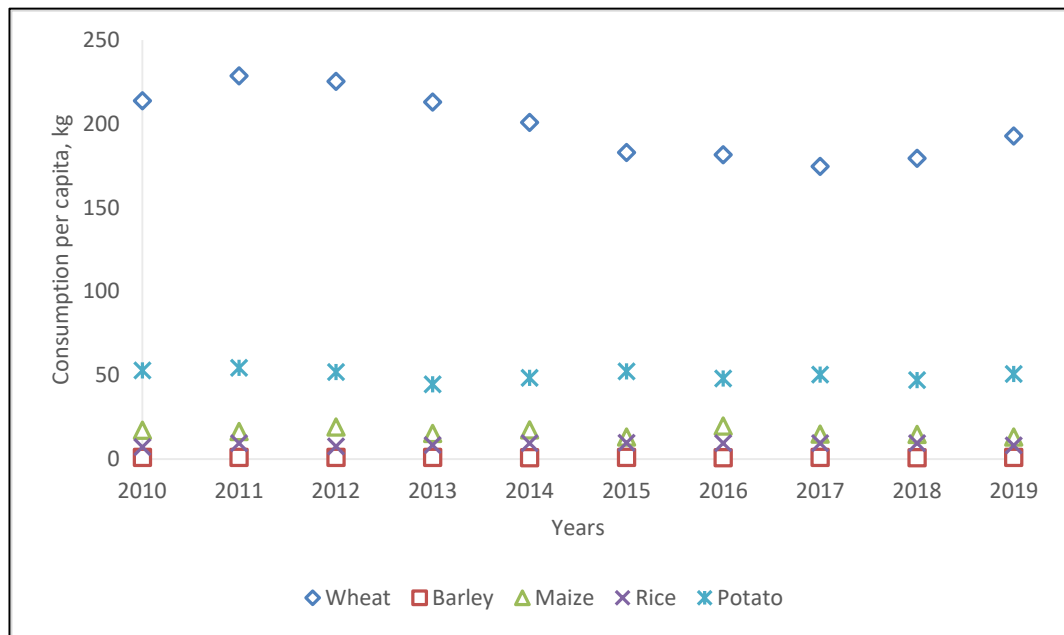


Figure 4.1.1 (b): Consumption per capita of wheat, barley, corn, rice and potato in Turkey, kg.

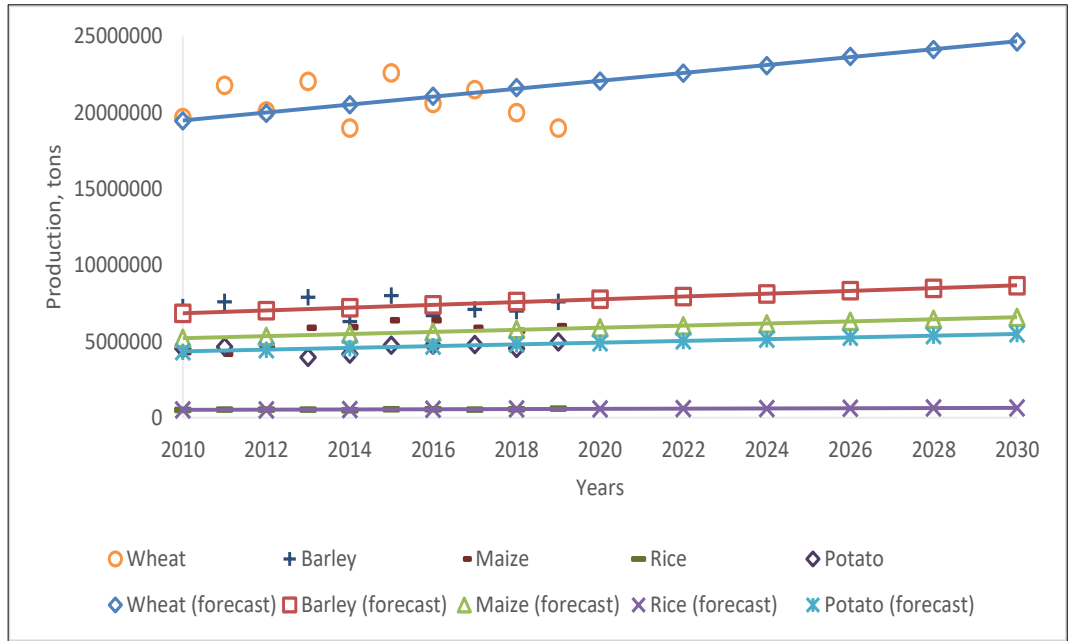


Figure 4.1.1 (c): Wheat, barley, corn, rice and potato production forecasts in Turkey between 2010 and 2030, tons.

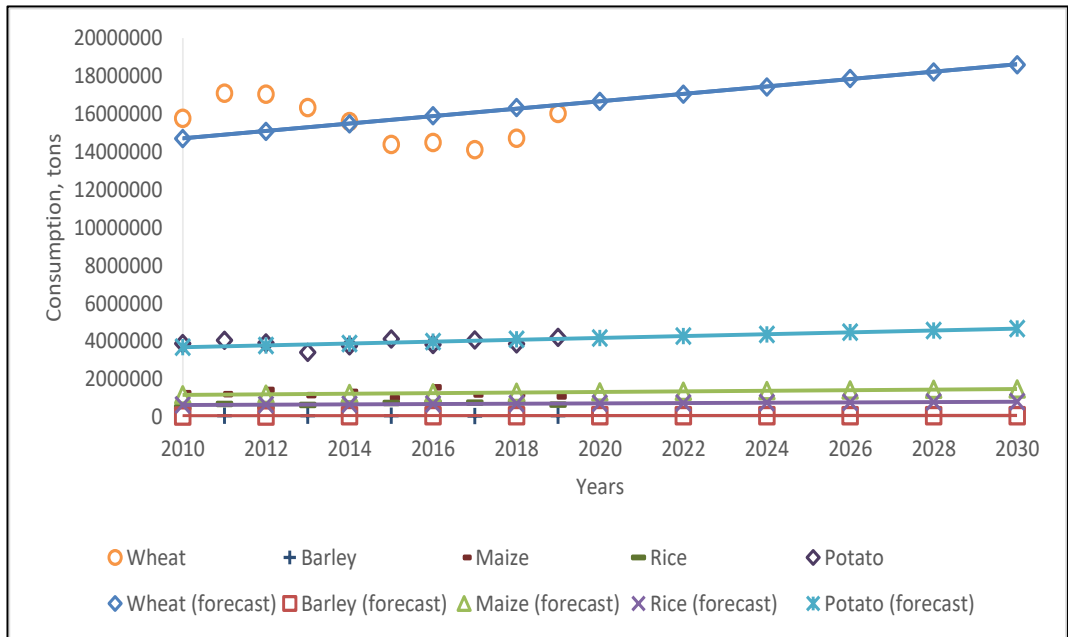


Figure 4.1.1 (d): Wheat, barley, corn, rice and potato consumption forecasts in Turkey between 2010 and 2030, tons.

As can be seen from Figure 4.1.1, timeline data for production and consumption values between 2010 and 2019 were extrapolated by statistical analysis (on hand) and validated by the statistical function given in Microsoft Excel 2013 (colored solid lines). As can be seen from Figure 4.1.1, data generated using population data is different

than potential linear extrapolations (which are not given in this Figure but calculated). Moreover, the coefficients of determination, R^2 , of these linear extrapolations were significantly lower than the forecasts given in Figure 4.1.1. It should be emphasized here that the straight lines given in Figure 4.1.1 were created to provide baseline data for a business-as-usual (BAU) scenario in order to evaluate robustness of the forecasts generated in this thesis study.

According to the forecasts generated in this thesis study, it was estimated that Turkey's average [mean] wheat, barley, corn, rice and potato production till 2030 could reach to 22.1, 7.8, 5.9, 0.58 and 4.9 million tons, respectively. Similarly, it is estimated that Turkey's average (mean) wheat, barley, corn, rice and potatoes consumption till 2030 could reach to 16.7, 0.1, 1.3, 0.7 and 4.2 million tons, respectively.

It was estimated that wheat, barley, corn, rice and potato production in 2030 could reach 24.6, 8.7, 6.6, 0.7, and 5.5 million tons, respectively. Likewise, it was estimated that Turkey's wheat, barley, corn, rice and potato consumption in 2030 could reach to 18.6, 0.08, 1.5, 0.8 and 4.7 million tons, respectively.

It was estimated in OECD-FAO Agricultural Outlook 2019-2028 that Turkey's wheat, corn, coarse grain and rice production will be 26.223, 7.639, 9.548, and 0.630 million tons, respectively, in 2028 [Web 7]. Similarly, in the same publication, Turkey's wheat, corn, coarse grain and rice consumption in 2028 is estimated to be 24.985, 8.826, 9.984, and 0.861 million tons, respectively [Web 7]. As a note, production and consumption data of potato were not available in this reference publication [Web 7]. Thus, the forecasts generated in this study match very well with the OECD-FAO forecasts.

As a key finding of this study, the results and discussion given above clearly showed that Turkey's corn, coarse grains and rice production could not meet the demand for consumption. This is important for Turkey's food safety and strategy policies and it is an important factor, which could crucially affect the country's biohydrogen production plans from corn, coarse grain and rice-based food waste.

Estimates of Turkey's wheat, barley, corn, rice and potatoes production and consumption losses between 2009 and 2019 were given in Figure 2.3. As can be seen from this figure, Turkey's wheat, barley, corn, rice and potato production values and production losses between 2009 and 2019 were accepted as constant by TurkStat, and consumption related losses between 2009 and 2019 vary around different average values. As stated in chapter 3, these average (mean) values were calculated with the

equations given in this thesis study and were reported in Table 3.2.3. Turkey's wheat, barley, corn, rice and potato production and consumption values and production and consumption losses between 2019 and 2030 would follow the same trend based on the average values estimated for the timeline between 2010 and 2019. Turkey's wheat, barley, corn, rice and potato production and consumption losses were estimated using the production and consumption estimates given in Figure 4.1.1 and the data in Tables 3.1.1 and 3.1.2, and equation (3.1.3) and (3.1.4). The results of this analysis shown in Figure 4.1.2. As can be seen from this figure, it was estimated that Turkey's wheat, barley, corn, rice and potato production losses between 2010 and 2030 could reach to 1.12, 0.47, 0.18, 0.01, and 0.08 million tons, respectively. Similarly, Turkey's wheat, corn, rice and potato consumption losses between 2010 and 2030 were estimated to reach to 0.62, 0.18, 0.17, 0.02, and 0.14 million tons, respectively.

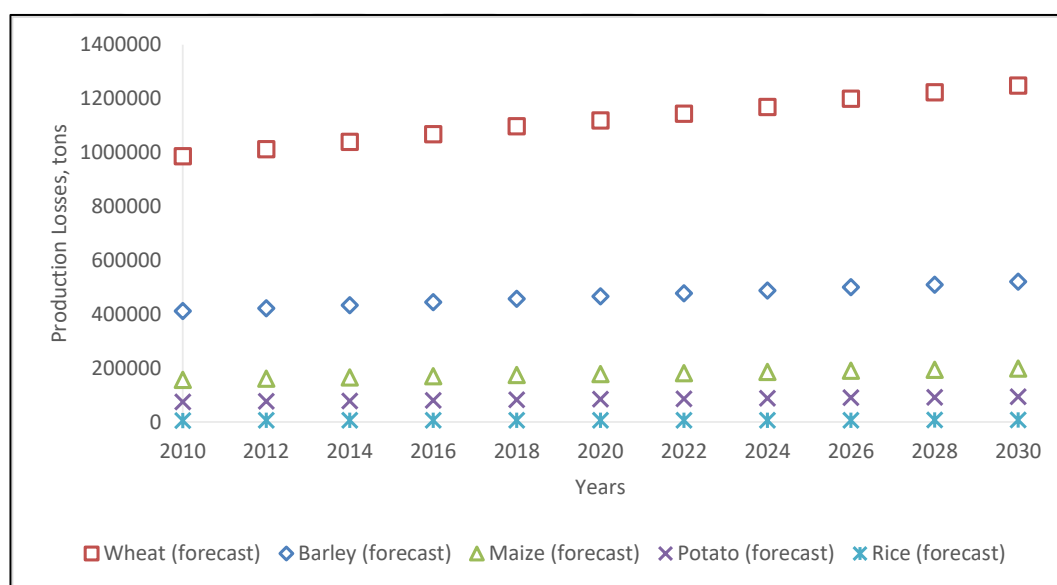


Figure 4.1.2 (a): Forecasts for production losses of wheat, barley, corn, rice and potato in Turkey between 2010 and 2030, tons.

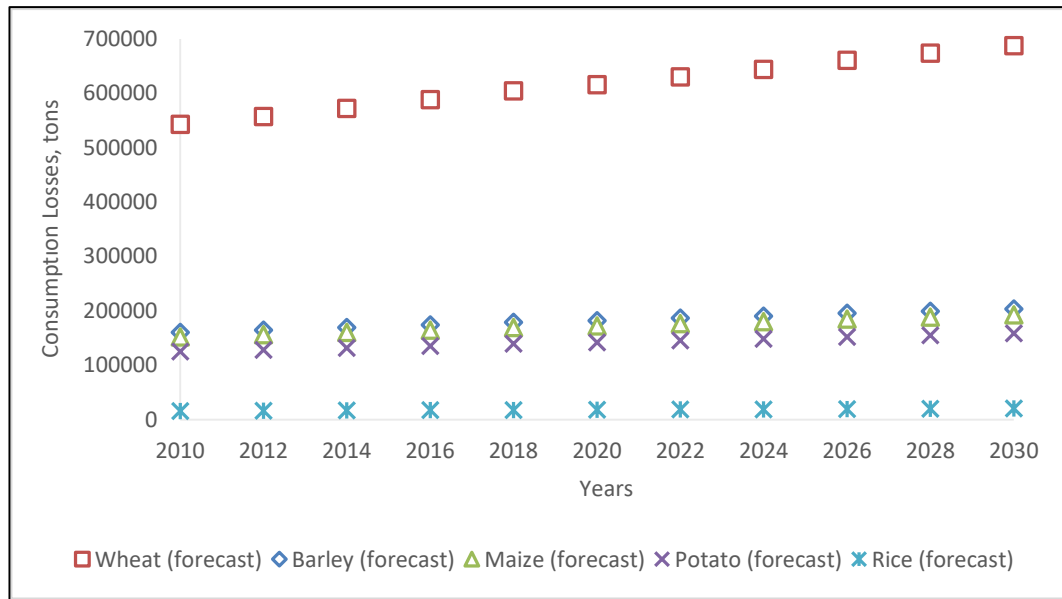


Figure 4.1.2 (b): Forecasts for consumption losses of wheat, barley, corn, rice and potato in Turkey between 2010 and 2030, tons.

4.2. Forecasting Turkey's Biohydrogen Generation Potential from Wheat, Barley, Corn, Rice and Potato Production and Consumption Losses between 2010 and 2030 and Calculating Biohydrogen Yield from Generic Food Waste

In order to calculate biohydrogen potential of Turkey's wheat, barley, corn, rice and potato production and consumption losses first potential biohydrogen conversion ratios of these cereals and crops must be found. As a result of a detailed literature review, Table 4.2.1 was prepared by using the data given in the Table 2.1.1 and Table 2.1.3. The data in Table 4.2.1 shows average maximum biohydrogen yields for wheat, barley, corn, rice and potato. An average maximum biohydrogen yield value for food waste (generic) was created for the first time in the literature by using the yields of wheat, barley, corn, rice and potato.

Table 4.2.1: An average of maximum hydrogen production yield value for wheat, barley, corn, rice, potato and food waste.

Substrate	Average maximum production yield [L of H ₂]/kg	References
Wheat waste	55.50	[Guo et al., 2010]
Barley waste	222.20	[Ljunggren, 2011]
Corn waste	130.00	[Tiryaki & Irmak, 2020]
Rice waste	78.50	[Guo et al., 2010]
Potato waste	102.00	[Chatellard et al., 2016]
Food Waste*	117.70	This study
*The average value for food waste was calculated from the yield values given for wheat, barley, corn, rice and potatoes.		

Turkey's potential biohydrogen production yield from wheat, barley, corn, rice and potato production and consumption losses between 2010 and 2030 were estimated by using the data given in Table 4.2.1 and Figures 3.1 and 4.1.1. The results are shown in Figure 4.2.1. It should be noted that the values for biohydrogen production yields are the maximum achievable values, since the availability factor, which was represented by A in equations (3.2.1) and (3.2.2) were assumed to be 1.0 or 100%.

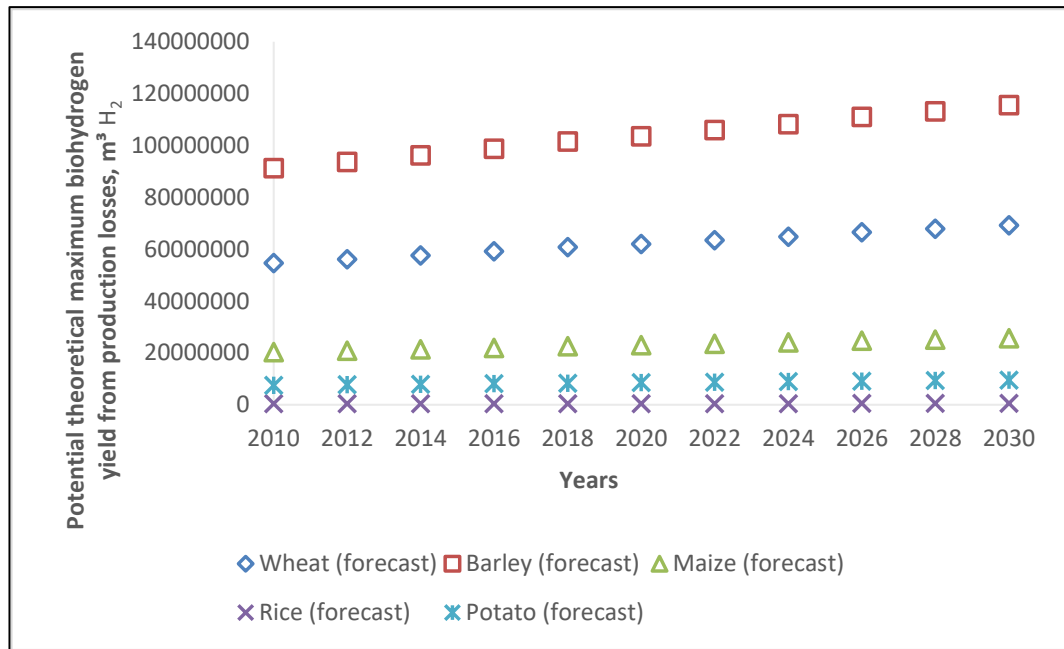


Figure 4.2.1 (a): Forecasted theoretical maximum biohydrogen generation from wheat, barley, corn, rice and potato production losses, $\text{m}^3 \text{H}_2$.

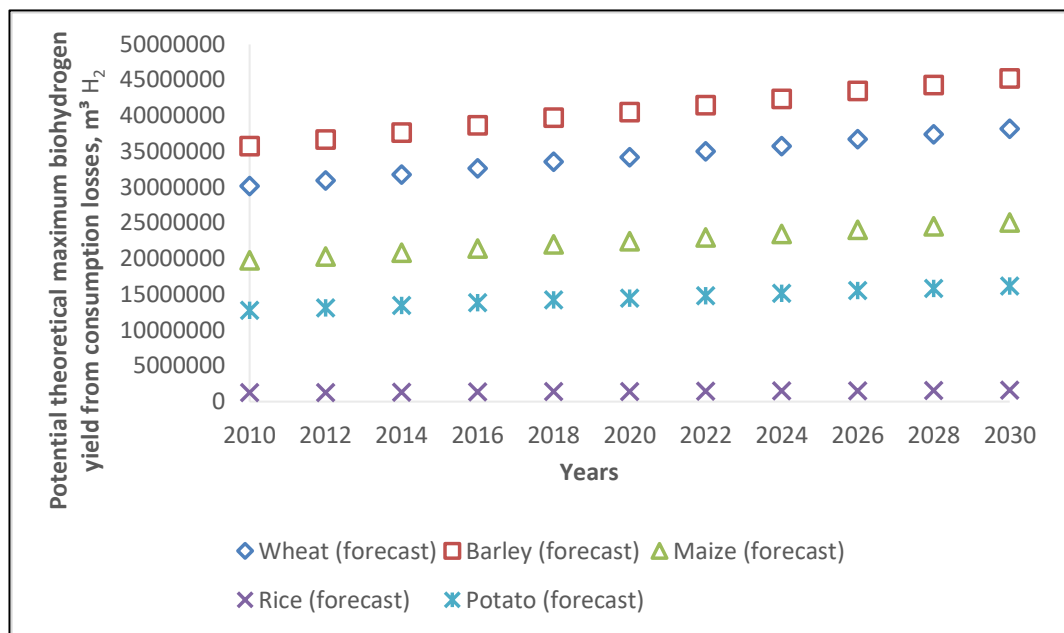


Figure 4.2.1 (b): Forecasted theoretical maximum biohydrogen generation potential from wheat, barley, corn, rice and potato consumption losses, $\text{m}^3 \text{H}_2$.

The collection, storage and processing of agricultural wastes, which have been continuously increasing due Turkey's growing population had become a fundamental economic, environmental and ethical problem. Therefore, any research suggesting an alternative route for processing these agricultural wastes is highly important. In this

thesis, it was assumed that 1.0% of Turkey's wheat, barley, corn, rice and potato production and consumption losses could be recovered for further bioprocessing for biohydrogen generation based on current social-economic habits and waste generation patterns. Figure 4.2.1 (a) and (b) showed the theoretical maximum biohydrogen generation potential if 100% of all production and consumption losses are recovered. Figure 4.2.1 (c) and (d) shows the theoretical maximum biohydrogen generation potential if 1.0% of the waste streams could be recovered, which is highly probable based on current socio-economic dynamics.

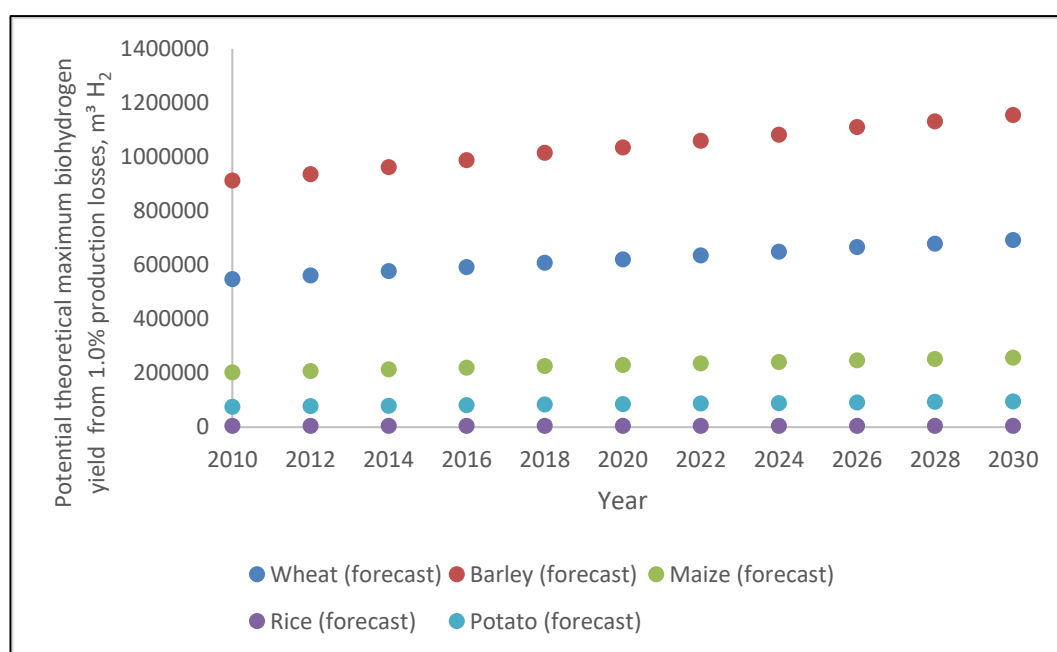


Figure 4.2.1 (c): Forecasted theoretical maximum biohydrogen generation potential if 1.0% of wheat, barley, corn, rice and potato production losses are recovered, m³ H₂.

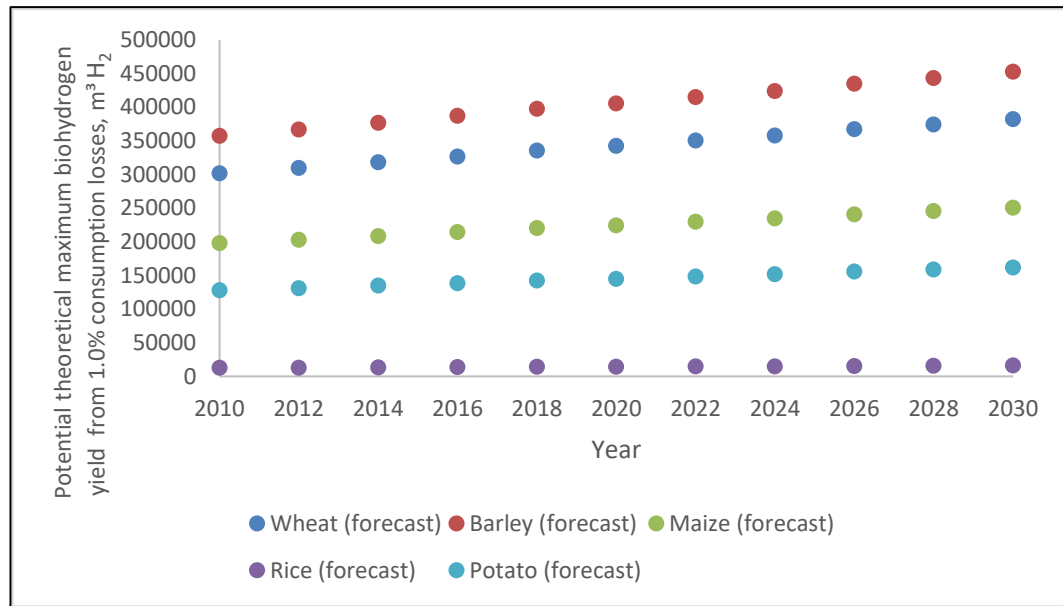


Figure 4.2.1 (d): Forecasted theoretical maximum biohydrogen generation potential if 1.0% of wheat, barley, corn, rice and potato consumption losses are recovered, m³ H₂.

As can be seen from Figure 4.2.1 (a) and (b), biohydrogen generation from Turkey's wheat, barley, corn, rice and potato production losses in 2030 could be 69.2, 115.5, 25.6, 0.5, and 9.5 million m³, respectively if 100% of all wastes are recovered and bioprocessed. Similarly, biohydrogen generation from Turkey's wheat, barley, corn, rice and potatoes consumption losses in 2030 could be 38.2, 45.2, 25.1, 1.6, and 16.2 million m³, respectively if 100% of all wastes are recovered and bioprocessed. When the Figure 4.2.1 (c) and (d) examined, biohydrogen generation from Turkey's wheat, barley, corn, rice and potato production losses in 2030 could be 692.6, 1155.2, 256.7, 5.1, and 95.1 thousand m³, respectively if 1.0% of all wastes are recovered and bioprocessed. Similarly, biohydrogen generation from Turkey's wheat, barley, corn, rice and potatoes consumption losses in 2030 could be 382.0, 452.4, 250.5, 16.0, and 161.9 thousand m³, respectively if 1.0% of all wastes are recovered and bioprocessed.

The demand for food is increasing increasing in Turkey as a result of the country's increasing population and eating habits. While the food industry is trying to meet the demand for food for everyone, the problem of food waste has emerged due to population growth. Food waste can be generated during handling, storage, shipping and processing, starting from the post-harvest/slaughter production/supply chain [Melikoglu et al., 2013]. Food waste in Turkey generally comprises vegetables, fruits, bread, and meat/meat products. Considering the content of the food waste, vegetables,

fruits and bread have higher percentage, while meat/meat products are generally less. Novel to this study, for the first time in the literature Table 4.2.2 is generated to show maximum H₂ production potentials for vegetables, fruits, bread and meat/meat products in the content of food waste generated in Turkey.

Table 4.2.2: Maximum H₂ production yields for vegetable waste, fruit waste, bread waste and meat/meat products wastes.

Substrate	Maximum assessed production yield [L of H₂]/kg	References
Vegetable waste	62.00	[Karthikeyan et al., 2017]
Fruit waste (contains 60% apple, 20% banana and 20% orange)	200.71	[Akinbomi & Taherzadeh, 2015; Lu et al., 2016]
Meat/meat product waste	30.40	[Cieciura-Włoch & Borowski, 2019]
Bread waste	103.00	[W. Han et al., 2017]
Food waste*	112.75	This study
* The average value for food waste was calculated from the yield values given for vegetables, fruit, meat and bread using by ratio.		

Novel to this thesis study, the content of domestic food waste in Turkey was generated. This generic food waste assumed to contain 30% of vegetable, 30% of fruit (containing 60% apple, 20% banana and 20% orange), 30% of bread and 10% of meat/meat products. This generic food waste content was created by taking into account the daily habits and eating trends of Turkish people. In Table 4.2.2, maximum H₂ production yield was estimated for this generic food waste. Graphical expression of Tables 4.2.1 and 4.2.2 are given as Figures 4.2.2 (a) and (b) respectively.

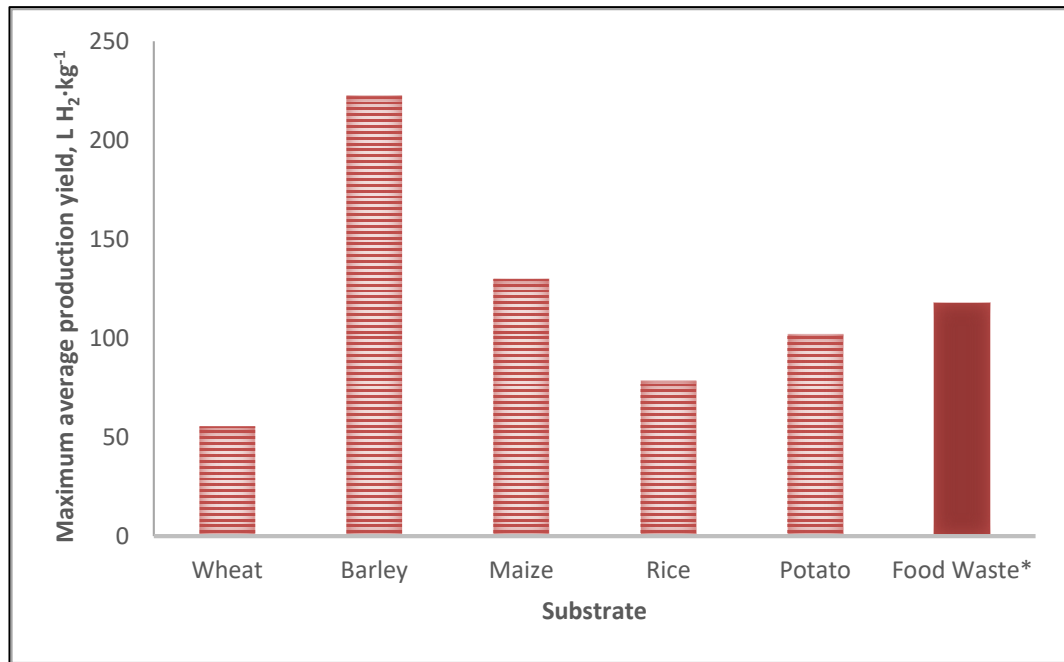


Figure 4.2.2 (a): Average maximum biohydrogen production yield for wheat, barley, corn, rice, potato and food waste.

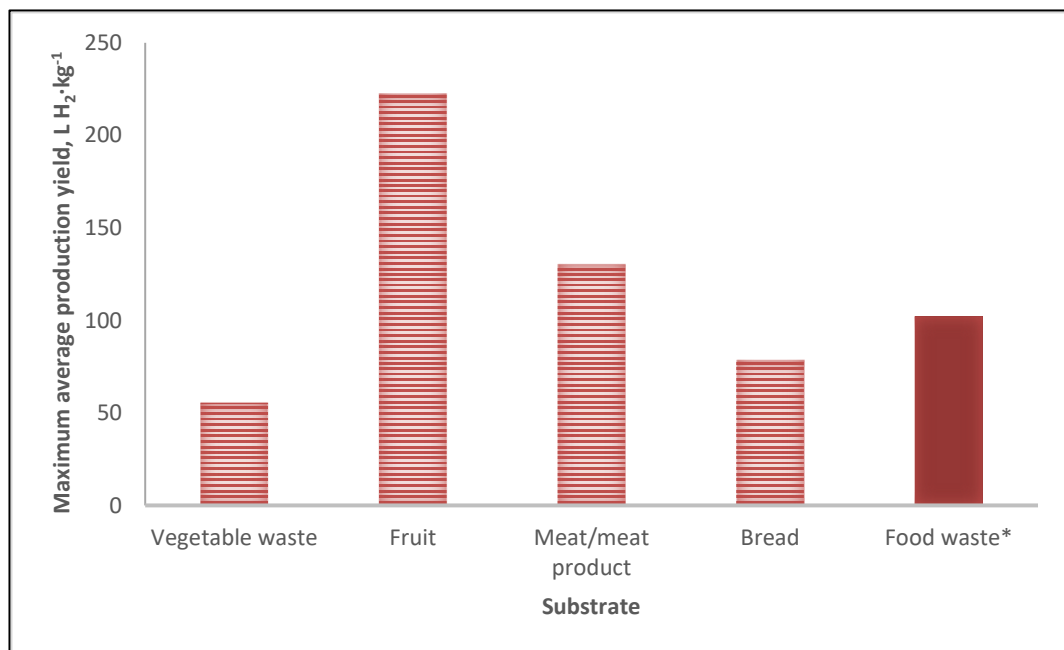


Figure 4.2.2 (b): Average maximum biohydrogen production yield for vegetable waste, fruit waste, bread waste, meat/meat product wastes and food (generic).

As a result, the average maximum H₂ production yield for food waste is 117.7 L H₂/kg when calculated over agricultural crops and grain materials given in Table 4.2.1. When the generic food waste is taken then this value changes to 112.8 L H₂/kg

(data from Table 4.2.2). It is clearly seen that the calculated average maximum theoretical yields are very close to each other. The deviation between these two values is only 6.0% or the match between these two values is 94.0%. This is a novel finding.

4.3. From Global to Local: Waste Analysis for Wheat, Barley, Corn, Rice and Potato Production around the World and Estimating Biohydrogen Yield from Food Waste in Turkey

Turkey is located between Asia and Europe and its cuisine covers European, Asian and American food items. Food production and consumption in Turkey including agricultural products is similar to that of Italy, the U.S. and South Korea, which are taken as representatives for Asia, Europe and America. Wheat, barley, corn, rice and potato production data South Korea, the U.S. and Italy between 2010 and 2019 are shown in the Figure 4.3.1 [Web 3].

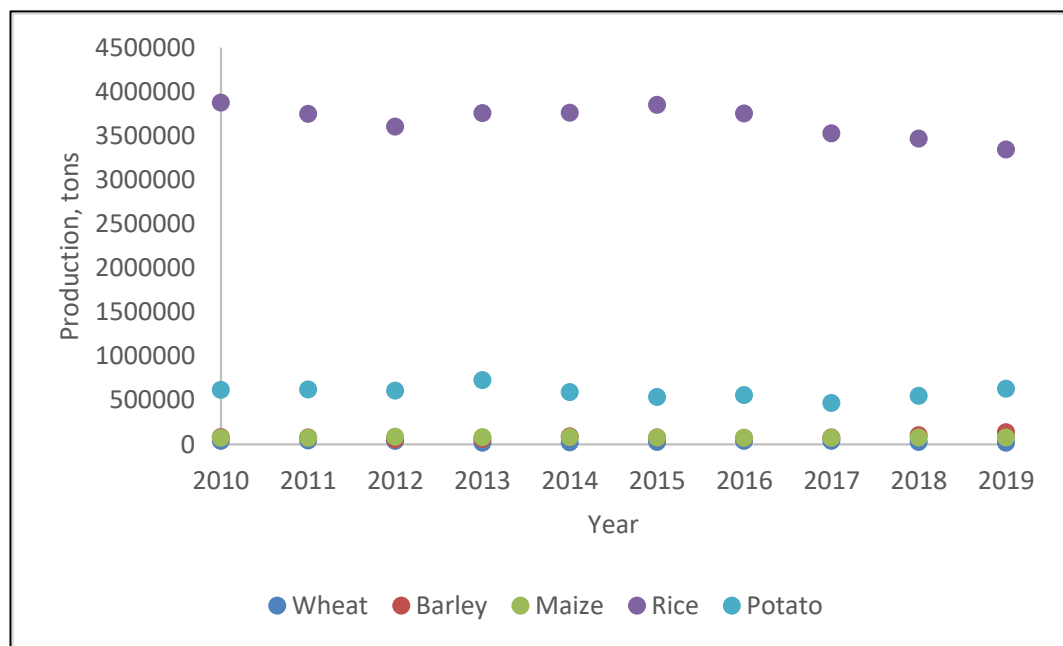


Figure 4.3.1 (a): Wheat, barley, corn, rice and potato production in South Korea between 2010 and 2019.

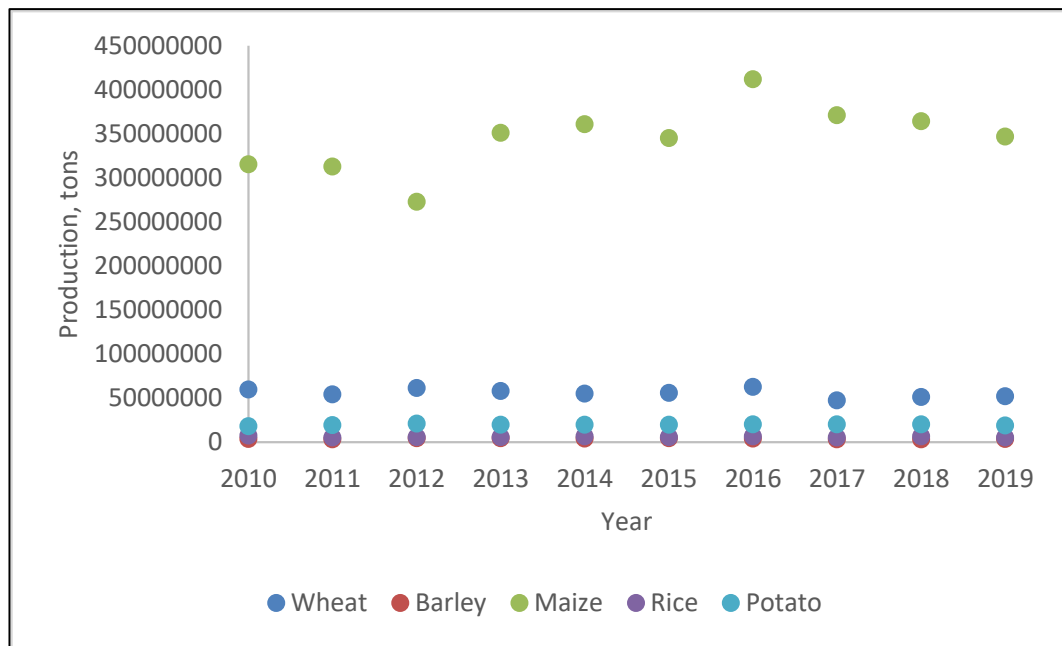


Figure 4.3.1 (b): Wheat, barley, corn, rice and potato production in the U.S. between 2010 and 2019.

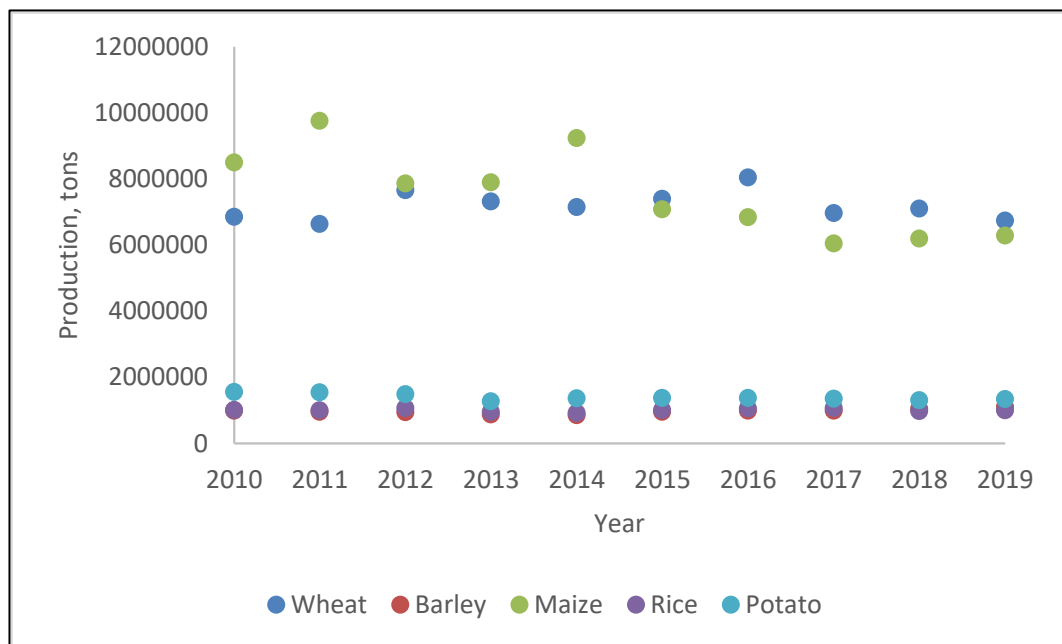


Figure 4.3.1 (c): Wheat, barley, corn, rice and potato production in Italy between 2010 and 2019.

Amongst these 5 different crops and cereals, as can be seen in Figure 4.3.1 (a), rice production in South Korea ranks first with an annual average of 3.7 million tons, while potato production ranks second with an annual average of 0.6 million tons. As can be seen from the graph, the amount of rice production is quite high compared to

wheat, barley, corn and potato. Figure 4.3.1 (b) shows grain and crop production for the U.S. between 2010 and 2019. When Figure 4.3.1 (b) is examined, the U.S. is the leader in the world with an average annual corn production of 345.4 million tons. Corn production is followed by wheat with an annual production of 55.9 million tons. Figure 4.3.1 (c) shows grain and crop production for Italy between 2010 and 2019. As can be seen from Figure 4.3.1 (c), Italy shows a more condensed structure in terms of production. Even though barley and corn production may differ from year to year, they are generally close. When we look at Figure 4.3.1 (c), an annual average of 7.2 million tons of barley and 7.6 million tons of corn was produced between 2010 and 2019.

There are differences between crop and cereal production between countries due to climatic and economic conditions. Between 2010 and 2019, rice production was highest in South Korea, whereas corn production was highest in the U.S. When Italy was considered corn and wheat production were very close. The reason for this is related to lifestyle and eating habits of people and climatic conditions of the respected countries.

Agricultural waste is a type of food waste. Therefore, at this point food waste problem in these countries must be analyzed to have a clearer assessment. In Figure 4.3.2, food waste generation (kg per capita) was given for South Korea, the U.S. and Italy for 2020 [Web 12]. In 2020, the amount of food waste per capita in South Korea was higher than that of the U.S. and Italy. Annual household food waste per capita for South Korea, Italy and the U.S. was 71, 67 and 59 kg, respectively [Web 12].

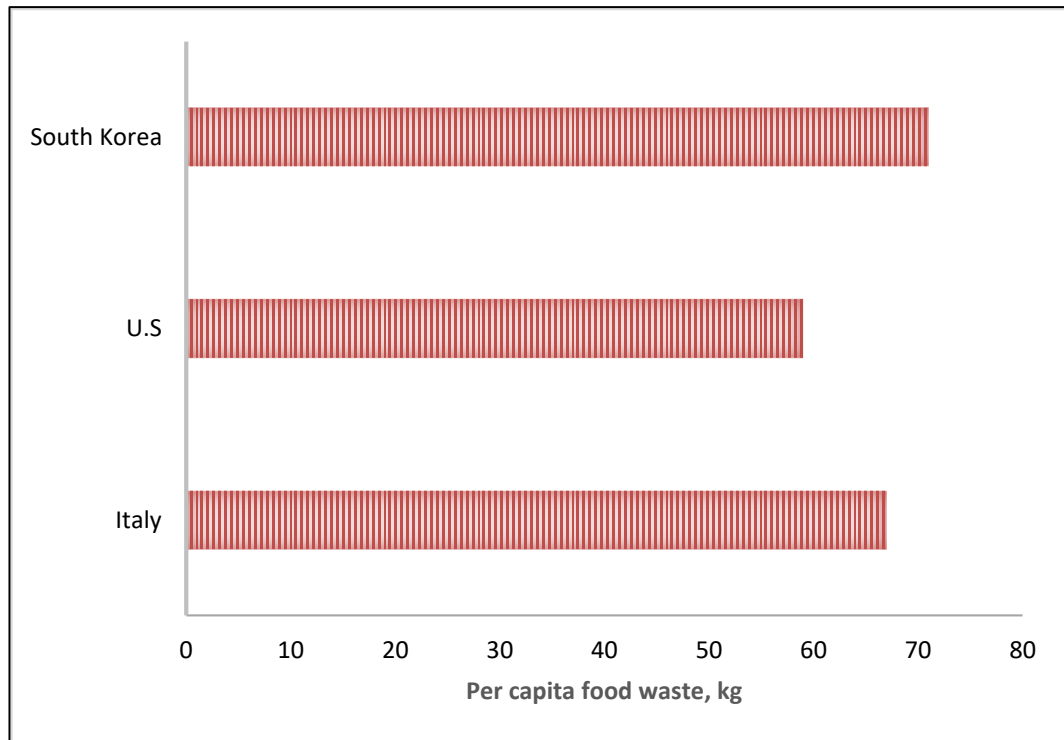


Figure 4.3.2: Annual per capita household food waste of Italy, the U.S. and South Korea in 2020, kg.

Global data on food loss from post-harvest to distribution in 2019 is given in Figure 4.3.3 [FAO, 2019]. As can be seen from this figure, global food loss from post-harvest to distribution was 13.8% in 2019 [FAO, 2019]. In this figure, the world is divided into different regions by the FAO. These regions are Western Asia and Northern Africa, Sub-Saharan Africa, Oceania (Excluding Australia and New Zealand), Northern America and Europe, Latin America and The Caribbean, Eastern Asia and South-Eastern Asia, Central and Southern Asia, Australia and New Zealand and food wastes generated from these regions are estimated as 10.8%, 14.0%, 8.9%, 15.7%, 11.6%, 7.8%, 20.7%, 5.8% of the total, respectively [FAO, 2019].

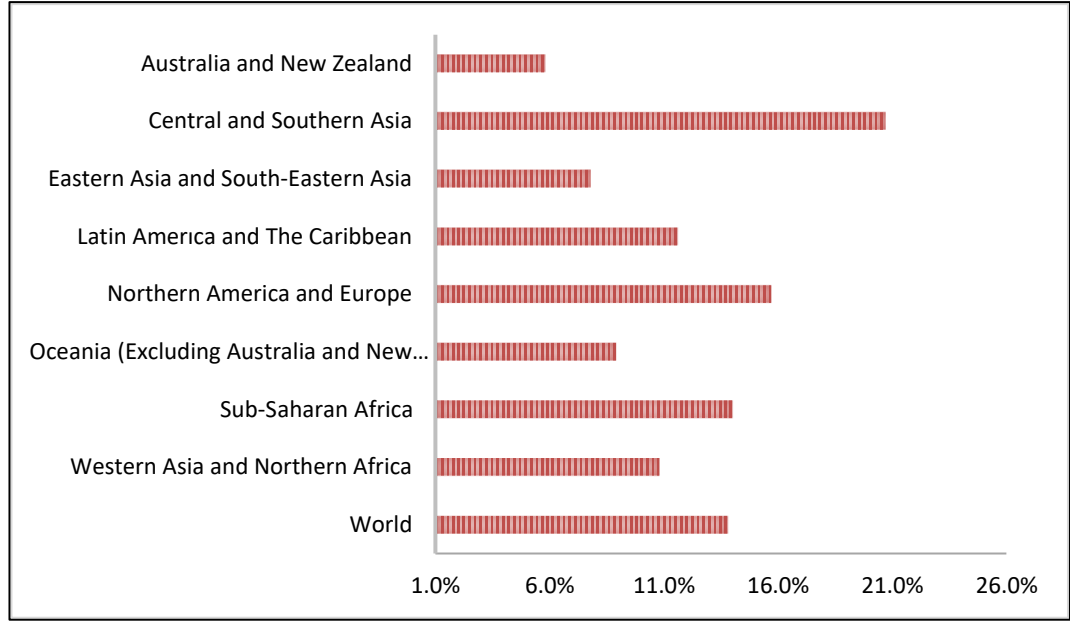


Figure 4.3.3: Global data on food loss from post-harvest to distribution in 2019.

From the global to the local, the annual amount of household food waste per capita in Turkey was 93.0 kg in 2020 [Web 12]. Using Turkey's population forecast till given in Table 3.2.2 and taking this base figure as constant, Turkey's annual food waste generation till 2030 was estimated for the first time in the literature using equation (4.3.1). Then, Turkey's annual biohydrogen yield from food wastes waste was forecasted using equation (4.3.2).

$$F_w(t) = P(t) \times F_{wpc} \times A + \varepsilon_t \quad (4.3.1)$$

$$B_{fw}(t) = F_w(t) \times B_y + \varepsilon_t \quad (4.3.2)$$

In equations (4.3.1) and (4.3.2), t represents the year, which is ≥ 2010 , $F_w(t)$ is the food waste generation forecast in year t in tons, $P(t)$ is Turkey's population in year t , which is taken from Table 3.2.2, F_{wpc} is the annual household food waste per capita in tons, which is taken as 93.0 kg, $B_{fw}(t)$ is the biohydrogen generation forecast from food waste in year t in liters, B_y biohydrogen yield from the generic food waste in liter of H_2 per kg, which is taken as 112.8 L H_2 /kg (data from Table 4.2.2), A is the availability factor of the food waste that could be recovered, which varies between 0 and 1.0 (0% and 100%), and ε_t is a "random" error term.

Figure 4.3.4 (a) shows the forecast for Turkey's annual food waste generation between 2010 and 2030. This figure was generated by taking the A factor as 1.0 or 100% in equation (4.3.1). It was estimated that average annual food waste generation in Turkey between 2010 and 2030 could be 7.8 million tons and the annual food waste in 2030 could reach up to 8.2 million tons.

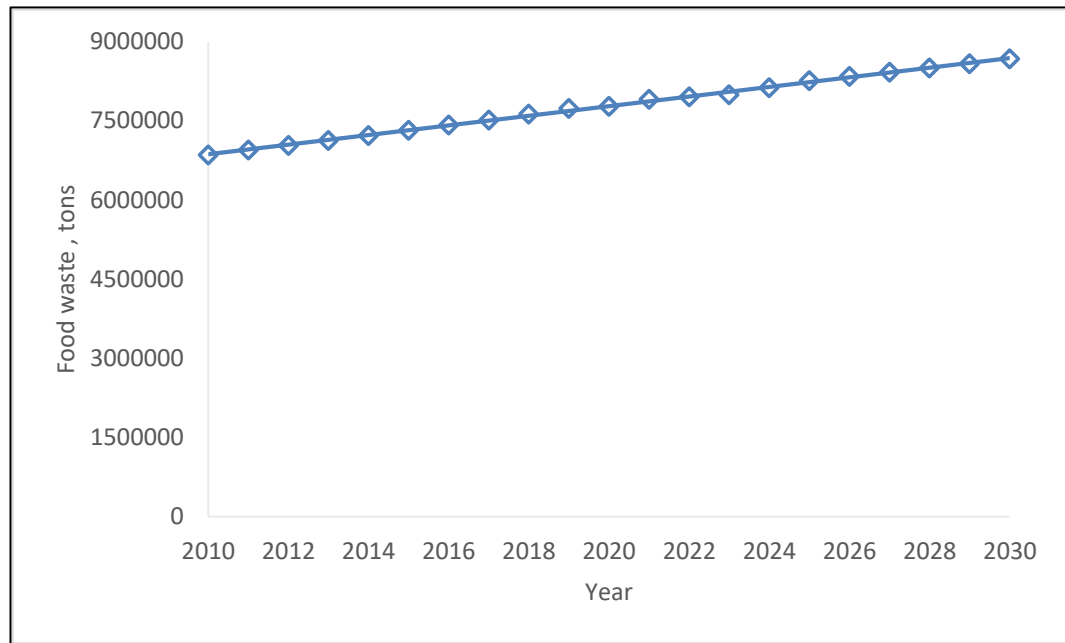


Figure 4.3.4 (a): Household food waste calculated forecast for Turkey by using forecast population between 2010 and 2030, tons.

Figure 4.3.4 (b) shows the scenario where 0.1%, 0.5%, 1.0%, 3.0% and 5.0% of the food waste generated in Turkey could be recovered (A factors in equation 4.3.1) for further bioprocessing. According to this hypothetical scenario, when 0.1%, 0.5%, 1.0%, 3.0% and 5.0% of Turkey's food waste was recycled between 2010 and 2030, an average of 7,779.7, 38,898.5, 77,797.1, 233,391.2, and 388,985.4 tons of food waste could be recovered, respectively. According to the same scenario, when 0.1%, 0.5%, 1.0%, 3.0%, and 5.0% of Turkey's food waste was recycled between 2020 and 2030, an average of 8,194.8, 40,974.1, 81,948.3, 245,844.8, and 409,741.4 tons of food waste could be recovered, respectively.

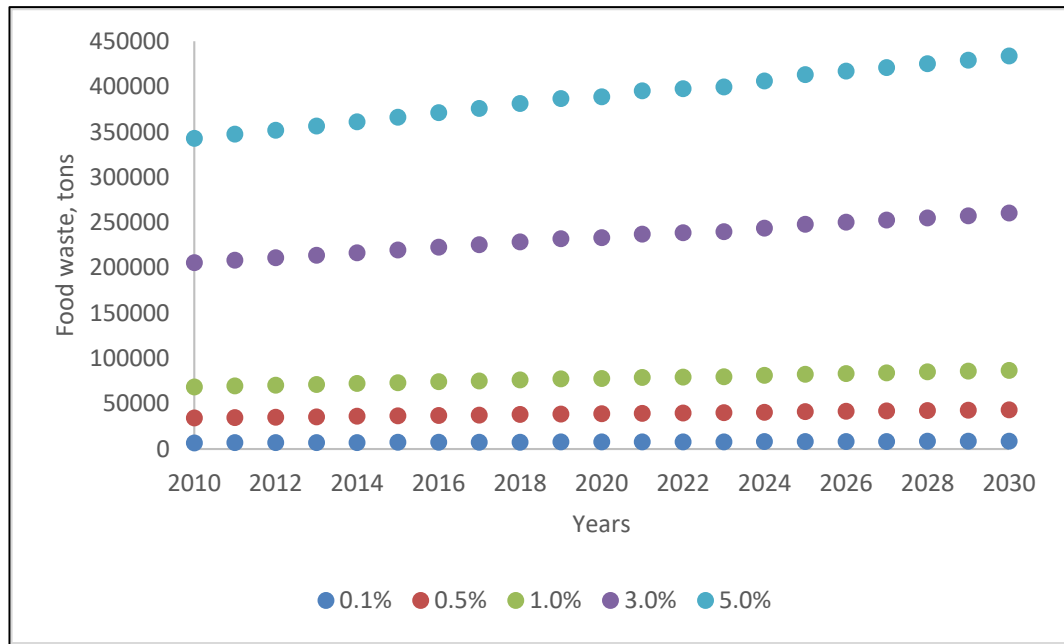


Figure 4.3.4 (b): 0.1%, 0.5%, 1.0%, 3.0% and 5.0% of the food waste generated in Turkey between 2010 and 2030, tons.

Figure 4.3.4 (c) shows the maximum theoretical amount of biohydrogen that could be generated from 0.1%, 0.5%, 1%, 3% and 5.0% of food wastes (A factors in equation 4.3.1) that could be generated in Turkey between 2010 and 2030. The values in Figure 4.3.4 (c) were generated using equations (4.3.1) and (4.3.2).

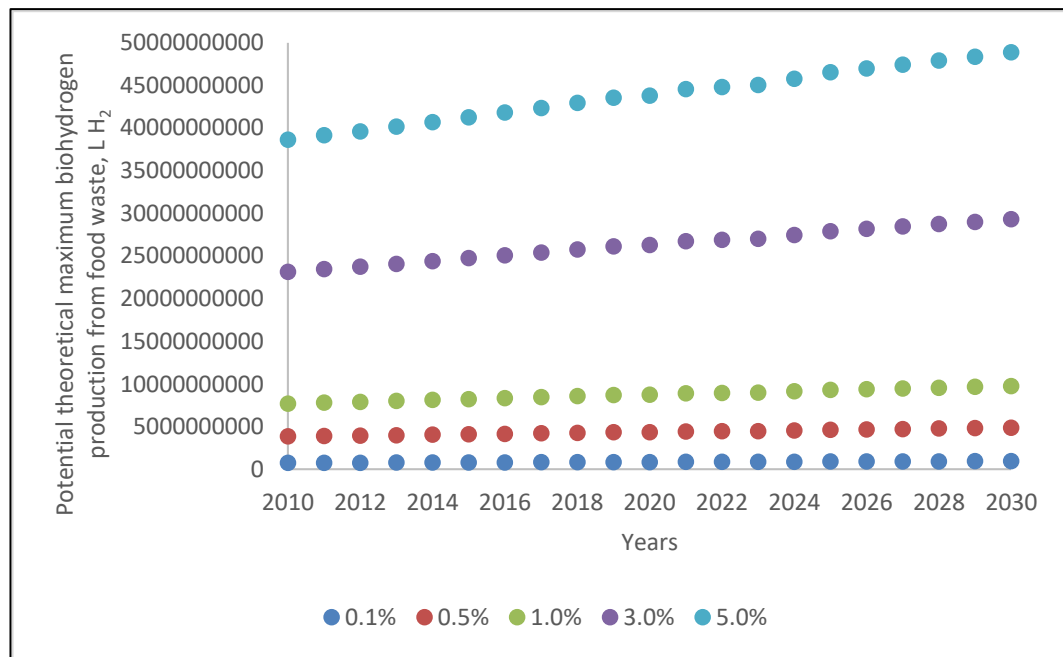


Figure 4.3.4 (c): Generation of maximum assessed H_2 for the amount of food waste that generated after the recycling at the rates of 0.1%, 0.5%, 1.0%, 3.0% and 5.0% between 2010 and 2030 in Turkey, L H_2 .

As can be seen from Figure 4.3.4 (c), it was calculated that nearly 877,162, 4,385,810, 8,777,620, 26,314,860, and 43,858,100 m^3 of H_2 could be generated between 2010 and 2030 when the recovery rates of food wastes were 0.1%, 0.5%, 1.0%, 3.0%, and 5.0%, respectively. Between the 2020 and 2030, when the recovery rates of food wastes were 0.1%, 0.5%, 1.0%, 3.0%, and 5.0%, it was estimated that the H_2 production of could be 924,000, 4,620,000, 9,240,000, 27,719,005, and 46,198,342 m^3 , respectively.

Consequently, the results of this study clearly showed that food waste generation in Turkey is higher than the global average and this trend will continue in the years to come. The increase in the amount of food waste generation is directly proportional to Turkey's population rise. There is a great potential for biohydrogen generation in Turkey if food wastes could be recovered more efficiently. When food wastes are recycled using new technologies at a higher rate then value added products from food wastes could be generated in bulk quantities. Thus, the next step is to carry out a techno-economic analysis on biohydrogen generation from food wastes to have an insight about the sustainability of this novel idea.

4.4. Techno-economic Evaluation

Today, the levelized cost of producing hydrogen from natural gas is between 0.5 and 1.7 US\$ per kilogram [Web 6]. Yet, this figure increases to a range between 3.0 and 8.0 US\$ per kg if electricity from renewable energy sources are used for its production [Web 6]. According to a recent report, the average retail price of hydrogen, which can be used as fuel in California, was nearly 16.5 US\$ per kg [Web 2]. As the topic of this thesis, one of the promising sources for biohydrogen generation is biogas that is generated from food wastes. Biohydrogen production from food and agricultural wastes is a very promising solution to waste disposal. We anticipate that biohydrogen production from food wastes will reduce the cost of waste disposal and decrease the retail price of biohydrogen.

Hydrogen generation becomes easier with the recent developments in production technologies. Along with the development of new technologies production costs decrease and global distribution costs become more important. Value chain steps in the projected costs for hydrogen production in Europe in 2030 is given in Table 4.4.1 [Web 6]. This table indicates that hydrogen production costs in Europe would be quite small when compared to other costs. The main cost items would be distribution and storage. Also, the preparation time for distribution must be considered for updating these costs. As a result, localized or local generation of biohydrogen from food wastes could reduce both the raw material and distribution-storage costs significantly.

Table 4.4.1: Value chain steps in the projected costs for hydrogen in Europe in 2030.

H ₂ value chain	Exemplar end user	Exemplar value chain steps			Cost, US\$/kg
		Renewable /low carbon production	Conversion/transmission	Distrubution	
Onsite	Industrial, large scale offtaker	1.6-2.3 US\$/kg	0.5 US\$/kg	-	~2-3
Regional	H ₂ refueling stations	1.6-2.3 US\$/kg	0.7-1.0 US\$/kg	1.0-2.0 US\$/kg	~3-5
International	Industrial, large scale offtaker	1.0-1.4 US\$/kg	0.6-3.5 US\$/kg	0.1-2.0 US\$/kg	~2-7
*2.0, 4.5 and 7.0 are the average cost value for the H ₂ production for Europe in 2030.					

From global to local, the storage and disposal of food wastes in Turkey is a major problem [Melikoglu, 2020c]. In order to provide a synergistic solution to these problems a techno-economic investigation was made to assess the feasibility of biohydrogen generation from food wastes. As can be seen from Table 4.4.1, the maximum production cost of hydrogen in 2030 was estimated as 7.0 US\$ per kg. This figure is taken as the reference cost for biohydrogen generation since when the technology matures biohydrogen generation from food wastes would decrease to the price of hydrogen that could be generated from fossil fuels and renewable energy sources. Equations (4.4.1) – (4.4.3) are used for estimating food waste generation, biohydrogen production both in litres and kg, production cost and sale costs, and net return for different recovery rates.

$$C_{b_{fw}}(t) = B_{fw}(t) \times U_{bc}[t] + \varepsilon_t \quad (4.4.1)$$

$$S_{b_{fw}}(t) = B_{fw}(t) \times U_{bs}[t] + \varepsilon_t \quad (4.4.2)$$

$$N_{b_{fw}}(t) = S_{b_{fw}}(t) - C_{b_{fw}}(t) + \varepsilon_t \quad (4.4.3)$$

In equations (4.4.1) – (4.4.3), t represents the year, which is ≥ 2010 , $C_{b_{fw}}(t)$ is the cost of biohydrogen generated from food waste in year t in US\$, $S_{b_{fw}}(t)$ is the sale cost of biohydrogen generated from food waste in year t in US\$, $N_{b_{fw}}(t)$ is the net return

of biohydrogen generated from food waste in year t in US\$, $B_{fw}(t)$ is the biohydrogen generation forecast from food waste in year t in liters, which is given in equation (4.3.2) and calculated from equation (4.3.1), $U_{bc}(t)$ is the unit cost of biohydrogen generation in year t , which is taken as 7.0 US\$ per kg (data from Table 4.4.1), $U_{bs}(t)$ is the unit sale price of biohydrogen generated in year t , which is taken as 16.5 US\$ per kg (data given above), and ε_t is a "random" error term [Web 2; Web 6]. In these calculations there is a hidden A factor (located in equation (4.3.1)), which is the availability factor of the food waste that could be recovered that varies between 0.1 and 1.0 (0% and 100%) is also used.

The amount of food waste to be obtained in Turkey with 0.1%, 0.5%, 1.0%, 3.0% and 5.0% recovery rates between the years 2010 and 2030 were shown in Figure 4.3.4 (b). The maximum amount of biohydrogen that could be produced from these wastes were also given in Figure 4.3.4 (c). Consequently, Table 4.4.2 is generated using the data given in the previous sections and equation (4.4.1), which shows amount of food waste that could be recycled, the amount of biohydrogen that could be generated both in kg and litres, production and sale costs and estimated net return values based on recovery rates changing between 0.1 and 100% between 2010 and 2030.

Table 4.4.2 (a): Forecasts for food waste geneation, biohydrgoen production both in litres and kg, production cost and sale costs, and net return when the recovery rate is 100%.

Year	Food waste, recovery, tons	H ₂ production, L	H ₂ production, kg	H ₂ production cost, US\$	H ₂ sale cost, US\$	Net return, US\$
2010	6,856,238	773,040,821,421	54,731,290,157	383,119,031.096	903,613,600.486	520,494,569.389
2011	6,949,357	783,540,003,667	55,474,632,260	388,322,425.817	915,886,178.606	527,563,752.789
2012	7,033,347	793,009,841,778	56,145,096,798	393,015,677.585	926,955,548.133	533,939,870.548
2013	7,130,111	803,920,054,938	56,917,539,890	398,422,779.227	939,708,583.577	541,285,804.350
2014	7,225,719	814,699,825,368	57,680,747,636	403,765,233.452	952,309,143.471	548,543,910.019
2015	7,322,918	825,658,996,495	58,456,656,952	409,196,598.663	965,119,406.275	555,922,807.612
2016	7,422,783	836,918,783,588	59,253,849,878	414,776,949.146	978,281,061.487	563,504,112.340
2017	7,515,379	847,358,962,519	59,993,014,546	419,951,101.824	990,484,670.160	570,533,568.336
2018	7,626,361	859,872,205,682	60,878,952,162	426,152,665.136	1,005,111,500.199	578,958,835.063
2019	7,733,415	871,942,509,793	61,733,529,693	432,134,707.853	1,019,220,575.237	587,085,867.384
2020	7,776,136	876,759,296,342	62,074,558,181	434,521,907.267	1,024,850,955.568	590,329,048.301
2021	7,908,975	891,736,889,984	63,134,971,811	441,944,802.676	1,042,358,384.597	600,413,581.921
2022	7,957,254	897,180,441,267	63,520,375,242	444,642,626.692	1,048,721,395.241	604,078,768.549
2023	7,994,025	901,326,265,645	63,813,899,608	446,697,297.254	1,053,567,482.522	606,870,185.269
2024	8,127,828	916,412,607,000	64,882,012,576	454,174,088.029	1,071,202,027.623	617,027,939.594
2025	8,262,579	931,605,766,691	65,957,688,282	461,703,817.972	1,088,961,433.531	627,257,615.559
2026	8,341,968	940,556,905,020	66,591,428,875	466,140,002.128	1,099,424,490.733	633,284,488.605
2027	8,422,120	949,594,048,482	67,231,258,633	470,618,810.428	1,109,988,080.023	639,369,269.595
2028	8,503,042	958,718,023,438	67,877,236,059	475,140,652.416	1,120,653,167.341	645,512,514.925
2029	8,584,742	967,929,664,192	68,529,420,225	479,705,941.573	1,131,420,727.911	651,714,786.338
2030	8,679,557	978,620,094,821	69,286,302,713	485,004,118.993	1,143,916,857.796	658,912,738.803

For the years 2010, 2020 and 2030 food waste recovery, biohydrgoen production, production cost and sale costs, and net return was calculated as 6,856,238

tons, 773,040,821 thousand litres, 383,119 and 903,613,600 US\$, and 520,494,569 US\$; 7,776,136 tons, 876,759,296 thousand liters, 434,521,907 and 1,024,850,956 thousand US\$, and 590,329,048 US\$; 8,679,557 tons, 978,620,095 thousand liters, 485,004,118 and 1,143,916,857 US\$, and 658,913 thousand US\$, respectively. Thus, it was projected that in 2030 a net return greater than 658.9 million US\$ could be generated in Turkey from food waste if 100% is recovered for biohydrogen generation. However, this is not possible.

Table 4.4.2 (b): Forecasts for food waste geneation, biohydrgoen production both in litres and kg, production cost and sale costs, and net return when the recovery rate is 0.1%.

Year	Food waste, recovery, kg	H ₂ production, L	H ₂ production, kg	H ₂ production cost, US\$	H ₂ sale cost, US\$	Net return, US\$
2010	6,856,238	773,040,821	54,731,290	383,119.031	903,613.600	520,494.569
2011	6,949,357	783,540,004	55,474,632	388,322.426	915,886.179	527,563.753
2012	7,033,347	793,009,842	56,145,097	393,015.678	926,955.548	533,939.871
2013	7,130,111	803,920,055	56,917,540	398,422.779	939,708.584	541,285.804
2014	7,225,719	814,699,825	57,680,748	403,765.233	952,309.143	548,543.910
2015	7,322,918	825,658,996	58,456,657	409,196.599	965,119.406	555,922.808
2016	7,422,783	836,918,784	59,253,850	414,776.949	978,281.061	563,504.112
2017	7,515,379	847,358,963	59,993,015	419,951.102	990,484.670	570,533.568
2018	7,626,361	859,872,206	60,878,952	426,152.665	1,005,111.500	578,958.835
2019	7,733,415	871,942,510	61,733,530	432,134.708	1,019,220.575	587,085.867
2020	7,776,136	876,759,296	62,074,558	434,521.907	1,024,850.956	590,329.048
2021	7,908,975	891,736,890	63,134,972	441,944.803	1,042,358.385	600,413.582
2022	7,957,254	897,180,441	63,520,375	444,642.627	1,048,721.395	604,078.769
2023	7,994,025	901,326,266	63,813,900	446,697.297	1,053,567.483	606,870.185
2024	8,127,828	916,412,607	64,882,013	454,174.088	1,071,202.028	617,027.940
2025	8,262,579	931,605,767	65,957,688	461,703.818	1,088,961.434	627,257.616
2026	8,341,968	940,556,905	66,591,429	466,140.002	1,099,424.491	633,284.489
2027	8,422,120	949,594,048	67,231,259	470,618.810	1,109,988.080	639,369.270
2028	8,503,042	958,718,023	67,877,236	475,140.652	1,120,653.167	645,512.515
2029	8,584,742	967,929,664	68,529,420	479,705.942	1,131,420.728	651,714.786
2030	8,679,557	978,620,095	69,286,303	485,004.119	1,143,916.858	658,912.739

For the years 2010, 2020 and 2030 food waste recovery, biohydrogen production, production cost and sale costs, and net return was calculated as 6,856.24 thousand tons, 773,040.82 thousand litres, 383 and 904 thousand US\$, and 520 thousand US\$; 7,776.1 thousand tons, 876,759.30 thousand liters, 435 and 1,025 thousand US\$, and 590 thousand US\$; 8,679.6 thousand tons, 978,620.10 thousand liters, 485 thousand and 1,143 thousand US\$, and 659 thousand US\$, respectively.

Thus, it was projected that in 2030 a net return greater than 0.65 million US\$ could be generated in Turkey from food waste if 0.1% is recovered for biohydrogen generation.

Table 4.4.2 (c): Forecasts for food waste geneation, biohydrgoen production both in litres and kg, production cost and sale costs, and net return when the recovery rate is 0.5%.

Year	Food waste, recovery, kg	H ₂ production, L	H ₂ production, kg	H ₂ production cost, US\$	H ₂ sale cost, US\$	Net return, US\$
2010	34,281,189	3,865,204,107	273,656,451	1,915,595.155	4,518,068.002	2,602,472.847
2011	34,746,785	3,917,700,018	277,373,161	1,941,612.129	4,579,430.893	2,637,818.764
2012	35,166,734	3,965,049,209	280,725,484	1,965,078.388	4,634,777.741	2,669,699.353
2013	35,650,557	4,019,600,275	284,587,699	1,992,113.896	4,698,542.918	2,706,429.022
2014	36,128,595	4,073,499,127	288,403,738	2,018,826.167	4,761,545.717	2,742,719.550
2015	36,614,590	4,128,294,982	292,283,285	2,045,982.993	4,825,597.031	2,779,614.038
2016	37,113,915	4,184,593,918	296,269,249	2,073,884.746	4,891,405.307	2,817,520.562
2017	37,576,894	4,236,794,813	299,965,073	2,099,755.509	4,952,423.351	2,852,667.842
2018	38,131,805	4,299,361,028	304,394,761	2,130,763.326	5,025,557.501	2,894,794.175
2019	38,667,074	4,359,712,549	308,667,648	2,160,673.539	5,096,102.876	2,935,429.337
2020	38,880,678	4,383,796,482	310,372,791	2,172,609.536	5,124,254.778	2,951,645.242
2021	39,544,873	4,458,684,450	315,674,859	2,209,724.013	5,211,791.923	3,002,067.910
2022	39,786,272	4,485,902,206	317,601,876	2,223,213.133	5,243,606.976	3,020,393.843
2023	39,970,123	4,506,631,328	319,069,498	2,233,486.486	5,267,837.413	3,034,350.926
2024	40,639,140	4,582,063,035	324,410,063	2,270,870.440	5,356,010.138	3,085,139.698
2025	41,312,894	4,658,028,833	329,788,441	2,308,519.090	5,444,807.168	3,136,288.078
2026	41,709,841	4,702,784,525	332,957,144	2,330,700.011	5,497,122.454	3,166,422.443
2027	42,110,601	4,747,970,242	336,156,293	2,353,094.052	5,549,940.400	3,196,846.348
2028	42,515,212	4,793,590,117	339,386,180	2,375,703.262	5,603,265.837	3,227,562.575
2029	42,923,710	4,839,648,321	342,647,101	2,398,529.708	5,657,103.640	3,258,573.932
2030	43,397,787	4,893,100,474	346,431,514	2,425,020.595	5,719,584.289	3,294,563.694

For the years 2010, 2020 and 2030 food waste recovery, biohydrogen production, production cost and sale costs, and net return was calculated as 34,281.2 thousand tons, 3,865.2 million litres, 1.916 and 4.518 million US\$, and 2.602 million US\$; 38,880.7 tons, 4,383.8 million liters, 2.173 and 5.124 million US\$, and 2.952 million US\$; 43,397.8 tons, 4,893.1 million liters, 2.425 and 5.720 million US\$, and 3.295 million US\$, respectively. Thus, it was projected that in 2030 a net return greater than 3.3 million US\$ could be generated in Turkey from food waste if 0.5% is recovered for biohydrogen generation.

Table 4.4.2 (d): Forecasts for food waste geneation, biohydrgoen production both in litres and kg, production cost and sale costs, and net return when the recovery rate is 1.0%.

Year	Food waste, recovery, kg	H ₂ production, L	H ₂ production, kg	H ₂ production cost, US\$	H ₂ sale cost, US\$	Net return, US\$
2010	68,562,379	7,730,408,214	547,312,902	3,831,190.311	9,036,136.005	5,204,945.694
2011	69,493,570	7,835,400,037	554,746,323	3,883,224.258	9,158,861.786	5,275,637.528
2012	70,333,467	7,930,098,418	561,450,968	3,930,156.776	9,269,555.481	5,339,398.705
2013	71,301,114	8,039,200,549	569,175,399	3,984,227.792	9,397,085.836	5,412,858.044
2014	72,257,191	8,146,998,254	576,807,476	4,037,652.335	9,523,091.435	5,485,439.100
2015	73,229,179	8,256,589,965	584,566,570	4,091,965.987	9,651,194.063	5,559,228.076
2016	74,227,830	8,369,187,836	592,538,499	4,147,769.491	9,782,810.615	5,635,041.123
2017	75,153,788	8,473,589,625	599,930,145	4,199,511.018	9,904,846.702	5,705,335.683
2018	76,263,610	8,598,722,057	608,789,522	4,261,526.651	10,051,115.002	5,789,588.351
2019	77,334,147	8,719,425,098	617,335,297	4,321,347.079	10,192,205.752	5,870,858.674
2020	77,761,357	8,767,592,963	620,745,582	4,345,219.073	10,248,509.556	5,903,290.483
2021	79,089,746	8,917,368,900	631,349,718	4,419,448.027	10,423,583.846	6,004,135.819
2022	79,572,545	8,971,804,413	635,203,752	4,446,426.267	10,487,213.952	6,040,787.685
2023	79,940,245	9,013,262,656	638,138,996	4,466,972.973	10,535,674.825	6,068,701.853
2024	81,278,280	9,164,126,070	648,820,126	4,541,740.880	10,712,020.276	6,170,279.396
2025	82,625,789	9,316,057,667	659,576,883	4,617,038.180	10,889,614.335	6,272,576.156
2026	83,419,681	9,405,569,050	665,914,289	4,661,400.021	10,994,244.907	6,332,844.886
2027	84,221,202	9,495,940,485	672,312,586	4,706,188.104	11,099,880.800	6,393,692.696
2028	85,030,423	9,587,180,234	678,772,361	4,751,406.524	11,206,531.673	6,455,125.149
2029	85,847,420	9,679,296,642	685,294,202	4,797,059.416	11,314,207.279	6,517,147.863
2030	86,795,574	9,786,200,948	692,863,027	4,850,041.190	11,439,168.578	6,589,127.388

For the years 2010, 2020 and 2030 food waste recovery, biohydrgoen production, production cost and sale costs, and net return was calculated as 68,562.4 thousand tons, 7,730.41 million liters, 3.831 and 9.036 million US\$, and 5.205 million US\$; 77,761.4 tons, 8,767.6 million liters, 4.345 and 10.249 million US\$, and 5.903 million US\$; 86,795.6 tons, 9,786.2 million liters, 4.850 and 11.439 million US\$, and 6.589 million US\$, respectively. Thus, it was projected that in 2030 a net return greater than 6.6 million US\$ could be generated in Turkey from food waste if 1.0% is recovered for biohydrogen generation.

Table 4.4.2 (e): Forecasts for food waste geneation, biohydrgoen production both in litres and kg, production cost and sale costs, and net return when the recovery rate is 3.0%.

Year	Food waste, recovery, tons	H ₂ production, L	H ₂ production, kg	H ₂ production cost, US\$	H ₂ sale cost, US\$	Net return, US\$
2010	205,687,137	23,191,224,643	1,641,938,705	11,493,570.933	27,108,408.015	15,614,837.082
2011	208,480,711	23,506,200,110	1,664,238,968	11,649,672.775	27,476,585.358	15,826,912.584
2012	211,000,401	23,790,295,253	1,684,352,904	11,790,470.328	27,808,666.444	16,018,196.116
2013	213,903,341	24,117,601,648	1,707,526,197	11,952,683.377	28,191,257.507	16,238,574.131
2014	216,771,572	24,440,994,761	1,730,422,429	12,112,957.004	28,569,274.304	16,456,317.301
2015	219,687,538	24,769,769,895	1,753,699,709	12,275,897.960	28,953,582.188	16,677,684.228
2016	222,683,490	25,107,563,508	1,777,615,496	12,443,308.474	29,348,431.845	16,905,123.370
2017	225,461,365	25,420,768,876	1,799,790,436	12,598,533.055	29,714,540.105	17,116,007.050
2018	228,790,831	25,796,166,170	1,826,368,565	12,784,579.954	30,153,345.006	17,368,765.052
2019	232,002,442	26,158,275,294	1,852,005,891	12,964,041.236	30,576,617.257	17,612,576.022
2020	233,284,070	26,302,778,890	1,862,236,745	13,035,657.218	30,745,528.667	17,709,871.449
2021	237,269,239	26,752,106,700	1,894,049,154	13,258,344.080	31,270,751.538	18,012,407.458
2022	238,717,634	26,915,413,238	1,905,611,257	13,339,278.801	31,461,641.857	18,122,363.056
2023	239,820,736	27,039,787,969	1,914,416,988	13,400,918.918	31,607,024.476	18,206,105.558
2024	243,834,840	27,492,378,210	1,946,460,377	13,625,222.641	32,136,060.829	18,510,838.188
2025	247,877,366	27,948,173,001	1,978,730,648	13,851,114.539	32,668,843.006	18,817,728.467
2026	250,259,043	28,216,707,151	1,997,742,866	13,984,200.064	32,982,734.722	18,998,534.658
2027	252,663,605	28,487,821,454	2,016,937,759	14,118,564.313	33,299,642.401	19,181,078.088
2028	255,091,270	28,761,540,703	2,036,317,082	14,254,219.572	33,619,595.020	19,365,375.448
2029	257,542,261	29,037,889,926	2,055,882,607	14,391,178.247	33,942,621.837	19,551,443.590
2030	260,386,721	29,358,602,845	2,078,589,081	14,550,123.570	34,317,505.734	19,767,382.164

For the years 2010, 2020 and 2030 food waste recovery, biohydrogen production, production cost and sale costs, and net return was calculated as 205,687.1 thousand tons, 23,191.2 million liters, 11,493.6 and 27.108 million US\$, and 15.615 million US\$; 233,284.1 tons, 26,302.8 million liters, 13.036 and 30.746 million US\$, and 17.710 million US\$; 260,386.7 tons, 29,358.6 million liters, 14.550 and 34.318 million US\$, and 19.767 million US\$, respectively. Thus, it was projected that in 2030 a net return greater than 19.8 million US\$ could be generated in Turkey from food waste if 3.0 % is recovered for biohydrogen generation.

Table 4.4.2 (f): Forecasts for food waste geneation, biohydrgoen production both in litres and kg, production cost and sale costs, and net return when the recovery rate is 5.0%.

Year	Food waste, recovery, tons	H ₂ production, L	H ₂ production, kg	H ₂ production cost, US\$	H ₂ sale cost, US\$	Net return, US\$
2010	342,811,894	38,652,041,071	2,736,564,508	19,155,951.555	45,180,680.024	26,024,728.469
2011	347,467,851	39,177,000,183	2,773,731,613	19,416,121.291	45,794,308.930	26,378,187.639
2012	351,667,336	39,650,492,089	2,807,254,840	19,650,783.879	46,347,777.407	26,696,993.527
2013	356,505,568	40,196,002,747	2,845,876,994	19,921,138.961	46,985,429.179	27,064,290.218
2014	361,285,954	40,734,991,268	2,884,037,382	20,188,261.673	47,615,457.174	27,427,195.501
2015	366,145,896	41,282,949,825	2,922,832,848	20,459,829.933	48,255,970.314	27,796,140.381
2016	371,139,150	41,845,939,179	2,962,692,494	20,738,847.457	48,914,053.074	28,175,205.617
2017	375,768,941	42,367,948,126	2,999,650,727	20,997,555.091	49,524,233.508	28,526,678.417
2018	381,318,051	42,993,610,284	3,043,947,608	21,307,633.257	50,255,575.010	28,947,941.753
2019	386,670,736	43,597,125,490	3,086,676,485	21,606,735.393	50,961,028.762	29,354,293.369
2020	388,806,783	43,837,964,817	3,103,727,909	21,726,095.363	51,242,547.778	29,516,452.415
2021	395,448,732	44,586,844,499	3,156,748,591	22,097,240.134	52,117,919.230	30,020,679.096
2022	397,862,723	44,859,022,063	3,176,018,762	22,232,131.335	52,436,069.762	30,203,938.427
2023	399,701,226	45,066,313,282	3,190,694,980	22,334,864.863	52,678,374.126	30,343,509.263
2024	406,391,400	45,820,630,350	3,244,100,629	22,708,704.401	53,560,101.381	30,851,396.980
2025	413,128,943	46,580,288,335	3,297,884,414	23,085,190.899	54,448,071.677	31,362,880.778
2026	417,098,406	47,027,845,251	3,329,571,444	23,307,000.106	54,971,224.537	31,664,224.430
2027	421,106,008	47,479,702,424	3,361,562,932	23,530,940.521	55,499,404.001	31,968,463.480
2028	425,152,117	47,935,901,172	3,393,861,803	23,757,032.621	56,032,658.367	32,275,625.746
2029	429,237,102	48,396,483,210	3,426,471,011	23,985,297.079	56,571,036.396	32,585,739.317
2030	433,977,869	48,931,004,741	3,464,315,136	24,250,205.950	57,195,842.890	32,945,636.940

For the years 2010, 2020 and 2030 food waste recovery, biohydrgoen production, production cost and sale costs, and net return was calculated as 342,812.9 thousand tons, 38,652.0 million liters, 19.156 and 45.180 million US\$, and 26.025 million US\$; 388,806.8 tons, 43,838.0 million liters, 21.726 and 51.243 million US\$, and 29.517 million US\$; 433,977.9 tons, 48,931.0 million liters, 24.250 and 57.196 million US\$, and 32.946 million US\$, respectively. Thus, it was projected that in 2030 a net return greater than 32.9 million US\$ could be generated in Turkey from food waste if 5.0 % is recovered for biohydrogen generation.

It was estimated biohydrogen worth 1,144 billion US\$ could be produced from Turkey's household food wastes in 2030, which also could deliver a net return of more than 650.0 million US\$ (if 100% is recovered). On top of this economic activity, utilization of food wastes for biohydrogen generation will provide a synergistic solution to uncontrolled greenhouse gas emissions from food wastes, which would otherwise decompose at landfill sites. Therefore, techno-economic analysis given in

this section clearly showed that there is a great potential of economic and environmental gain from food waste based biohydrogen generation in Turkey.



5. CONCLUSIONS

In this thesis study, it was found that Turkey's corn, coarse grains and rice production does not meet the country's demand for consumption. This is important for Turkey's food safety and strategy policies and it is an important factor, which could crucially affect the country's biohydrogen production plans from corn, coarse grains and rice in the near future. On the other hand, it was estimated that biohydrogen worth 1.114 billion US\$ (if 100% is recovered) could be produced from Turkey's household food wastes in 2030 and utilization of food wastes for biohydrogen generation could provide a synergistic solution to uncontrolled greenhouse gas emissions from otherwise landfilled food wastes. Finally, the analysis given in this thesis clearly showed that there is a great potential for economic and environmental gain from agricultural and food waste based biohydrogen generation in Turkey.



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