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Packaging Waste Recycling: A Pathway to Climate Change Mitigation in Türkiye

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Abstract: Climate change has significantly affected numerous aspects of our planet, with weather patterns being one of the most visibly impacted. The growing concentration of greenhouse gases (GHGs) in the atmosphere traps more heat, leading to disruptions in weather systems and amplifying the challenges posed by climate change. The main sources of greenhouse gas (GHG) emissions are fossil fuels, with the largest contributors being the power generation, transportation, and industrial combustion sectors. Additional significant sources include agriculture, fuel extraction, buildings, and waste management both globally and in Türkiye. Recycling packaging waste plays a vital role in mitigating climate change by reducing GHG emissions and conserving energy. It minimizes waste sent to landfills and promotes a circular economy, enabling the continual reuse and recycling of materials. This process decreases the reliance on new raw materials, further reducing environmental impacts and contributing to a more sustainable future.

Key words: Climate change, Greenhouse Gas (GHG), Recycling, Packaging waste.

Ambalaj Atığı Geri Dönüşüm: Türkiye'de İklim Değişikliğiyle Mücadele için Bir Yol

Özet: İklim değişikliği, gezegenimizin birçok yönünü önemli ölçüde etkilemiş olup, hava olayları en görünür şekilde etkilenen alanlardan biridir. Atmosferde artan sera gazı (GHG) yoğunluğu, daha fazla ısının tutulmasına neden olarak hava sistemlerinde bozulmalara yol açmakta ve iklim değişikliğinin yarattığı zorlukları artırmaktadır. Sera gazı (GHG) emisyonlarının başlıca kaynakları fosil yakıtlar olup, en büyük katkıyı enerji üretimi, ulaşım ve endüstriyel yanma sektörleri sağlamaktadır. Ayrıca, tarım, yakıt çıkarma, binalar ve atık yönetimi hem dünya genelinde hem de Türkiye'de önemli diğer önemli kaynaklar arasında yer almaktadır. Ambalaj atıklarının geri dönüşümü, sera gazı emisyonlarını azaltarak ve enerji tasarrufu sağlayarak iklim değişikliğiyle mücadelede hayati bir rol oynamaktadır. Bu süreç, depolama alanlarına gönderilen atık miktarını azaltmakta ve malzemelerin sürekli olarak yeniden kullanılıp geri dönüştürülmesini sağlayan döngüsel bir ekonomiyi teşvik etmektedir. Böylece yeni ham maddelere olan bağımlılık azalmakta, çevresel etkiler en aza indirilmekte ve daha sürdürülebilir bir geleceğe katkı sağlanmaktadır.

Anahtar kelimeler: İklim değişikliği, Sera gazı, Geri dönüşüm, Ambalaj atığı.

1. Introduction

Climate change has profoundly affected various aspects of our planet, with the weather being one of the most impacted. The increasing concentration of greenhouse gases in the atmosphere traps more heat, disrupting weather patterns and intensifying climate-related challenges [1].

Greenhouse gases (GHGs) in the atmosphere trap infrared radiation emitted by the earth, helping to retain heat-a phenomenon known as the greenhouse effect. Human activities have significantly increased GHG emissions, contributing to a global temperature rise of approximately 1.1°C. Greenhouse gases effects are categorized into two categories which are natural and enhanced effects. The natural greenhouse effect arises from naturally occurring greenhouse gases and is essential for sustaining life on Earth. The enhanced greenhouse effect, on the other hand, refers to the additional warming caused by increased concentrations of greenhouse gases (GHGs) due to human activities [2].

Since the start of the 21st century, global greenhouse gas (GHG) emissions have been on a steady upward trend, largely driven by contributions from China and other emerging economies. As of 2023, global GHG emissions reached a record high of 53 Gt CO_2 eq (excluding emissions from Land Use, Land Use Change, and Forestry). This marks a 1.9% increase or an additional 994 Mt CO_2 eq compared to 2022 levels [3]. According to

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research, the average global temperature has risen 1.1°C above pre-industrial levels and already exceeded the 1.5°C threshold at the beginning of 2024. During the same period, annual global greenhouse gas (GHG) emissions reached 59 billion tons of CO_2 eq. At this critical juncture, it is imperative to adopt a decisive stance to mitigate the GHG emissions driving climate change [4].

The primary sources of greenhouse gas (GHG) emissions are fossil fuels, with the power industry, transportation, and industrial combustion sectors being the largest contributors. Other significant sources include agriculture, fuel extraction, buildings, and waste management [5]. Globally, the primary greenhouse gases (GHGs) released by human activities are carbon dioxide (CO_2), methane (CH_4), nitrous Oxide (N_2O), and fluorinated gases. CO_2 emissions mainly arise from the combustion of fossil fuels. Additionally, deforestation, land clearing for agriculture, and soil degradation contribute to CO_2 release from the landscape. CH_4 emissions mainly result from agricultural activities, waste management, energy production and consumption, and biomass burning. N_2O emissions predominantly originate from agricultural practices, particularly fertilizer use while Fluorinated gases are released through industrial processes, refrigeration, and various consumer products. These include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) [6].

Energy efficiency and transitioning to renewable energy can address only 55% of global emissions. Achieving net-zero requires transforming how we produce and consume products, materials, and food. By incorporating the three principles of the circular economy into the design of products, services, and systems, it can tackled the GHG emissions linked to industry, agriculture, and land use emissions that the energy transition alone cannot resolve. Greenhouse gas emissions are reduced across the value chain by eliminating waste and pollution, energy is preserved in products and materials by keeping them in circulation, and carbon is sequestered in soil and products through nature regeneration [7].

2. Climate Change

Climate change is caused by human activities and threatens life on Earth. With increasing greenhouse gas emissions, climate change is occurring much faster than expected**.** Action must be dramatically increased at all levels to address climate change. While many measures are being taken worldwide such as increasing investment in renewable energy more must be done. The world needs to transform its energy, industry, transportation, food, waste management, agriculture, and forestry systems to limit global temperature increases to well below 2°C, and possibly even below 1.5°C [8].

To combat climate change, the United Nations Framework Convention on Climate Change (UNFCCC) was adopted in 1992, followed by the Kyoto Protocol in 1997, and the Paris Agreement in 2015 on a global scale. Türkiye continues its efforts to reduce greenhouse gas emissions and adapt to the adverse effects of climate change, in line with the "common but differentiated responsibilities and respective capabilities" principle of the UNFCCC, to which it became a party in 2004. Furthermore, Turkey has demonstrated its commitment to combating climate change by setting a net-zero emission targets and becoming a party to the Paris Agreement [4].

The Paris Agreement which is a legally binding international treaty on climate change is adopted by 196 parties at the UN Climate Change Conference (COP21) in Paris, France, by 2015. The primary goal of the agreement is to limit the increase in global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels. To achieve this, greenhouse gas emissions must peak no later than 2025 and decrease by 43% by 2030 [9].

2.1. Greenhouse Gas Emissions (GHGs)

Greenhouse gases (GHGs) warm the earth by absorbing energy and slowing the rate at which the energy escapes to space; they act like a blanket insulating the earth. The main greenhouse gases are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydro fluorocarbons (HFCs), perfluorocarbons (PFCs), and Sulphur hexafluoride (SF_6). Different GHGs can have different effects on the earth's warming. Two key ways in which these gases differ from each other are their ability to absorb energy (their "radioactive efficiency"), and how long they stay in the atmosphere (also known as their "lifetime") (Table 1) [10].

Table 1. Global Warming Potential (GWP) and Atmospheric Lifetime of Main GHGs [11].

Greenhouse Gases	Chemical Formula	Global Warming Potential *AR5 (GWP-100 year)	Atmospheric Lifetime (years)
Carbon dioxide	CO_2	1	*
Methane	CH_4	28	12.4
Nitrous Oxide	N_2O	265	121
Chlorofluorocarbons (CFC11)	CCl_3F	4,660	45
Hydrofluorocarbons (HFCs)	Various	12-12,400	<1-222
Perfluorocarbons (PFCs)	Various	6,630-11,100	2,600-50,000
Sulphur hexafluoride	SF_6	23,500	3,200

* No single lifetime can be given
AR5 refers to the IPCC Fifth Assessment Report (2014)

The waste sector is not only responsible for GHG emissions but also contributes to avoiding GHG emissions. In the waste sector, GHG emission reduction is achieved through material (reuse, recycling, composting, etc.) and energy (biogas, electricity, and heat generation) recovery and thus an environmental benefit accounted for as avoided emissions [12].

2.1.1. Greenhouse Gas Emissions (GHGs) by Sectors: A Global and Türkiye Overview

Global GHG emission reached 53 Gt (billion tons) CO_2 eq in 2023. The power industry was the largest contributor, responsible for 15.1 Gt CO_2 eq (28.5%) of the total emissions, followed by transportation sector with 8.4 Gt CO_2 eq (15.8%). The agriculture sector emitted 6.5 Gt CO_2 eq (12.3%), while industrial combustion and fuel exploitation accounted for 6.4 Gt CO_2 eq (12.1%) and 5.9 Gt CO_2 eq (11.1%), respectively. The processes sector contributed 4.9 Gt CO_2 eq (9.2%) of the total emissions, and buildings were responsible for 3.8 Gt CO_2 eq (7.2%). Waste management had the smallest share, emitting 2 Gt CO_2 eq (3.8%) (Fig.1). This distribution highlights the significant role of energy production, transportation, and agriculture in overall GHG emissions [5].

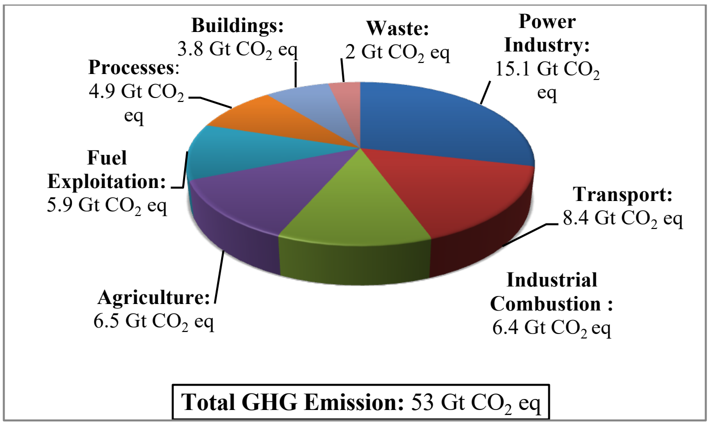

Figure 1. Global GHG Emissions by Sector, 2023 [5].

In 2022, Türkiye's total greenhouse gas (GHG) emissions amounted to 553 Mt (million tons) CO_2 eq (equivalent). The energy sector was the largest contributor, accounting for 400.6 Mt CO_2 eq (71.8%), followed by the agriculture sector with 71.5 Mt CO_2 eq (12.8%). Emissions from industrial processes and product use were 69.9 Mt CO_2 eq (12.5%), while the waste sector contributed the smallest share at 16.3 Mt CO_2 eq (2.9%) (Fig. 2) [13]. The data highlights the dominance of the energy sector in Türkiye's GHG emissions, followed by significant contributions from agriculture and industrial processes.

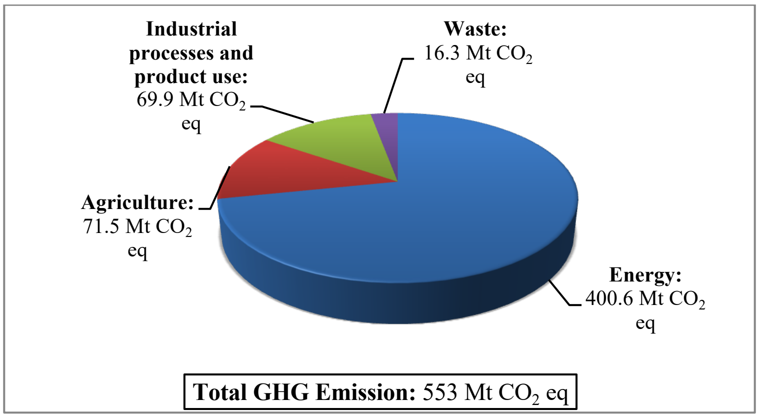

Figure 2. GHG Emissions in Türkiye by Sector, 2023 [13].

3. Material and Method

In Türkiye separately collected packaging waste including graphic paper mainly consists of paper-cardboard (e.g., newspapers, magazines, books, and packaging boxes), plastic (e.g., PET bottles, plastic bags, plastic packaging), glass (e.g., glass bottles and jars), and metal (e.g., aluminum beverage cans and tin cans). This study examines the avoided impacts specifically avoided GHG emissions and energy savings associated with the recycling of packaging waste, including paper-cardboard, plastic, and glass waste. To achieve this, data on municipal solid waste (MSW) production and composition were obtained from the literature. The avoided GHG emissions and energy savings data used in the analysis were sourced from [14], [15], [16]. Using these references, the avoided GHG emissions and energy savings from packaging waste recycling in Türkiye were calculated.

109.2 million tons of MSW were generated in Türkiye by 2022 [17]. According to Türkiye's waste characterization data, biowaste accounted for 55.54% of the total waste, paper-cardboard made up 8.11%, glass constituted 3.38%, metal represented 1.37%, and hazardous waste comprised 0.43%. The remaining 8.03% consisted of other types of waste [18].

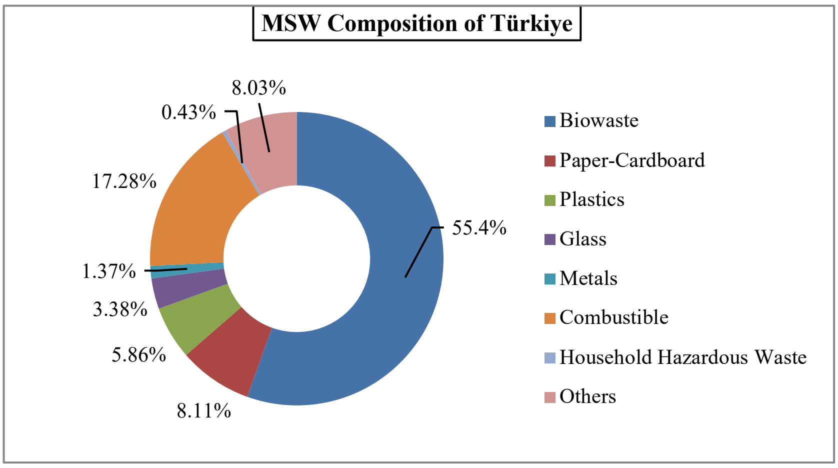

Figure 3. MSW Composition of Türkiye, 2016 [18].

Based on the MSW composition data in Fig. 3, the compositions of paper-cardboard, plastics, and glass waste were 8.11%, 5.86%, and 3.38% repectively. These packaging waste values constitute 17.35% of the total MSW (Table 2). These values of each recyclable in the table are multiplied by 100 and divided by the total packaging waste to calculate the amount in the total packaging waste.

Table 2. Calculation of Recyclable Waste in Total MSW and Packaging Waste.

Recyclable waste	**(%)**
Paper-Cardboard$_{(a)}$	8.11
Plastic$_{(a)}$	5.86
Glass$_{(a)}$	3.38
Total packaging waste	17.35

Secondly, the data on avoided GHG emissions and energy savings were obtained from the literature (Table 3). The percentage of materials used in primary and secondary production, as well as the cumulative energy consumption (CEC), GHG emissions, avoided energy, and avoided GHG emissions values associated with the primary and secondary production of recyclables, were used in the calculations.

Table 3. Savings (CEC and GHG emissions) through secondary production of marketable intermediate products from secondary raw materials compared to primary production [14], [15], [16].

	Primary Raw Material	**Secondary Raw Material**	**CEC**	**GHG Emissions**	**Avoided Energy**	**Avoided GHG**
	(%)		**(MJ/Mg)**	**(kg CO_2 eq)/Mg**	**(MJ/Mg)**	**(kg CO_2 eq/Mg)**
GLASS						
Primary production of green container glass	95		10.670	921		
Secondary production of green container glass		80% Broken Glass	7.270	506	3.400	415
PLASTICS						
PET beverage bottles, primary production	100		105.700	3.495		
PET beverage bottles, secondary production		30	78.700	2.685	27.000	810
PAPER-CARDBOARD						
Primary fibre paper	100		18.000	-		
Recycled Paper		100	7.200	-	10.800	160

The avoided GHG and avoided energy values for each type of recyclable waste were calculated by multiplying the avoided GHG and energy values from Table 2 by the corresponding amounts of glass, plastic, and paper-cardboard.

4. Results

Based on the MSW composition data in Table 2, packaging waste consisting of paper-cardboard, plastics, and glass accounts for 17.35% of the total waste. This corresponds to 18.96 million tons of packaging waste, including 8.86 million tons of paper-cardboard, 6.4 million tons of plastic, and 3.7 million tons of glass (Table 4).

Table 4. Amount of Recyclable Waste in MSW of Türkiye, 2022.

Recyclable Waste	Calculation	Result
Paper-Cardboard $_{(b)}$	(Paper-Cardboard$_{(a)}$ x Total MSW)/100	(8.11 x 109.2 Mt)/100 = 8.86 Mt
Plastic$_{(b)}$	(Plastic$_{(a)}$ x Total MSW)/100	(5.86 x 109.2 Mt)/100 = 6.4 Mt
Glass$_{(b)}$	(Glass$_{(a)}$ x Total MSW)/100	(3.38 x 109.2 Mt)/100 = 3.7 Mt
Total packaging waste	Paper-Cardboard$_{(b)}$ + Plastic$_{(b)}$ + Glass$_{(b)}$	8.86 Mt + 6.4 Mt + 3.7 Mt = 18.96 Mt

The values of each recyclable material in Table 4 are multiplied by 100 and divided by the total packaging waste to calculate their percentage in the total packaging waste. Based on these calculations, paper-cardboard comprises 46.73%, plastic comprises 33.75%, and glass comprises 19.52% of the total packaging waste (Table 5).

Table 5. Amount of Recyclable Waste in Total Packaging Waste of Türkiye, 2022.

Recyclable Waste	Calculation	Result
Paper-Cardboard	(Paper-Cardboard $_{(b)}$ x 100)/Total Packaging waste	(8.86 Mt x100)/18.96 Mt = 46.73%
Plastic	(Plastic$_{(b)}$ x 100)/Total Packaging waste	(6.4 Mt x100)/18.96 Mt = 33.75%
Glass	(Glass$_{(b)}$ x 100)/Total Packaging waste	(3.7 Mt x100)/18.96 Mt = 19.52%
Total packaging waste	Paper-Cardboard + Plastic + Glass	100%

The avoided greenhouse gas (GHG) emissions and energy savings were calculated by multiplying the values in Table 3 by the quantities of each recyclable material, as determined through inventory analysis. Based on these calculations, recycling 1 ton of packaging waste in Türkiye leads to a reduction of 419.1 kg CO_2 eq in GHG emissions and saves 13,540.7 MJ (3,764.3 kWh) of energy (Table 6).

Avoided GHG emission and energy savings are calculated by multiplying the total avoided GHG and energy values by the total packaging waste, as follow:

<u>Avoided GHG Emissions and Energy Values of Packaging Waste of Türkiye by 2022:</u>

•**Avoided GHG =** (Avoided GHG emissions per ton of packaging waste x total packaging waste)/1 ton

= (419.1 kg CO_2 eq x 10^{-3} tons/kg) x (18.96 x 10^6 tons/year)/1ton

= 7,946 x 10^3 tons CO_2 eq = 7.9 x 10^6 tons CO_2 eq/year

• **Avoided Energy =** (Avoided energy per ton of packaging waste x Total packaging waste)/1 ton

= (3,764.3 kWh) x (18.96 x 10^6 tons/year)/1ton

= 71,371 x 10^6 kWh/year

Based on these calculations, recycling 1 ton of packaging waste in Türkiye resulted in a reduction of 7.9 x 10^6 tons of CO_2 eq GHG emissions and saved of 71,371 x 10^6 kWh of energy by 2022 (Table 7).

Table 6. Avoided GHG and Energy of Recyclable Waste.

Recycled Materials (1 ton)	Avoided GHG (kg CO_2 eq)	Avoided Energy (MJ)
Glass	0.415 (kg CO_2 eq/kg) x 195.2 kg = 81.1	3.4 (MJ/kg) x 195.2 kg = 663.7
Plastic	0.78 (kg CO_2 eq/kg) x 337.5 kg = 263.2	23.2 (MJ/kg) x 337.5 kg = 7,830
Paper-Cardboard	0.16 (kg CO_2 eq/kg) x 467.3 kg = 74.8	10.8 (MJ/kg) x 467.3 kg = 5,047
Total	419.1 kg CO_2 eq	13,540.7 MJ = 3,764.3 kWh

Table 7. GHG Emissions and Energy Values of Packaging Waste of Türkiye by 2022

GHG and Energy	Value
Total GHG (from Waste sector)	16.3 x 10^6 tons CO_2 eq/year
Avoided GHG	7.9 x 10^6 tons CO_2 eq/year
Avoided Energy	71,371 x 10^6 kWh/year

5. Conclusions

Waste management is closely linked to climate change, as the way waste is managed has significant effects on greenhouse gas (GHG) emissions and the broader environment. In particular, effective waste management through practices such as recycling, composting, and diverting waste from landfills can play a crucial role in reducing GHG emissions and supporting global efforts to combat climate change.

Addressing GHG emissions in these key sectors will be essential for climate mitigation efforts. Based on the findings in this study, global GHG emissions amounted to 53 Gt (billion tons) CO_2 eq in 2023. The power industry was the largest contributor, responsible for 15.1 Gt CO_2 eq (28.5%) of the total emissions, followed by transportation sector with 8.4 Gt CO_2 eq (15.8%). The agriculture sector emitted 6.5 Gt CO_2 eq (12.3%), while industrial combustion and fuel exploitation accounted for 6.4 Gt CO_2 eq (12.1%) and 5.9 Gt CO_2 eq (11.1%), respectively. The processes sector contributed 4.9 Gt CO_2 eq (9.2%) of the total emissions, and buildings were responsible for 3.8 Gt CO_2 eq (7.2%). Waste management had the smallest share, emitting 2 Gt CO_2 eq (3.8%). This distribution highlights the significant role of energy production, transportation, and agriculture in overall GHG emissions

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CO_2 eq (12.8%). Emissions from industrial processes and product use totaled 69.9 Mt CO_2 eq (12.5%), while the waste sector contributed the smallest share at 16.3 Mt CO_2 eq (2.9%). 109.2 million tons of MSW were generated, with packaging waste comprising paper-cardboard, plastic, and glass making up 17,35% of the total MSW. Recycling 1 ton of packaging waste saves 419.1 kg CO_2 eq in GHG emissions and 13,540.7 MJ (3,764.3 kWh) of energy. These values correspond to a reduction of 7.9 Mt CO_2 eq GHG and a recovery of 71,371 million kWh of energy, if all 18.96 Mt of packaging waste produced in 2022 were to be recycled.

Recycling packaging waste helps mitigate climate change by reducing greenhouse gas emissions and conserving energy. It also decreases the amount of waste sent to landfills, fostering a circular economy where materials are continually reused and recycled. This reduces the demand for new raw materials and the associated environmental impacts, including GHG emissions.

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