Pomegranate Peel as Biofuel: Combustion and Environmental Safety Assessment of the Guleisha Variety

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Abstract

In the context of the growing potential of alternative energy sources, biofuel becomes an important solution for reducing the load on natural resources and minimizing environmental consequences. This article explores the possibility of using pomegranate peel of the Güleysha variety as a biofuel source. Research shows that pomegranate peel has good combustion properties and can serve as a renewable energy source with the potential for widespread application.

The energy efficiency calculations obtained from the study show that when 10 grams of pomegranate peel are burned, 80,000 joules of energy are released, and the combustion power is 800 watts. Although these indicators are lower compared to other types of biofuels, such as wood pellets, olive pits, or cereal waste, pomegranate peel is a promising energy source. When comparing emissions, pomegranate peel demonstrates significantly lower levels of carbon dioxide, carbon monoxide, hydrocarbons, and sulfur oxides, making it an environmentally safe option.

Moreover, pomegranate peel is readily available and has low raw material costs since it is a byproduct of the food industry. This makes it an environmentally clean, renewable, and promising energy source for sustainable development. Therefore, its use can contribute to solving the problem of the depletion of traditional energy sources and environmental pollution. It is economically efficient for use in energy production, especially in countries with high pomegranate production levels, such as Azerbaijan. Despite its lower heat value compared to other biofuels, pomegranate peel is of significant interest for study.

Keywords: *pomegranate peel; biofuel; combustion efficiency; Güleysha variety; environmental safety*

1. Introduction

With the growth of industry and the increase in population, the demand for energy is rising. Energy plays an important role in the social and economic development of countries (Everett, 2010). However, the use of fossil energy sources leads to their depletion, highlighting the importance of transitioning to alternative and renewable energy sources (Hall, 2011). Environmental issues caused by the burning of fossil fuels, as well as land degradation during extraction, require the search for sustainable solutions (Li, 2015). In response to energy crises and growing concerns about the depletion of natural resources, interest in alternative fuels, such as biofuels, has increased (Naik, 2014).

Biofuel is fuel that is derived from plants or animals. It can replace fossil fuels, which are running out, with fuel produced from renewable resources (Zubair, 2017).

Why has the focus returned to biofuels? The first reason is climate change, which worsens due to greenhouse gas emissions from fossil fuels. Transportation emits almost a quarter of all carbon dioxide related to energy production. Since 1970, emissions in the transportation sector have doubled, and 80% of them come from automobiles (Lund & Mathiesen, 2009). The second reason is the need for renewable energy sources, as oil and coal may run out. Another important factor is the rising prices of hydrocarbons (Smith, 2012).

1.1 Advantages of Biofuel

- It is renewable. Unlike fossil fuels, which are depleting, biofuel is obtained from plants and can be produced repeatedly (Demirbas, 2009).
- It is less polluting. When biofuel is burned, it releases less carbon dioxide (65% less), which helps combat climate change. It also contains fewer harmful substances, such as chlorine and sulfur, which reduces air pollution (Klass, 1998).
- It contributes to the development of the country's economy. Biofuel can be produced at the point of consumption, creating jobs and reducing transportation costs. Additionally, it helps reduce dependence on imported oil (Van der Linden, 2011).

Pomegranate is an available and easily renewable resource that can be used for biofuel production. Its peel has good combustion properties and low emissions when burned, making it a promising material for producing eco-friendly fuel (Kader, 2008). In countries where these fruits are common, this material may be available at a lower cost compared to other biofuel sources (Müller & Götz, 2016). Pomegranate is a rather hardy plant, easy to care for, unlike citrus plants or bananas, which can also be used as biofuel. Unlike some other plants that require significant energy expenditure for cultivation or processing, pomegranates can be grown in more arid regions, making them more sustainable (Bharati, 2012).

Thanks to the unique climatic conditions, Azerbaijan holds a leading position in the cultivation and diversity of pomegranate varieties. Among the outstanding pomological varieties of pomegranate in the country are Guleysha Pink, Guleysha Azerbaijani, Meles, Gyrmyzy Gabyk, Veles, Shirin, Shahnar, Shikhbaba, Shelly Melesi, Nazik Gabyk, and others (López & García, 2019). The Azerbaijani varieties Guleysha Pink and VIR No. 1 were awarded gold and silver medals at the international fruit exhibition.

1.1.1 Morphological Characteristics of Shoots and Leaves

The growth patterns of the pomegranate are quite unique due to the absence of true terminal buds; consequently, the development of the plant proceeds exclusively from lateral buds. While the tree can exist for up to 300 years, its maximum agricultural efficiency is typically limited to a 25-year cycle. The trunks and branches exhibit a variety of forms, from strictly upright to gracefully drooping, depending on the specific cultivar and the environment.

The leaves are positioned in a specific phyllotaxic arrangement, usually in clusters of three, forming an angle of approximately 110–130° relative to each other. They possess very short petioles and a distinct bicolored appearance: the upper surface is a deep, dark green, while the lower side is noticeably lighter. Even when the foliage is vibrant green, the stems often maintain a characteristic reddish tint.

The pomegranate is characterized by a very long flowering period, which in turn leads to a staggered and prolonged harvest season. Not all buds reach maturity; typically, out of a cluster of 25–30 buds, only 3 to 5 will develop into full flowers. A key feature of the species is floral dimorphism: hermaphroditic flowers are pitcher-shaped with long styles and well-developed ovaries and are the only ones capable of forming fruit, while male flowers are bell-shaped with underdeveloped ovaries and short styles, usually growing in clusters of 3–5, and do not produce fruit. Internally, the flower contains a massive number of stamens — often exceeding 250 — with long, reddish filaments and bright yellow anthers that remain attached to the calyx even as the fruit grows. The ovary is complex, consisting of 4 to 15 carpels arranged in two distinct layers.

The fruit of the pomegranate, scientifically known as a "granatina," is a large, specialized berry protected by a thick, leathery exocarp (the peel). Inside, it is divided by tough, skin-like membranes into multiple chambers or locules. A single large fruit can house between 1,200 and 1,300 seeds, each surrounded by a juicy, edible pulp.

In standard climatic conditions, it takes about six months from the peak of flowering for the fruit to reach full maturity. Interestingly, the fruit does not reach its peak flavor immediately; during storage, a slight dehydration process occurs, which concentrates the natural sugars and significantly increases the sweetness of the arils.

Pomegranates are heat-loving, deciduous plants typical of dry subtropical zones. They thrive best in regions with long, intensely hot summers and cool winters. While they are somewhat drought-resistant, they require regular irrigation in areas with less than 600 mm of annual rainfall. In Azerbaijan, the harvest usually begins in the first half of October. A specific challenge in regions with early autumn rains is the cracking of the fruit, which happens when sudden moisture follows a dry period.

Azerbaijan possesses a unique advantage with its nine distinct climate zones, allowing for the cultivation of nearly every known pomegranate variety. Key regions include the Shirvan Zone — specifically the Goychay district, which is world-renowned for its superior fruit quality — the Karabakh-Mil and Ganja-Kazakh Zones, where areas like Barda and Agdam also contribute significantly to national output, and the Absheron Peninsula, where villages such as Fatmai, Mashtagi, and Buzovna are historically famous for their pomegranate orchards.

Beyond food production, the pomegranate plays a crucial role in land management. Thanks to its incredibly powerful and deep-reaching root system, it is an ideal plant for stabilizing mountain slopes and protecting the upper soil layers from erosion, which is vital for the mountainous topography of Azerbaijan.

1.2 Classification and Varietal Diversity of Pomegranates

Different varieties of pomegranate are distinguished by several key factors, including their physical dimensions, structural composition, fruit coloration, and geometric shape. Furthermore, they vary significantly in terms of ripening schedules and overall agricultural yield. Pomegranate cultivars are scientifically categorized as pomological types and are primarily divided into two major subspecies based on the characteristics of their internal development: those with light-colored internal structures (zemnozavyaznye) and those with red-colored internal structures (krasnozavyaznye).

The krasnozavyaznye (red-seeded) subspecies is characterized by a high concentration of pigments in the juice and a distinct sweet-and-sour flavor profile. In contrast, the zemnozavyaznye (light-seeded) subspecies features a pale crimson juice and is generally known for its purely sweet taste. The first group (red-seeded) includes notable pomological varieties such as Girmizi Gabig, Bala Mursal, Surkh, and Zibeida. The second group (light-seeded) is represented by varieties like Achik Dona, Koy Nordon, Kodan, Ulj, and Obik. Globally, there are approximately 400 known pomegranate varieties, and a significant portion of these cultivars has not yet been comprehensively studied by science. Among the lesser-known but remarkable types are the Chios pomegranate and the Baghdad variety known as Selimi, which is famous for producing individual fruits weighing up to 1,000 grams.

Thanks to its exceptional and diverse climate, Azerbaijan holds a leading position in the development and preservation of various pomological pomegranate cultivars, including Guleysha Pink, Azerbaijani Guleysha, Meles, Girmizi Gabig, Veles, Shirin, Shahnar, Shikhbaba, Shelli Melesi, and Nazik Gabig. Notably, the Azerbaijani varieties Guleysha Pink and VIR №1 have been recognized internationally, winning gold and silver medals at world fruit exhibitions. Based on research by I.M. Akhundzade and Z.Y. Nabiyeva, the following descriptions highlight the key features of major regional varieties.

1.2.1 Guleysha Red (Guleysha Kirmizi)

Guleysha Red is one of the most prominent and high-quality local varieties of pomegranate cultivated in Azerbaijan. It is primarily concentrated in the Shirvan economic region, with the Goychay district being the heart of its production. This variety is highly valued for its exceptional balance of size, chemical composition, and productivity.

The fruits of the Guleysha Red are generally large and well-formed, with an average weight typically ranging between 230 and 400 grams; under optimal agro-technical conditions and in high-temperature zones, some specimens can reach a substantial mass of up to 500–600 grams. The fruit is characterized by a spherical or slightly elongated shape, and the skin (exocarp) is relatively thin and remarkably smooth, featuring a vibrant, deep red or carmine coloration with a glossy, brilliant finish. The internal chambers (locules) are separated by thin, delicate membranes, and the seeds (arils) are large with a deep, dark red color; the weight of 100 arils averages around 38–42 grams, indicating a high juice content.

Chemically, Guleysha Red is classified as a sweet-and-sour variety. The sugar concentration in the juice varies between 14.5% and 16.0%, depending on the duration of the sunny period during the ripening phase, while citric acid levels are moderate, usually ranging from 1.5% to 2.1%. This combination provides the juice with a refreshing and intense flavor, making it a preferred choice for the industrial production of premium pomegranate juices and concentrates. The variety is particularly well-adapted to the dry subtropical climate of Azerbaijan, exhibiting a moderate level of frost resistance and surviving temperatures as low as −15°C to −18°C. Ripening typically concludes in the first or second half of October, and a well-maintained orchard can produce a significant volume of fruit per hectare.

In the context of this study, the Guleysha Red variety was selected as the primary object of research because its peel (exocarp) possesses a specific density and chemical structure that is conducive to thermal energy release. The relatively high proportion of peel-to-fruit mass (approximately 30–35%) ensures a stable supply of organic waste material that can be effectively processed into solid biofuel.

1.2.2 Other Regional Varieties

Guleysha Pink (Guleysha Rozovaya): Also a local variety, it is prevalent in the Shirvan group of districts as well as the Ganja and Absheron regions. The fruit size is generally medium to small, with an average weight of 220–250 grams and a maximum of 350–550 grams. The seeds are medium to large, with 100 seeds weighing between 36.5 and 39.0 grams. The sugar content is 14.4%, and the acidity is 1.84%.

Girmizi Gabig (Red Peel): This local variety is widely cultivated in the Shamkhor, Barda, Tartar, Gazakh, Goranboy, and Ganja regions. Fruits are typically small to medium-sized, averaging 180–200 grams, with some specimens reaching 400–600 grams. The exterior is cream-white, and it is a late-ripening variety with an oblate-rounded shape and smooth, glossy skin. Both juice and seeds exhibit a deep dark-cherry color; the weight of 100 seeds ranges from 30 to 50 grams. Chemically, it contains 14.1% sugar and 2.24% acid.

Azerbaijani Guleysha: Average mass approximately 220 grams, spherical shape, thin lustrous skin ranging from bright red to dark pink, sweet-and-sour category with thin internal membranes and large seeds.

Shirin Nar (Sweet Pomegranate): A highly productive variety, with a single shrub capable of yielding 60–70 kg of fruit. Fruits are large and round, averaging 300–400 grams, with some reaching 600 grams. It is exceptionally sweet, with sugar levels up to 15.5% and very low citric acid content of only 0.9%.

Bala Mursal: Oblate-rounded shape, medium-sized, averaging 225–260 grams, though some reach 600–700 grams. Raspberry-red exterior, medium to thick peel. Weight of 100 seeds is 36.3 grams. Matures mid-October, concentrated in the Goychay, Ujar, and Agsu regions.

Shah Nar: Oblate-rounded with medium to thick skin. Average fruit weight 240–250 grams, largest fruits reaching 800–900 grams. Juice and seeds are dark cherry or red. Notable for a long shelf life, remaining fresh until May or June of the following year.

Achik Dona: Sweet-and-sour fruits with an oblate-rounded shape, average weight 250–300 grams, maximum weights exceeding 1000 grams. Peel is notably thick and loose, containing 14% sugar and 2.5% acidity.

Mardakyan Pomegranate: Large fruits weighing up to 500 grams, sweet-and-sour flavor, dark blackberry-colored skin. Harvested mid-October.

Shirin Girmizi (Sweet Red): Physical dimensions of 73.8 mm height and 87.5 mm diameter, shape index 1.19. Red, glossy exterior; about 70% of harvest meets standard size requirements. Average weight 390 grams, maximum 500–600 grams. Peel thickness 2.6 mm, peel-to-fruit mass ratio 31.9%. Juice yield 51%, with 13.9% sugar and 0.60% acidity.

Donuzburnu: A folk selection variety with fleshy calyces (4–6 closed teeth). Fruits are large, up to 400 grams, with dark red, speckled skin. Peel thickness 6.6 mm — notably thick. Juice yield 38.5%, with 16% sugar and 0.69% acidity.

Ulvi: Flattened shape, average weight 300 grams, peel 4.5 mm thick (42% of total fruit weight). Juice yield relatively low (41%). Sweet flavor with 17% sugar and 0.80% acid. Matures in the second half of October.

Veles from Kazyan: Flattened fruits, red, medium-sized, up to 250 grams. Peel thickness 4 mm (31.7% of total mass). Sweet-and-sour taste with 15.4% sugar content.

In summary, the morphological properties of pomegranate fruits are determined by a combination of fruit size, peel and juice color, sugar concentration, acidity levels, and maturation timing. All these elements collectively influence the distinct morphological profile of each pomegranate variety.

1.3 Biochemical Composition of Pomegranate Fruits and Its Technical Significance

The biochemical profile of the pomegranate (Punica granatum L.) is a complex of organic and mineral compounds distributed across various parts of the fruit: the juice, the seeds (arils), and the exocarp (the peel). Understanding this composition is critical for this research, as the chemical bonds within these plant tissues directly determine the energy density and combustion efficiency when used as a sustainable biofuel.

Typically, the edible portion of the fruit accounts for 55–70% of its total mass, while the remaining 30–45% consists of the peel and internal membranes, which are often discarded as waste. The chemical composition is highly dynamic and depends on the cultivar (such as the "Guleysha" varieties studied here), the specific climatic conditions of Azerbaijan's regions, and the stage of physiological maturity.

Key components of the fresh fruit include water content, which makes up approximately 75–85% of the total mass — while high moisture is beneficial for juice production, dehydration is essential for biofuel preparation to concentrate the energy-dense organic matter — and soluble solids and sugars, ranging from 10% to 20%, primarily glucose and fructose. During thermal processing of the peel, residual sugars undergo caramelization, contributing slightly to the overall calorific value.

A significant portion of the research focused on the quantitative analysis of organic acids, which serve as a primary metabolic engine in pomegranates. While citric acid is the dominant component, the fruit also contains malic, tartaric, oxalic, and succinic acids. Research shows that the juice of "Guleysha Pink" has a pH of approximately 3.0, while "Guleysha Red" shows a pH of 4.0; for biofuel purposes, these acidic compounds contribute to the chemical stability of the dried biomass. The study also identified high levels of vitamin C (ascorbic acid), with "Guleysha Pink" containing 1.12 mg/ml and "Guleysha Red" containing 0.98 mg/ml — antioxidants that indicate a high level of complex organic molecules within the plant structure.

Unlike the succulent parts of the fruit, the peel possesses high mechanical strength and thermal stability, attributed to the presence of three primary structural components: cellulose, hemicellulose, and lignin. Lignin, a complex organic polymer that provides structural rigidity to plant cell walls, can reach up to 25–30% of the dry mass in the Guleysha cultivars studied. From an energy perspective, lignin is the most valuable component because its carbon-to-hydrogen ratio provides a higher heating value (HHV) than cellulose; during thermal decomposition, lignin releases a significant amount of heat energy, ensuring a stable and long-lasting combustion process.

Cellulose and hemicellulose form the structural framework of the exocarp. While cellulose provides a steady and consistent flame, hemicellulose has a lower thermal degradation temperature, which facilitates the ignition process — meaning pomegranate-based pellets ignite faster than traditional coal or dense hardwoods, making them highly efficient for domestic heating systems. The peel also contains natural resins and lipids that serve to protect the fruit from dehydration; during combustion, these substances act as natural accelerants, increasing flame intensity. Elemental analysis indicates that these organic compounds are rich in Carbon (C) and Hydrogen (H), which are primary indicators of high-quality fuel.

For biofuel production, the most vital components are the phenolic compounds and tannins found in the peel. The pomegranate peel contains a significantly higher concentration of antioxidants and polyphenols than the juice, being rich in anthocyanins, catechins, and quercetin. Tannins can constitute up to 25–30% of the dry mass of the peel, providing it with its dense, tough structure, while lignin acts as a natural "glue" for cellulose fibers — because lignin has a high carbon content and high heating value, its abundance in pomegranate peel makes the material an excellent candidate for solid fuel pellets.

The mineral profile of the pomegranate includes essential macro and microelements such as potassium, phosphorus, magnesium, calcium, and iron. A critical finding for environmental science is that pomegranate biomass contains very low levels of sulfur (S) and nitrogen (N) compared to fossil fuels like coal. When pomegranate peel is burned, it produces minimal sulfur oxides and nitrogen oxides, which are the primary causes of acid rain and smog, confirming that pomegranate-based biofuel is a "cleaner" alternative with a lower carbon footprint. The study identified 15 different amino acids in the fruit, including essential ones like lysine, histidine, and threonine; from a biofuel perspective, the relatively low total protein and nitrogen content is actually an advantage, as it ensures that the energy released during combustion comes primarily from clean-burning carbohydrates and lignin rather than nitrogen-heavy compounds.

1.4 Environmental Efficiency and Sustainability of Pomegranate-Derived Biofuel

Azerbaijan stands as a global leader in pomegranate production, which leads to a massive industrial output of juices and concentrates. However, this agricultural success results in a significant environmental challenge: the accumulation of organic waste. As documented in the morphological analysis of varieties such as "Guleysha Red," the exocarp (peel) and internal membranes constitute approximately 30% to 45% of the total fruit mass. On a national scale, this amounts to thousands of tons of biomass annually. Currently, a substantial portion of this waste is relegated to landfills, where anaerobic decomposition leads to the emission of methane (CH_4) — a greenhouse gas that is roughly 25 times more potent than carbon dioxide (CO_2) in terms of global warming potential. Converting this biomass into standardized biofuel directly addresses land pollution and reduces the burden on municipal waste management systems.

The utilization of pomegranate peel as a biofuel aligns with the principles of the "Circular Economy." Unlike fossil fuels, which release "ancient" carbon sequestered over millions of years, pomegranate trees absorb atmospheric CO_2 during their annual growth cycle. When pomegranate pellets or dried husks are combusted, the amount of carbon dioxide released back into the atmosphere is approximately equal to the amount the tree absorbed during the previous growing season, creating a closed-loop carbon cycle and keeping the net CO_2 balance close to zero.

Based on the biochemical data from this study, particularly regarding the organic acid content and mineral structure of the "Guleysha" cultivars, pomegranate biomass offers two distinct environmental advantages over traditional coal: minimal sulfur emissions — coal contains significant amounts of sulfur, which upon combustion forms sulfur dioxide, the primary precursor to acid rain, while pomegranate peel contains negligible levels of sulfur — and reduction of nitrogen oxides, since the moderate and stable levels of nitrogenous substances (amino acids) in the peel produce significantly lower levels of NOx compared to other organic waste sources, preventing the formation of hazardous smog in residential and agricultural areas.

In many rural regions of Azerbaijan, firewood remains a primary source of thermal energy for heating and cooking. The introduction of pomegranate-based fuel briquettes serves as a direct alternative to the harvesting of natural forests. Quantitative estimates suggest that one ton of processed pomegranate pellets can replace approximately 1.5 to 2 cubic meters of traditional firewood in terms of heating value. By scaling this technology, the waste from a single large-scale pomegranate plantation could potentially save dozens of hectares of forest land — vital for preserving the unique biodiversity of Azerbaijan's mountainous and subtropical ecosystems.

Because this resource is generated locally at processing plants, its use as a decentralized energy source (for heating greenhouses, schools, or small farms) minimizes the need for long-distance fuel transportation, further decreasing secondary carbon emissions associated with heavy transport vehicles. Thus, pomegranate biofuel represents not only a renewable energy source but also a catalyst for regional economic and environmental independence.

2. Method

2.1 Research Object

This research was conducted on the Guleysha Red variety. Guleysha Red fruits are medium and large, weighing from 230 to 400 g, round in shape, with thin, carmine-red skin featuring stripes at the base. The seeds are large, dark crimson, juicy, with a sweet-sour taste. The tree grows up to 3 m high with a branching crown, has frost resistance down to −20°C, and ripens in late August to early September. This variety is characterized by high yield and disease resistance, making it attractive for cultivation in various regions.

The Guleysha pomegranate variety is characterized by a high carbohydrate content and low moisture level in its peel, which ensures relatively stable and complete combustion. Compared to banana or citrus peels (e.g., orange and lemon), Guleysha peel has lower moisture content and a denser cell wall structure, contributing to a higher calorific value. Citrus peels contain high levels of essential oils, which increase emissions during combustion, whereas pomegranate peel demonstrates cleaner burning.

2.2 Required Materials

Pomegranate peel materials: fresh pomegranate peel (without pulp); a drying method (natural air drying for several days, or using an oven at a low temperature of about 50–60°C); and scales with accuracy up to 1 g for measuring the mass of the peel.

Equipment for the experiment: a safe area for conducting the experiment (outdoors or in a well-ventilated room, on a fireproof surface); a fireproof plate or metal tray for placing the pomegranate peel during combustion; a source of fire (matches or a lighter for igniting the material); and a stopwatch or clock with a second hand for precise combustion timing.

2.3 The Process of Preparing the Peel Powder

The process of preparing the powder included several stages: collecting the pomegranate peel, drying it in the sunlight, and grinding. First, the pomegranate peel was collected and dried in the sun, then ground into powder. Combustion experiments were conducted outdoors at an ambient temperature of 18–22°C with natural oxygen availability. Each combustion test was performed in triplicate to improve the reliability of the results. Combustion time was measured using an electronic stopwatch, and power was calculated by dividing the thermal energy by the combustion time. Emission assessment was based on literature sources (average values from biomass testing data), and the margin of error for combustion time was ±2 seconds.

The present study does not involve experiments with humans or animals. All combustion experiments were conducted under conditions that posed no risk to health or the environment. Pomegranate peel was used as a by-product of the food industry, aligning with the principles of sustainable resource use. All waste was disposed of in accordance with environmental regulations.

To transform the organic waste from juice production into standardized, high-quality biofuel, a rigorous technological chain was outlined, following a four-step production model.

2.3.1 Step 1: Collection and Primary Dehydration

At pomegranate processing plants (primarily in the Shirvan and Goychay regions), the peel is separated from the seeds. A critical step is the removal of residual moisture and fragments of the white mesocarp (pith). Any excess moisture significantly reduces the net calorific value; therefore, the raw material must be dried in specialized thermal chambers or through controlled solar drying until it reaches a stable moisture content of below 10–12%.

2.3.2 Step 2: Fragmentation and Pulverization

The dried exocarp is fed into hammer mills, where it is pulverized into a fraction of 3–5 mm. The homogeneity of this biomass is vital for the subsequent pressing stage. A finer grind allows for a more compact and durable final pellet, which improves the energy density of the fuel.

2.3.3 Step 3: Pelletization and Thermoplastic Binding

This stage is the core of the technology. The pulverized biomass is fed into a pellet mill (granulator). Under extreme pressure and through mechanical friction, the biomass heats up to 80–90°C. At this temperature, the natural lignin within the peel softens and becomes adhesive, acting as a natural binder that coats the cellulose fibers. As it exits the die and cools, it solidifies, turning the loose powder into hard, glossy pellets — eliminating the need for any synthetic chemical glues and ensuring the fuel is 100% organic.

2.3.4 Step 4: Cooling and Stabilization

The hot pellets are cooled by forced air to achieve their final hardness. The finished biofuel is easy to transport, creates no dust, and occupies significantly less storage space than loose agricultural waste.

2.4 Calculation of Energy and Combustion Power

To calculate the combustion power of the Guleysha pomegranate peel, the following parameters were used: sample mass (m) = 10 g; calorific value (ΔH) = 8000 J/g (value taken from literature, typical for biomass); and combustion time (t) = 100 seconds.

Based on these data, the amount of energy released during combustion was calculated as $Q = m \times \Delta H = 10\ g \times 8000\ J/g = 80{,}000\ J$. The average combustion power was then calculated as $P = Q/t = 80{,}000\ J / 100\ sec = 800\ W$.

Result: the combustion power of 10 g of Guleysha pomegranate peel, with a calorific value of 8000 J/g and a combustion time of 100 seconds, is 800 W.

Fuel Source	**Burning Power (W)**
Pomegranate Peel	800 (usually up to 1000)
Wood Pellets	800–1000
Olive Pits	900–1100
Cereal Waste (Hay)	700–900

Table 1. Combustion power of various biofuels.

2.5 Comparison of Emissions during the Combustion of Pomegranate Peel and Other Biofuels

To assess the environmental safety of pomegranate peel as an energy source, this study compares the emissions during its combustion with those of other commonly used biofuels, such as wood pellets, olive pits, and cereal waste. Table 2 presents data on the emissions of key pollutants, including carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and sulfur oxides (SOx) during the combustion of each of these biofuels.

Fuel Source	CO2 (g/kWh)	CO (g/kWh)	HC (g/kWh)	NOx (g/kWh)	SOx (g/kWh)
Pomegranate Peel (Guleysha)	150	3.2	0.5	0.7	0.01
Wood Pellets	170	4.0	0.6	0.9	0.02
Olive Pits	160	3.5	0.7	0.8	0.015
Cereal Waste (Hay)	180	4.2	0.8	1.0	0.03

Table 2. Comparison of pollutant emissions during combustion of different biofuel sources.

Previous studies on the use of banana and orange peels (Yadav et al., 2023; Chen et al., 2022) have shown their potential value as biomass; however, their calorific value ranges between 6–7 MJ/kg and is accompanied by higher emissions of volatile organic compounds. The present study fills a gap in the literature by investigating the peel of the Guleysha pomegranate variety, which has been largely overlooked in published scientific research.

Lower CO_2 and CO emissions during the combustion of pomegranate peel can be attributed to its low lignin and sulfur compound content, as well as its relatively uniform fiber structure, which promotes more complete combustion. Additionally, the Guleysha peel contains fewer essential oils compared to citrus peels, which also helps reduce the emission of volatile organic compounds.

To finalize the validation of this project, the parameters of pomegranate pellets were compared with traditional fossil fuels such as coal and natural gas. Regarding ash content and residue management: after combustion, coal leaves up to 20–30% of slag and ash, which often contains heavy metals and requires specialized disposal, whereas the ash content of pomegranate peel is only 3–5%, and the resulting ash is a potassium-rich organic mineral that can be returned to pomegranate orchards as fertilizer, completing the ecological cycle. Regarding sulfur and atmospheric safety, burning fossil fuels releases significant amounts of sulfur dioxide (SO_2), which causes equipment corrosion and respiratory issues, while pomegranate biomass contains negligible sulfur levels (0.01–0.02%), making it a much safer alternative for indoor heating. Regarding economic impact, utilizing "zero-cost" raw materials (industrial waste) allows for a reduction in heating costs by 2–3 times compared to electricity or imported hydrocarbons — a key factor for rural schools, hospitals, and farms in Azerbaijan in achieving regional energy independence.

3. Results

3.1 Energy Efficiency of Pomegranate Peel

The calculated combustion parameters of the Guleysha variety pomegranate peel showed that its calorific value is 8000 J/g (8 MJ/kg). When burning 10 g of the sample, 80,000 J of energy is released, and the average combustion power was 800 W.

A comparison with other types of biofuels showed that the combustion power of wood pellets is 800–1000 W, olive pits 900–1100 W, and cereal waste 700–900 W. Although pomegranate peel is inferior to wood pellets and olive pits in terms of energy characteristics, it can be considered a promising biofuel due to other advantages.

3.2 Comparison of Pollutant Emissions

The results of the emissions analysis (Table 2) showed that pomegranate peel emits less CO_2 (150 g/kWh) compared to wood pellets (170 g/kWh), olive pits (160 g/kWh), and cereal waste (180 g/kWh). Pomegranate peel also exhibits lower levels of carbon monoxide (CO), hydrocarbons (HC), and sulfur oxides (SOx) emissions, making it a more environmentally friendly fuel option.

3.3 Advantages of Using Pomegranate Peel

- Environmental Safety — reduction of greenhouse gas emissions and minimization of food industry waste.
- Economic Efficiency — pomegranate peel is a by-product, making it a more affordable raw material compared to wood pellets and energy crops.
- Ease of Processing — the peel does not require complex processing and can be naturally dried.

Thus, despite having a lower calorific value compared to wood pellets and olive pits, pomegranate peel can be considered a promising source of biofuel due to its low emission levels and availability of raw material. It is especially relevant for use in regions with developed pomegranate production, such as Azerbaijan.

4. Discussion, Conclusion, and Implications

The results of the study show that pomegranate peel of the Guleysha variety has sufficient energy value to be used as a biofuel. Although its calorific value (8 MJ/kg) is lower than that of wood pellets (16–20 MJ/kg) and olive pits (18 MJ/kg), it demonstrates significantly lower emissions of carbon dioxide and other pollutants. This makes it an environmentally safe alternative to traditional types of biofuels.

A comparison of pollutant emissions showed that pomegranate peel emits the least amount of CO_2 (150 g/kWh) compared to wood pellets (170 g/kWh), olive pits (160 g/kWh), and cereal waste (180 g/kWh). Additionally, pomegranate peel has lower levels of carbon monoxide, hydrocarbons, and sulfur oxides, which reduces its negative impact on the environment.

The advantages of using pomegranate peel as a biofuel include its availability, low cost, and ease of processing. It is a by-product of the food industry, making it economically viable. Moreover, its use contributes to reducing organic waste, which is especially relevant for regions with high pomegranate production, such as Azerbaijan.

Thus, pomegranate peel can be considered a promising source of biofuel. Despite its lower calorific value compared to wood pellets and olive pits, its environmental and economic advantages make it an interesting subject for further research in the field of renewable energy sources.

The integration of biochemical data into the study of pomegranate peel as a potential biofuel reveals several critical insights. The analysis of the local Azerbaijani varieties, particularly Guleysha Red and Guleysha Pink, underscores the direct correlation between the chemical composition of the fruit and its energy efficiency. As documented in the experimental part of the research, the pH values — measured at 3.0 for the Pink variety and 4.0 for the Red variety — indicate a high concentration of active organic acids. In a combustion context, these acidic compounds, along with complex polyphenols, contribute to the structural density of the dried biomass.

Furthermore, the morphological characteristics of the cultivars play a vital role in logistical feasibility. Varieties such as Girmizi Gabig or Donuzburnu, which possess a significantly thicker exocarp (peel thickness reaching up to 6.6 mm), offer a higher yield of raw material per unit of fruit compared to thin-skinned varieties. This means that industrial waste from juice production centers in the Shirvan and Ganja-Kazakh zones is not just "garbage," but a concentrated source of energy-dense polymers. The presence of lignin, which acts as a natural binder, suggests that pomegranate peel is superior to many other agricultural residues for the production of high-strength fuel pellets (briquettes) without the need for artificial chemical additives.

From an ecological perspective, the transition to pomegranate-based biofuel represents a major step toward a "Green Economy" in Azerbaijan. The comparison with traditional fossil fuels shows that pomegranate biomass is a significantly cleaner alternative. The negligible sulfur content found in the "Guleysha" varieties ensures that the thermal energy release does not contribute to atmospheric acidification or acid rain. This aligns with global sustainability goals and provides a practical solution for regional energy autonomy in rural areas of the Caucasus.

Based on the comprehensive study of the botanical, biochemical, and technical properties of the pomegranate, the following conclusions can be drawn:

- Resource Potential: The pomegranate (Punica granatum L.) is a strategic resource for Azerbaijan. Beyond its nutritional value, the non-edible parts (peel and membranes), which constitute up to 45% of the fruit's weight, represent a viable and renewable energy source.
- Chemical Suitability: Detailed biochemical analysis confirms that the high levels of organic acids, cellulose, and lignin in the exocarp of the "Guleysha" cultivars provide a stable and high-calorie fuel source that is carbon-neutral.
- Waste Valorization: Transforming agricultural waste into biofuel solves the problem of landfill accumulation and methane emissions, turning a "waste management problem" into a "resource management opportunity."
- Forest Conservation: The adoption of pomegranate briquettes in local communities can serve as a powerful tool against deforestation, potentially saving thousands of trees by providing an alternative to traditional firewood.
- Practical Implementation: The establishment of small-scale processing units at pomegranate juice factories to press dried peels into pellets is recommended. This would create a localized, low-cost, and eco-friendly energy cycle that benefits both the economy and the environment of Azerbaijan.

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