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Some physical, chemical, and germination properties of *Peganum harmala* L. seeds

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Abstract

In this study, the aim was to determine some physical and chemical properties of the seeds of *Peganum harmala*, known as rue or harmel, and to determine the effects of some implementations to break the seed dormancy. The mean length, width, thickness, and surface area values for the *P. harmala* seeds were 4.78 mm, 1.81 mm, 1.53 mm, and 14.14 mm^2, respectively. Linked to the dimensions, the arithmetic mean diameter, geometric mean diameter, and sphericity values were calculated as 2.71 mm, 2.34 mm, and 0.50. The bulk density and true density values were measured as 0.5379 and 1.015 g cm^{-3}, respectively, and the porosity value calculated linked to these values was 46.98%. The static friction angles on two different surfaces of galvanized metal and polyvinyl chloride (PVC) were measured as 15.67° and 17.67°, and the static friction coefficient values linked to these angles were 0.28 for galvanized metal and 0.32 for PVC. Terminal velocity experiments determined the velocity for *P. harmala* seeds was 5.03 ms^{-1}. According to analysis results for the chemical structure of *P. harmala*, dry matter ratio was 89.7%, crude ash ratio was 11.0%, crude protein was 10.3%, crude fiber was 42.0%, and crude oil ratio was 10.8%. In seed dormancy studies, the effects of sulfuric acid, precooling, soaking in water, and mechanical scarification (sanding) applications were determined. Accordingly, the most effective method for germination of *P. harmala* seeds was sanding with 84.0% germination rate. This was followed by soaking in water (78.0%) and 5 min H_2SO_4 (75.0%) applications.

Practical Applications

Turkey is a country with a current account deficit in the seed import–export balance. Therefore, the efficient use of seeds in each step of farming and postharvest operations is essential to reduce the seed waste. Determining the engineering properties of seeds will help to provide more efficient systems. The physical properties of seeds are important to design, develop, and adjustment of planters, storage structures, transporting systems, and postharvest systems. Chemical properties are essential to determine the optimum storage conditions and postharvest chemical processes for optimum utilization of seeds as foods or as raw materials for medicinal and industrial purposes. Seed dormancy-breaking features will be useful to determine optimum presowing conditions and breeding conditions of the seeds.

1 | INTRODUCTION

Peganum harmala L. in the Zygophyllaceae family is a hairless perennial herbaceous plant growing from 30 to 70 cm height in semiarid regions (Passos & Mironidou-Tzouveleki, 2016). The plant is commonly observed in the Mediterranean and southwest Asia but is distributed in many places around the world (Moshiri, Etemad, Javidi, & Alizadeh, 2013). It is found in empty fields and barren pastures in Turkey (Kırıcı, Kayıran, & Tokuz, 2018). *P. harmala* is not grazed by animals. However, grazing of the plant in some situations where there is no green grass is reported to have toxic effects on animals, with serious effects reported in young animals in the dry season especially (Mahmoudian, Jalilpour, & Salehian, 2002; Moshiri et al., 2013). The seeds and roots have a broad range of use in medicine, led by production of alkaloids with cardiovascular effects (Wang et al., 2018), while it is used for herbicide production in the struggle against weeds in agriculture (Sodaeizadeh, Rafieiolhossaini, & Van Damme, 2010), for industrial paint production, and for practices related to traditional beliefs (Moloudizargari, Mikaili, Aghajanshakeri, Asghari, & Shayegh, 2013).

In addition to the security of production supply in sustainable agriculture, it is important to be able to obtain adequate production quality (Evcim, Değirmencioğlu, Özgünaltay Ertuğrul, & Aygün, 2012). With multiple uses, in order to be able to determine the appropriate quality level for use of *P. harmala* seeds and possible potential in industry, medicine, and food production, it is important to know the physical and chemical features of seeds in relation to activities like sowing, germination, storage, long-term storage, transport, and processing and to design and develop equipment suitable for these activities (Besharati, Navid, Karimi, Behfar, & Eskandari, 2019; Copeland & McDonald, 1999; Ertuğrul, 2010; Lei et al., 2021; Önal & Ertuğrul, 2011a; Özdemir & Değirmencioglu, 2020). In one of the most critical stages in plant production of seeding, distribution of seeds regularly and equally within the space is important in order to provide suitable development conditions for sowing and to obtain best yield values linked to this. In order to provide suitable living space with machine sowing, success is linked to the regularity of seed flow and the regularity of seed distribution in the row. Studies to determine and increase the performance of seeding machines revealed models showing that the physical characteristics of seeds affect the seed flow regularity and the regularity of seed distribution in the row (Ertuğrul, 2010; Lei et al., 2021; Önal & Ertuğrul, 2011a; Önal & Ertuğrul, 2011b). In order to create the most appropriate conditions for storage and transport of seeds, knowing the physical properties along with the chemical structures is beneficial. The most appropriate germination environment will ensure a successful sowing process; additionally, knowing the dormancy features of seeds will be effective in determining practices to develop germination performance (León-Lobos et al., 2020).

Studies were performed related to the physical features of a variety of seeds including cumin (Singh & Goswami, 1996), sunflower (Gupta & Das, 1997), quinoa (Vilche, Gely, & Santalla, 2003), amaranth (Abalone, Cassinera, Gaston, & Lara, 2004), sesame (Tunde-Akintunde & Akintunde, 2004), safflower (Baümler, Cuniberti, Nolasco, & Riccobene, 2006), flax (Coşkuner & Karababa, 2007), and chia (Ixtaina, Nolasco, & Tomas, 2008). Additionally, there are fewer examples of studies combining comprehensive physical analyses with chemical analyses and seed dormancy studies (Karaj & Müller, 2010; Kwiatkowski, Krzyżaniak, Załuski, Stolarski, & Tworkowski, 2020). The chemical composition, pharmacological significance, and toxicity of rue seeds have been extensively studied (Apostolico et al., 2016; Asgarpanah & Ramezanloo, 2012; Mahmoudian et al., 2002), whereas little is known about their physical parameters and effective methods of preparing rue seeds for sowing. There is also one research that reports some physical properties of *P. harmala* seeds at four different moisture levels (Taheria, Mirzabea, Bavanib, & Kianmehra, 2017). In the study, length, width, and thickness measurements are made by image processing, and geometric mean diameter, arithmetic mean diameter, and equivalent diameter are calculated accordingly. Although the angle of repose criteria is ignored, static friction angles are determined on various surfaces, galvanized, iron, rubber, and plywood. Bulk density, true density, and porosity values are defined. It is possible to come across plants with different characteristics, as there may be different derivatives of the same plant in different regions and under different conditions. Therefore, in this study, the aim was to determine a wider range of physical properties and chemical properties including practices to break dormancy of the seeds of the *P. harmala* plant that are naturally grown in Turkey.

2 | MATERIAL AND METHOD

The *P. harmala* L. seeds used in the study were collected from the Aksaray region located in the Central Anatolia region of Turkey. Before analyses, foreign objects and broken seeds were removed and seeds were cleaned (Figure 1). In order to determine the moisture content of the seeds, samples were kept in a dry oven at 105 ± 1°C for 24 hr with three replications. The relative moisture content of the seeds is calculated as 5.14% (d.b) according to scaling before and after drying (Altuntaş, Gül, & Gök, 2020; Jahanbakhshi, 2018; Jahanbakhshi et al., 2019).

2.1 | Physical properties

Just as seed dimensions can be measured manually or with a digital micrometer (Gupta & Das, 1997; Ixtaina et al., 2008; Tunde-Akintunde & Akintunde, 2004; Vilche et al., 2003), they may be determined with image processing methods (Abalone et al., 2004; Fisklements & Barrett, 2014). To determine the sizes of the seeds of the rue plant, 100 seeds were chosen at random and each seed was photographed in three different positions. The length (*l*), width (*w*), and thickness (*t*) were determined with the web-based SketchAndCalc application (Dobbs, 2011). In order to perform the image processing well, before the measurement procedure calibration was performed with the metric measuring device included in the photograph

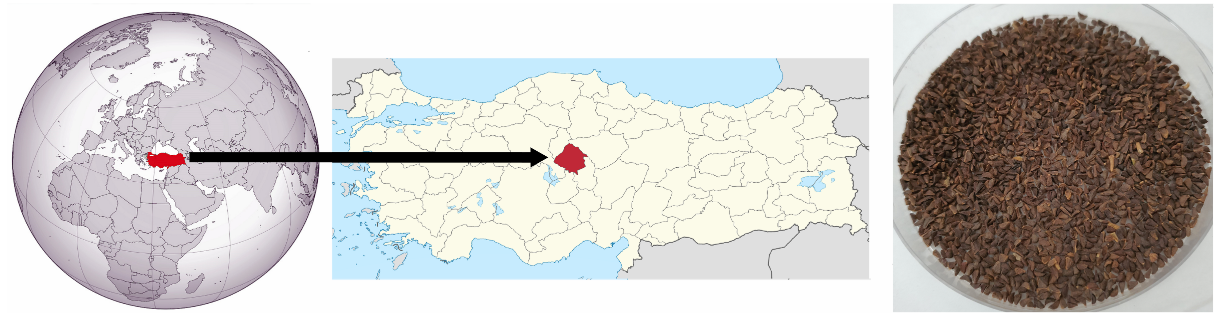

FIGURE 1 The geographical area where *Peganum harmala* L. was collected and image of the seeds

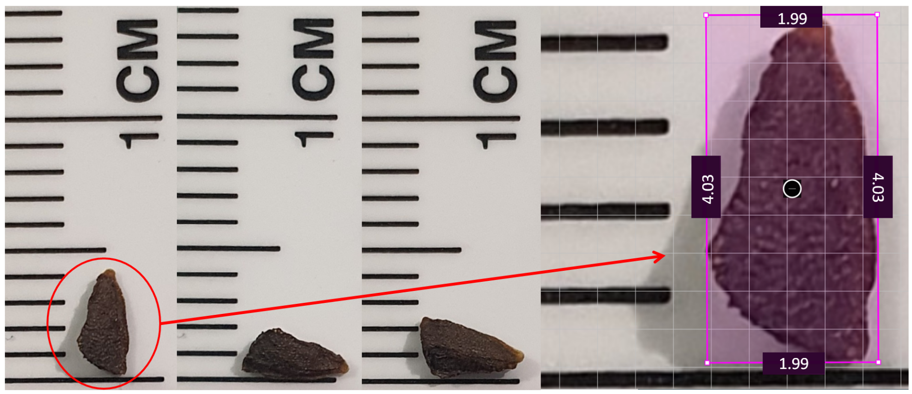

FIGURE 2 Determination of length–width–height values with image analysis of rue seeds using SketchAndCalc area calculator software

(Figure 2). To ensure the perpendicular angle of photographs, a vertical desktop camera, which is also called digital microscope, is used with a stabilizer camera stand. The photos taken are directly recorded to the computer by USB connection. The length, width, and thickness measurements of 20 seeds are validated with digital micrometer to confirm the accuracy of the image software. Using the length, width, and thickness measurements, the sphericity value (ϕ), arithmetic mean diameter (D_a), and geometric mean diameter (D_g) were calculated according to Equations (1), (2), and (3), respectively (Singh & Meghwal, 2020; Jahanbakhshi, Abbaspour-Gilandeh, & Gundoshmian, 2018; Jahanbakhshi et al., 2019; Karaj & Müller, 2010; Mohsenin, 1986).

$$\phi = \frac{\sqrt[3]{l \cdot w \cdot t}}{l}, \tag{1}$$

$$D_a = \frac{l + w + t}{3}, \tag{2}$$

$$D_g = \sqrt[3]{l \cdot w \cdot t}. \tag{3}$$

Surface areas (*S*) of seeds are also calculated by Equation (4) that depends on the spherical assumption used by literature (Jahanbakhshi et al., 2018; Jahanbakhshi et al., 2019; Tunde-Akintunde & Akintunde, 2004).

$$S_t = \pi \cdot {D_g}^2. \tag{4}$$

Seeds were placed in subgroups with each group containing 100 seeds, and 1,000 seed mass (W_{1000}) measurements were made with an OHAUS PA214C weighing scale, production of the OHAUS company with 0.0001 g sensitivity (Ixtaina et al., 2008; Tunde-Akintunde & Akintunde, 2004; Vilche et al., 2003). With the same weighing device, after measuring the weight of rue seeds required to fully fill a container with known volume and tare, the ratio of the mass of the rue seeds against the container volume was used to complete bulk density (ρ_b) calculations (Karaj & Müller, 2010; Razavi, Yeganehzad, & Sadeghi, 2009; Yilar & Altuntas, 2017). The fluid exchange method was used to determine true density (ρ_t) values; toluene was used since it is not absorbed by the seeds as much as water. The volume of toluene displaced observed in three replications on the graduated scale on the cylindrical container was equal to volume of seed sample (Ahangarnezhad, Najafi, & Jahanbakhshi, 2019; Altuntas & Demirtola, 2007; Mohsenin, 1986). Since the toluene bulk mass is 0.867 g cm^{-3} at room temperature (around 20°C), volume of seed sample and true density are calculated accordingly (Ahangarnezhad et al., 2019). Using the true density and bulk density values, the porosity values were calculated with the aid of Equation (5) (Ixtaina et al., 2008).

$$\varepsilon = \frac{\rho_t - \rho_b}{\rho_t}. \tag{5}$$

To determine the static friction angles for rue seeds on galvanized and polyvinyl chloride (PVC) surfaces, the static friction angle setup

FIGURE 3 Determination of static friction angle with galvanized and PVC surfaces

FIGURE 4 Setup to determine angle of repose

shown in Figure 3 was used. On the galvanized and PVC surfaces, a metallic cylindrical container with a diameter of 50 mm, height of 50 mm, and thickness of 5 mm was filled with rue seeds. The angles of slopes of both surfaces (Θ_g for galvanized surface and Θ_p for PVC surface) were measured when the container began to slide. The friction coefficients (μ_g for galvanized surface and μ_p for PVC surface) were calculated using Equation (6) (Aviara, Gwandzang, & Haque, 1999; Ixtaina et al., 2008; Razavi et al., 2009; Singh & Goswami, 1996).

$$\mu = \tan \Theta. \tag{6}$$

To determine the angle of repose, the setup shown in Figure 4 was used. Rue seeds were filled into a funnel with discharge point closed set at a height of 12.5 cm above the table level. The lid was opened and the flowing seeds formed a pile on the table and the angle of repose was determined by proportioning the diameter of the base of the pile to the length of the pile edge (Alayunt, 2000; Frączek, Złobecki, & Zemanek, 2007).

When the force of gravity affecting a seed is equal to the upward force of the air, the velocity of the seed in air is defined as the terminal velocity (Karaj & Müller, 2010; Singh & Goswami, 1996). The terminal velocity values for *P. harmala* seeds were measured with a pneumatic conveyor and anemometer (Figure 5). Experiments were replicated five times, and a small sample of seeds was released into the air stream for each experiment. The samples were placed into the sample intake while the airflow was increased gradually until the particles were suspended in the transparent observation tube. The measuring systems for static frictions, angle of repose, and terminal velocity belong to laboratories of Department of Agricultural Engineering and Technologies at Ege University and previously manufactured.

2.2 | Some chemical features of seeds and implementations to break dormancy

2.2.1 | Chemical features

The *P. harmala* seeds were ground in a mill, passed through a sieve with 1-mm pores, and prepared for analysis. Then, the following contents were determined:

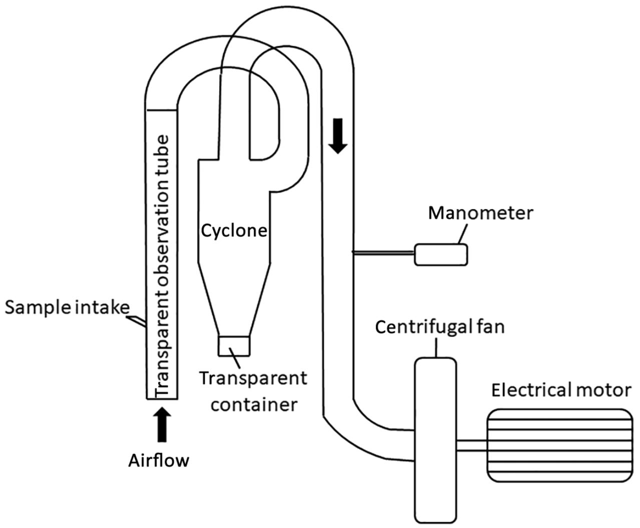

FIGURE 5 Terminal velocity measurement setup

- Dry matter ratio (DMR): After drying in an oven (Thermomac model VO) set to 105°C for 24 hr until fixed weight, seeds were cooled in a desiccator, weighed on a precision scale, and then dry matter content was determined (AOAC, 2005).
- Crude ash (CA) content was determined by burning in an ash oven (Thermomac model CMF) at 550°C for 4 hr (AOAC, 2005).
- Crude fiber content was determined using ANKOM 200 fiber analyzer manufactured by ANKOM Technology, Macedon, New York, according to the Ankom crude fiber method (Anonymous, 2021).
- Nitrogen content was determined using Gerhardt VAP50 Nitrogen-Protein analyzer manufactured by "C. Gerhardt GmbH & Co. KG" according to the Kjeldahl method and these values were multiplied by the coefficient 6.25 to obtain crude protein (CP) rates (AOAC, 2005).
- Crude oil (CO) analysis was performed with a Gerhardt SOX-414 automatic oil measuring device manufactured by "C. Gerhardt GmbH & Co. KG" according to the method stated in AOAC (2005).

2.2.2 | Seed dormancy

In the study performed with the aim of encouraging germination by abrading the shells of the *P. harmala* seeds, following procedures are conducted, when the radicle length reached 2 mm, it was considered as germinated (Demir, Özden, Gökdaş, Njie, & Aydın, 2020; Nedjimi, 2020);

- *Sulfuric acid implementation*: Plant seeds were treated with 99% concentrated sulfuric acid for 0, 1, 5, and 15 min and then washed well with flowing water. Later seeds were left for germination on petri dishes (25 seeds). Germination was monitored daily. The humidity in the petri dishes was checked.
- *Precooling studies*: Before placing the *P. harmala* seeds in the germination cabinet that belongs to laboratories of Department of Plant Protection at Kırşehir Ahi Evran University, they were left in a refrigerator (4°C) for 1 week and then left in petri dishes for germination.
- *Soaking in water*: Seeds were firstly left in sterile distilled water for 72 hr, and at the end of the duration, they were placed in petri dishes in the germination cabinet.
- *Mechanical scarification* (*sanding*): The shells of the plant seeds were abraded between two sheets of P150 sandpaper, taking care not to harm the seed embryo. Later, seeds were placed in petri dishes and placed in the germination cabinet.

After applying treatments to break the dormancy of *P. harmala* seeds and encourage germination, the seeds were spread homogeneously with 25 in each petri dish containing two layers of blotting paper and humidified (6 ml distilled water). Petri dishes were left for germination at 25°C with 12-hr darkness and 12-hr light conditions. Petri dishes were checked every day, and the number of germinating seeds was noted. The percentage of germination rates of the seeds were calculated according to Equation (7), where GS is the number of germinating seeds and TS is the total number of seeds (Bozdoğan et al., 2019; Özkurt, 2008).

$$FG = \frac{GS}{TS} \times 100. \quad (7)$$

3 | RESULTS AND DISCUSSION

3.1 | Physical properties

The physical properties of rue seeds reported in this study are essential to develop and adjust sowers, improve storage structures and transporting systems, and provide a date to design proper postharvest systems.

Research findings of physical features of seeds with moisture content of 5.14% (d.b.) are given in Table 1.

Mean length, width, and thickness values for the dimensions of *P. harmala* seeds were determined as 4.78, 1.81, and 1.53 mm, respectively. Taheria et al. (2017) investigated some physical properties of *P. harmala* seeds and reported relatively lower sizes 0.712 mm length, 0.475 mm width, and 0.442 mm thickness. Soliman, El-Tarras, and El-Awady (2010) measured 2.622 mm length and 1.786 mm width for *P. harmala* collected from Taif province, Saudi Arabia. Different seed sizes can be observed in different varieties, with different maturation levels and/or under different growing conditions of the plants (Araujo et al., 2018; Kaliniewicz, Anders, Markowski, Tylek, & Owoc, 2021). The length, width, and thickness values have been reported for relatively smaller seeds as 2.88, 1.64, and 1.24 mm for sage (Yilar & Altuntas, 2017); 2.80, 1.69, and 0.82 mm for sesame (Tunde-Akintunde & Akintunde, 2004); 2.045, 2.015, and 0.930 mm for quinoa (Vilche et al., 2003); for bigger seeds as 9.52, 5.12, and 3.27 mm for sunflower (Gupta & Das, 1997); and 5.39, 4.5, and 3.29 mm for terebinth (Altuntaş et al., 2020). When the dimensional frequency

TABLE 1 Physical properties of *Peganum harmala* L.

Physical properties	x	SD	CV (%)
Length (mm)	4.76	0.316	6.6
Width (mm)	1.81	0.109	6.0
Thickness (mm)	1.54	0.083	5.4
Sphericity	0.50	0.004	0.9
Arithmetic mean diameter (mm)	2.70	0.066	2.5
Geometric mean diameter (mm)	2.34	0.067	2.9
Surface area (mm^2)	17.30	9.926	57.4
One thousand seed mass (g)	2.46	0.165	6.7
Bulk density ($g\ cm^{-3}$)	0.54	0.003	0.5
True density ($g\ cm^{-3}$)	1.02	0.038	3.3
Porosity (%)	46.98	2.004	4.3
Angle of static friction on galvanized surface (°)	15.67	0.577	3.7
Coefficient of static friction on galvanized surface	0.28	0.011	3.9
Angle of static friction on PVC surface (°)	17.67	0.577	3.3
Coefficient of static friction on PVC surface	0.32	0.011	3.5
Angle of repose (°)	27.37	1.197	4.4
Terminal velocity ($m\ s^{-1}$)	5.03	0.030	0.6

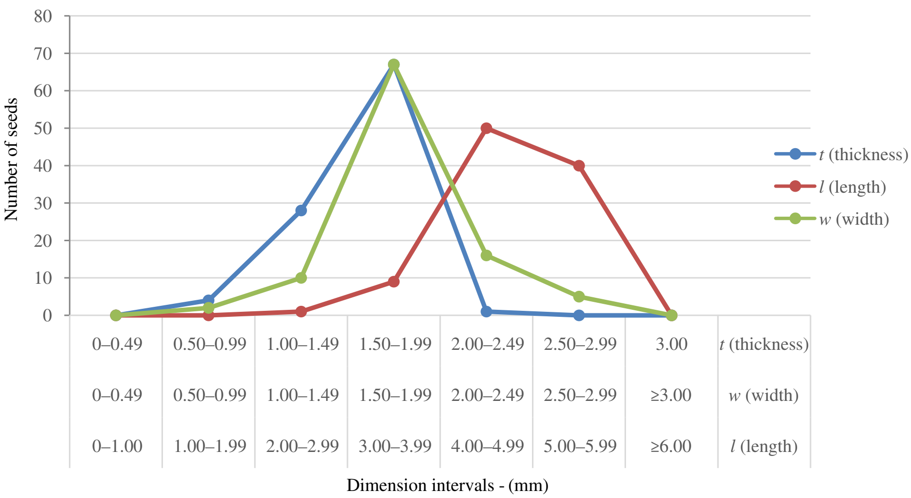

FIGURE 6 Dimensional frequency distribution of length (*l*), width (*w*), and thickness (*t*) values (mm) for *Peganum harmala* seeds

distribution of *P. harmala* L. seeds is investigated, length values for 50% of the sample were from 4.00 to 4.99 mm, 67% had width values from 1.50 to 1.99 mm, and 67% had thickness values of 1.50–1.99 mm (Figure 6).

The *P. harmala* seeds had an arithmetic mean diameter of 2.71 mm and a geometric mean diameter of 2.34 mm. The sphericity, surface area, and theoretical surface area values were 50%, 14.14 mm^2, and 17.34 mm^2, respectively. It is possible that the surface area and theoretical surface area differences are due to the low sphericity of the seeds since the theoretical surface area is traditionally calculated considering that seeds are completely spherical (Tunde-Akintunde & Akintunde, 2004). The sphericity values for *P. harmala* were lower compared to values previously reported for coated and uncoated canola (Ertuğrul, 2010), quinoa (Vilche et al., 2003), amaranth (Abalone et al., 2004), and chia (Ixtaina et al., 2008). Values were similar to those obtained for sesame (Tunde-Akintunde & Akintunde, 2004), carrot (Önal & Ertuğrul, 2011a), and sunflower seeds (Gupta & Das, 1997). In terms of surface area, though *P. harmala* seeds were larger compared to small seeds like sesame (Tunde-Akintunde & Akintunde, 2004), chia (Ixtaina et al., 2008), and amaranth (Abalone et al., 2004), the seeds had similar 1,000 seed mass compared to these seeds. One thousand seed mass, bulk density, true density, and porosity mean values were determined as 2.46 g, 0.54 $g\ cm^{-3}$, 1.02 $g\ cm^{-3}$, and 46.98%, respectively (Table 1).

The angle of repose and static friction coefficient value for *P. harmala* seeds are given in Table 1. The angle of repose was 27.37°, and the static friction coefficients and angle values were 0.32–17.67° for the PVC surface and 0.28–15.67° for the galvanized metal surface. Accordingly, the *P. harmala* seeds adhered to the PVC surface at higher rates compared to the galvanized metal surface which could be attributed to either a higher porosity feature of the PVC surface relative to the galvanized metal surface (Kaliniewicz, Markowski, Anders, & Jadwisieńczak, 2015) or the electrostatic charges on the friction plates were not neutralized. However, porosity features of the surfaces were not analyzed due to lack of adequate equipment. The friction parameters for the *P. harmala* seeds were similar to onion seeds, lower than carrot seeds, and higher than the coated and uncoated forms of canola seeds (Ertuğrul, 2010; Önal & Ertuğrul, 2011a). The friction values were lower compared to the pumpkin seeds (Joshi, Das, & Mukherjee, 1993) and sunflower seeds (Gupta & Das, 1997) which are relatively larger.

Terminal velocity was measured as 5.03 m s^{-1}, which was higher than the values determined for pumpkin (Joshi et al., 1993), quinoa (Vilche et al., 2003), and cumin (Singh & Goswami, 1996) and lower than the values determined for sunflower (Gupta & Das, 1997).

3.2 | Some chemical properties of *P. harmala* seeds and germination tests

3.2.1 | Chemical features

Chemical properties are important to assess the optimum storage conditions and assist decisions in developing postharvest chemical processes.

P. harmala L. from the Zygophyllaceae family is an invasive species found in grasslands in Turkey and Mediterranean countries like Turkey, Greece, Italy, Israel, Algeria, and Tunisia (Kırıcı et al., 2018). *P. harmala* seeds collected from grasslands in Aksaray in the Central Anatolia region had a DMR of 89.69%, CA ratio of 11.0%, CP ratio of 10.3%, crude fiber ratio of 42.0%, and CO ratio of 10.8% (Table 2).

TABLE 2 Determination of some chemical contents of *Peganum harmala* seeds

Chemical analysis	Proportion %
Dry matter ratio	89.7
Crude ash	11.0
Crude protein ratio	10.3
Crude fiber	42.0
Crude oil	10.8

3.2.2 | Seed dormancy

Dormancy-breaking applications will be useful to determine optimum sowing preparation and breeding conditions of the seeds.

As a result of dormancy breakage studies, it was determined that the most effective method for germination of *P. harmala* seeds was sanding with 84.0% germination rate. This was followed by soaking in water (78.0%) and 5 min H_2SO_4 (75.0%) (Table 3).

Additionally, cooling at 4°C, the 1 min H_2SO_4 and the control group were identified to have the same germination rate (64%). Treatment with H_2SO_4 for 15 min caused a reduction in germination of seeds compared to treatment for 1 and 5 min durations (Table 3 and Figure 7).

Sanding provided the highest average germination amounts in the earlier period compared to all other methods including the control

TABLE 3 Effect of implementations on *Peganum harmala* seed germination

Implementations	Germination %
Control	$64.0^{d} \pm 0.81$
1-min H_2SO_4	$64.0^{d} \pm 0.81$
5-min H_2SO_4	$75.0^{c} \pm 1.08$
15-min H_2SO_4	$52.0^{e} \pm 0.81$
+4°C	$64.0^{d} \pm 0.80$
Soaking in water (72 hr)	$78.0^{b} \pm 1.41$
Sanding	$84.0^{a} \pm 0.81$

Note: Means in the same letters were not significantly different as indicated by analysis of variance ($\alpha = .05$).

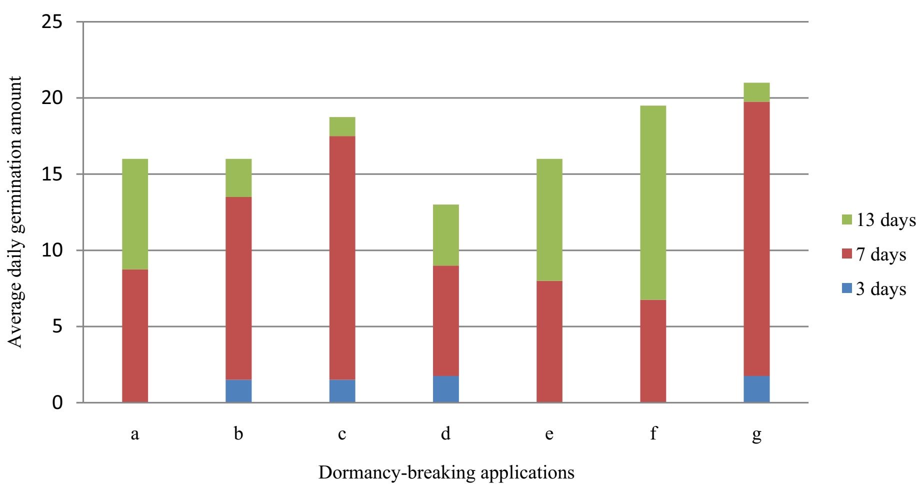

FIGURE 7 Daily variation in seed germination, where (a) Control, (b) 1 min H_2SO_4, (c) 5 min H_2SO_4, (d) 15 min H_2SO_4, (e) 4°C, (f) soaking in water, and (g) sanding

group. Most of the seeds were germinated in 7 days, and the highest germination rate is observed in 13 days; 5-min H_2SO_4 had also similar effect in 7 days, but lower germination was observed than soaking in water in 13 days (Figure 7). Therefore, it can be stated that sanding is preferable in seed germination of *P. harmala* in terms of earlier germination and germination rate.

In a study, the *P. harmala* seeds left for 1 week at 4°C had 82% germination, while the control group had 77.3% germination. Bozoğlu (1999) reported that leaving *P. harmala* seeds for 10 days at −10°C was effective on germination speed rather than germination rate. A study determining the effect of soaking in water on rue seeds reported that the germination rate for controls was 77.3%, while there was 86.7% germination rate for soaking for 24 hr, 95.3% germination rate for soaking for 48 hr, and 96.66% germination rate for soaking for 72 hr. The same study identified 78.7% germination rate with mechanical abrasion (Solak, 2007). Administration of H_2SO_4 for 5 min was reported to increase the speed of *P. harmala* seed germination (Bendif et al., 2019).

4 | CONCLUSION

The study tries to fill the knowledge gap for a variety of *P. harmala* that are naturally grown in Turkey and provide data to development of efficient systems, machinery, and seed processing practices.

The mean length, width, thickness, and surface area values for *P. harmala* L. seeds were determined as 4.78 mm, 1.81 mm, 1.53 mm, and 14.14 mm^2 with the image processing method. The arithmetic mean diameter, geometric mean diameter, and sphericity values were calculated as 2.71 mm, 2.34 mm, and 0.50 linked to these dimensions.

Bulk density and true density values were measured as 0.5379 and 1.015 g cm^{-3}, respectively, and the porosity value linked to these was calculated as 46.98%.

The static friction angles on two different surfaces formed from galvanized metal and PVC material were measured as 15.67° and 17.67°, respectively. Linked to these angles, the static friction coefficient values were 0.28 for the galvanized metal surface and 0.32 for the PVC surface.

Terminal velocity experiments determined the velocity values as 5.03 m s^{-1} for *P. harmala* seeds.

The *P. harmala* seeds contained 89.7% dry matter, 10.3% CP, and 10.75% oil, and the most effective method for germination was sanding with 84% germination rate. This was followed by soaking in water (78.0%) and treatment with H_2SO_4 for 5 min (75%).

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHOR CONTRIBUTIONS

Ömer Ertuğrul: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; validation; writing – original draft. **Melih Yılar:** Conceptualization; data curation; formal analysis; methodology; resources; writing – original draft. **Hakan Kır:** Conceptualization; data curation; formal analysis; investigation; methodology; writing – original draft. **Ceren Kömekçi:** Formal analysis; investigation.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

NOMENCLATURE

ADF	acid detergent fiber (%)
CA	crude ash ratio (%)
CV	coefficient of variation (%)
CP	crude protein ratio (%)
D_a	arithmetic mean diameter (mm)
D_g	geometric mean diameter (mm)
GS	number of germinating seeds
H_2SO_4	sulfuric acid
l	length (mm)
NDF	neutral detergent fiber (%)
PVC	polyvinyl chloride
S	surface area (mm^2)
SD	standard deviation
t	thickness (mm)
TS	total number of seeds
V	terminal velocity (m s^{-1})
W_{1000}	one thousand seed mass (g)
x	average
ε	porosity (%)
Θ_g	angle of static friction on galvanized surface (°)
Θ_p	angle of static friction on PVC surface (°)
Θ_r	angle of repose (°)
μ_g	coefficient of static friction on galvanized surface
μ_p	coefficient of static friction on PVC surface
ρ_b	bulk density (g cm^{-3})
ρ_t	true density (g cm^{-3})
ϕ	Sphericity

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REFERENCES

Abalone, R., Cassinera, A., Gastón, A., & Lara, M. A. (2004). Some physical properties of amaranth seeds. *Biosystems Engineering*, *89*(1), 109–117. https://doi.org/10.1016/j.biosystemseng.2004.06.012

Ahangarnezhad, N., Najafi, G., & Jahanbakhshi, A. (2019). Determination of the physical and mechanical properties of a potato (the Agria variety) in order to mechanise the harvesting and post-harvesting operations. *Research in Agricultural Engineering*, *65*, 33–39. https://doi.org/10.17221/122/2017-RAE

Alayunt F. N. (2000). Biyolojik Malzeme Bilgisi [in Turkish] (Biological Material Information). Izmir, Turkey. Ege Üniversitesi Ziraat Fakültesi Yayınları, Yayın No: 541.

Altuntas, E., & Demirtola, H. (2007). Effect of moisture content on physical properties of some grain legume seeds. *New Zealand Journal of Crop and Horticultural Science*, *35*(4), 423–433. https://doi.org/10.1080/01140670709510210

Altuntaş, E., Gül, E. N., & Gök, H. (2020). Menengiç meyve ve tohumlarının fiziksel, mekanik, renk ve kimyasal özellikleri. *Kahramanmaraş Sütçü İmam Üniversitesi Tarım ve Doğa Dergisi*, *23*(6). https://doi.org/10.18016/ksutarimdoga.v23i54846.722274

Anonymous (2021). Analytical Methods Fiber Analyzer A2000. https://www.ankom.com/analytical-methods-support/fiber-analyzer-a2000

Apostolico, I., Aliberti, L., Caputo, L., De Feo, V., Fratianni, F., Nazzaro, F., … Khadhr, M. (2016). Chemical composition, antibacterial and phytotoxic activities of *Peganum harmala* seed essential oils from five different localities in northern Africa. *Molecules*, *21*(9), 1235. https://doi.org/10.3390/molecules21091235

Araujo, M. E. V., Barbosa, E. G., Gomes, F. A., Teixeira, I. R., Lisboa, C. F., Araújo, R. S. L., & Corrêa, P. C. (2018). Physical properties of sesame seeds harvested at different maturation stages and thirds of the plant. *Chilean Journal of Agricultural Research*, *78*(4), 495–502. https://doi.org/10.4067/S0718-58392018000400495

Asgarpanah, J., & Ramezanloo, F. (2012). Chemistry, pharmacology and medicinal properties of Peganum harmala L. *African Journal of Pharmacy and Pharmacology*, *6*(22). https://doi.org/10.5897/ajpp11.876

Association of Official Analytical Chemists. (2005). *Official Methods of Analysis* (18th ed.). Washington, DC: Association of Official Analytical Chemists International.

Aviara, N. A., Gwandzang, M. I., & Haque, M. A. (1999). Physical properties of guna seeds. *Journal of Agricultural Engineering Research*, *73*(2), 105–111. https://doi.org/10.1006/jaer.1998.0374

Baümler, E., Cuniberti, A., Nolasco, S. M., & Riccobene, I. C. (2006). Moisture dependent physical and compression properties of safflower seed. *Journal of Food Engineering*, *72*(2), 134–140. https://doi.org/10.1016/j.jfoodeng.2004.11.029

Bendif, H., Harir, M., Yahiaoui, M., Zedam, A., Hadjkouider, B., Atek, Y., … Boudjeniba, M. (2019). Germinative performance of seeds of 14 species of medicinal plants. *Journal of Medicinal Botany*, *3*, 15–24. https://updatepublishing.com/journal/index.php/jmb/article/view/5463

Besharati, B., Navid, H., Karimi, H., Behfar, H., & Eskandari, I. (2019). Development of an infrared seed-sensing system to estimate flow rates based on physical properties of seeds. *Computers and Electronics in Agriculture*, *162*, 874–881. https://doi.org/10.1016/j.compag.2019.05.041

Bozdoğan, O., Uyar, F., Karaman, Y., Demirtaş, Ç., Uçar, K., & Tursun, N. (2019). *Myagrum perfoliatum* L. (Gönül Hardalı) Tohumlarında Dormansi Kırma Üzerine Araştırmalar. *Turkish Journal of Weed Science*, *22*(1), 45–52.

Bozoğlu S. (1999). Some investigations on biology and kontrol of *peganum harmala* L. [In Turkish]. Selçuk Üniversitesi, Ziraat Fakültesi, Bitki Koruma Ana Bilim Dalı, Konya (MSc thesis).

Copeland, L. O., & McDonald, M. B. (1999). The chemistry of seeds. In *Principles of seed science and technology*. Boston, MA: Springer. https://doi.org/10.1007/978-1-4615-1783-2_3

Coşkuner, Y., & Karababa, E. (2007). Some physical properties of flaxseed (*Linum usitatissimum* L.). *Journal of Food Engineering*, *78*, 1067–1073. https://doi.org/10.1016/j.jfoodeng.2005.12.017

Demir, I., Özden, E., Gökdaş, Z., Njie, E. S., & Aydin, M. (2020). Radicle emergence test predicts normal germination percentages of onion seed lots with different cultivars and genotypes. *Mustafa Kemal Üniversitesi Tarım Bilimleri Dergisi*, 434–442. https://doi.org/10.37908/mkutbd.697450

Dobbs, E. M. (2011). SketchAndCalc. Web. Retrieved from http://www.SketchAndCalc.com

Ertuğrul, O. (2010). Mathematical and statistical analysis of different seeding methods and the development of metering units for canola (*Brassica Napus* L. Sp. *Oleifera*) seeds (PhD dissertation). Izmir, Turkey: Ege University.

Evcim, H. Ü., Değirmencioğlu, A., Özgünaltay Ertuğrul, G., & Aygün, İ. (2012). Advancements and transitions in technologies for sustainable agricultural production. *Economic and Environmental Studies*, *12*(4), 459–466.

Fisklements, M., & Barrett, D. M. (2014). New methods for measuring surface area, seed coat separation, and 'chip and scratch' damage in almonds. *Journal of Food Engineering*, *142*, 1–8. https://doi.org/10.1016/j.jfoodeng.2014.05.021

Frączek, J., Złobecki, A., & Zemanek, J. (2007). Assessment of angle of repose of granular plant material using computer image analysis. *Journal of Food Engineering*, *83*, 17–22. https://doi.org/10.1016/j.jfoodeng.2006.11.028

Gupta, R. K., & Das, S. K. (1997). Physical properties of sunflower seeds. *Journal of Agricultural Engineering Research*, *66*(1), 1–8. https://doi.org/10.1006/jaer.1996.0111

Ixtaina, V. Y., Nolasco, S. M., & Tomás, M. C. (2008). Physical properties of chia (Salvia hispanica L.) seeds. *Industrial Crops and Products*, *28*(3), 286–293. https://doi.org/10.1016/j.indcrop.2008.03.009

Jahanbakhshi, A. (2018). Determine some engineering properties of snake melon (*Cucumis Melo* var. *flexuosus*). *CIGR Journal*, *20*(1), 171–176.

Jahanbakhshi, A., Abbaspour-Gilandeh, Y., Ghamari, B., & Heidarbeigi, K. (2019). Assessment of physical, mechanical, and hydrodynamic properties in reducing postharvest losses of cantaloupe (*Cucumis melo* var. *Cantaloupensis*). *Journal of Food Process Engineering*, *42*, e13091https://doi.org/10.1111/jfpe.13091

Jahanbakhshi, A., Abbaspour-Gilandeh, Y., & Gundoshmian, T. M. (2018). Determination of physical and mechanical properties of carrot in order to reduce waste during harvesting and post-harvesting. *Food Science & Nutrition*, *6*(7), 1898–1903. https://doi.org/10.1002/fsn3.760

Jahanbakhshi, A., Rasooli Sharabiani, V., Heidarbeigi, K., Kaveh, M., & Taghinezhad, E. (2019). Evaluation of engineering properties for waste control of tomato during harvesting and postharvesting. *Food Science & Nutrition*, *2019*(7), 1473–1481. https://doi.org/10.1002/fsn3.986

Joshi, D. C., Das, S. K., & Mukherjee, R. K. (1993). Physical properties of pumpkin seeds. *Journal of Agricultural Engineering Research*, *54*(3), 219–229. https://doi.org/10.1006/jaer.1993.1016

Kaliniewicz, Z., Anders, A., Markowski, P., Tylek, P., & Owoc, D. (2021). Analysis of the physical properties of spindle seeds for seed sorting operations. *Scientific Reports*, *11*, 13625. https://doi.org/10.1038/s41598-021-93166-z

Kaliniewicz, Z., Markowski, P., Anders, A., & Jadwisieńczak, K. (2015). Frictional properties of selected seeds. *Technical Sciences*, *18*(2), 85–101. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.1040.8455&rep=rep1&type=pdf

Karaj, S., & Müller, J. (2010). Determination of physical, mechanical and chemical properties of seeds and kernels of Jatropha curcas L.. *Industrial Crops and Products*, *32*(2), 129–138. https://doi.org/10.1016/j.indcrop.2010.04.001

Kırıcı, S., Kayıran, S. D., & Tokuz, G. (2018). Doğu Akdeniz Bölgesinde Üzerlik (*Peganum harmala* L.) Bitkisinin Tütsü Olarak Kullanımı [in Turkish]. (The Use of Smoke Syrian Rue (*Peganum harmala* L.) in Eastern Mediterranean Region). *Lokman Hekim Dergisi*, *8*(1), 1–12.

Kwiatkowski, J., Krzyżaniak, M., Załuski, D., Stolarski, M. J., & Tworkowski, J. (2020). The physical properties of fruits and the physiological quality of seeds of selected crambe genotypes. *Industrial Crops and Products*, *145*, 111977. https://doi.org/10.1016/j.indcrop.2019.111977

Lei, X., Hu, H., Wu, W., Liu, H., Liu, L., Yang, W., Zhou, Z., … Ren, W. (2021). Seed motion characteristics and seeding performance of a centralised seed metering system for rapeseed investigated by DEM simulation and bench testing. *Biosystems Engineering*, *203*, 22–33. https://doi.org/10.1016/j.biosystemseng.2020.12.017

León-Lobos, P., Bustamente-Sánchez, M. A., Nelson, C. R., Alarcón, D., Hasbún, R., Way, M., … Armesto, J. J. (2020). Lack of adequate seed supply is a major bottleneck for effective ecosystem restoration in Chile: Friendly amendment to Bannister et al. (2018). *Restoration Ecology*, *28*, 277–281. https://doi.org/10.1111/rec.13113

Mahmoudian, M., Jalilpour, H., & Salehian, P. (2002). Toxicity of *Peganum harmala*: Review and a case report. *Iranıan Journal of Pharmacology & Therapeutics*, *1*(1), 1735–2657.

Mohsenin, N. N. (1986). *Physical properties of plant and animal materials*. New York, NY: Gordon and Breach Science Publishers.

Moloudizargari, M., Mikaili, P., Aghajanshakeri, S., Asghari, M. H., & Shayegh, J. (2013). Pharmacological and therapeutic effects of *Peganum harmala* and its main alkaloids. *Pharmacognosy Reviews*, *7*(14), 199–212. https://doi.org/10.4103/0973-7847.120524

Moshiri, M., Etemad, L., Javidi, S., & Alizadeh, A. (2013). *Peganum harmala* intoxication, a case report. *Avicenna Journal of Phytomedicine*, *3*(3), 288–292.

Nedjimi, B. (2020). Germination characteristics of *Peganum harmala* L. (*Nitrariaceae*) subjected to heavy metals: Implications for the use in polluted dryland restoration. *International Journal of Environmental Science and Technology*, *17*, 2113–2122. https://doi.org/10.1007/s13762-019-02600-3

Önal, İ., & Ertuğrul, O. (2011a). Seed flow and in-row seed distribution uniformity of the top delivery type fluted roller for onion, carrot and canola seeds. *Journal of Agricultural Sciences*, *17*, 10–23.

Önal, İ., & Ertuğrul, O. (2011b). Seed flow and in-row seed distribution uniformity of the top delivery type mini fluted roller for onion, carrot and canola seeds. *Journal of Agricultural Machinery Science*, *7*(4), 437–448.

Özdemir, M. H., & Değirmencioğlu, A. (2020). Mathematical modelling of the volumetric efficiency for fluted rolls metering different crop seeds. *Turkish Journal of Agriculture - Food Science and Technology*, *8*(11), 2453–2459. https://doi.org/10.24925/turjaf.v8i11.2453-2459.3755

Özkurt, M. (2008). *Polygonum cognatum* Meissn. (Madımak) tohumlarının çimlenme Biyolojisi ve Klonları arasındaki Genetik Çeşitliliğin Belirlenmesi. Tokat, Turkey: Gaziosmanpaşa Üniversitesi, Fen Bilimleri Enstitüsü, Bitki Koruma Anabilim Dalı Yüksek Lisans Tezi.

Passos, I. D., & Mironidou-Tzouveleki, M. (2016). Hallucinogenic plants in the Mediterranean countries. In V. R. Preedy (Ed.), *Neuropathology of drug addictions and substance misuse* (pp. 761–772). London, UK: Elsevier. https://doi.org/10.1016/B978-0-12-800212-4.00071-6

Razavi, S. M. A., Yeganehzad, S., & Sadeghi, A. (2009). Moisture dependent physical properties of canola seeds. *Journal of Agricultural Science Technology*, *11*(3), 309–322. https://jast.modares.ac.ir/article-23-3411-en.pdf

Singh, H., & Meghwal, M. (2020). Physical and thermal properties of various ajwain (*Trachyspermum ammi* L.) seed varieties as a function of moisture content. *Journal of Food Process Engineering*, *43*, e13310. https://doi.org/10.1111/jfpe.13310

Singh, K. K., & Goswami, T. K. (1996). Physical properties of cumin seed. *Journal of Agricultural Engineering Research*, *64*(2), 93–98. https://doi.org/10.1006/jaer.1996.0049

Sodaeizadeh, H., Rafieiolhossaini, M., & Van Damme, P. (2010). Herbicidal activity of a medicinal plant, *Peganum harmala* L., and decomposition dynamics of its phytotoxins in the soil. *Industrial Crops and Products*, *31*(2), 385–394. https://doi.org/10.1016/j.indcrop.2009.12.006

Solak, H. (2007). Researches on the germination characteristics of some common weed seeds in Konya province [in Turkish]. Konya, Turkey: Selçuk Üniversitesi, Ziraat Fakültesi, Bitki Koruma Ana Bilim Dalı. (MSc thesis).

Soliman, M. S. A., El-Tarras, A. S., & El-Awady, M. A. (2010). Seed exomorphic characters of some taxa from Saudi Arabia. *Journal of American Science*, *6*(11), 906–910. http://www.jofamericanscience.org/journals/am-sci/am0611/125_4022am0611_906_910.pdf

Taheria, M., Mirzabea, A. H., Bavanib, N. B., & Kianmehra, M. H. (2017). Determination of some physical properties of harmala (*Peganum harmala* L.) seeds. *Ecology, Environment and Conservation*, *23*(1), 12–17.

Tunde-Akintunde, T. Y., & Akintunde, B. O. (2004). Some physical properties of sesame seed. *Biosystems Engineering*, *88*(1), 127–129. https://doi.org/10.1016/j.biosystemseng.2004.01.009

Vilche, C., Gely, M., & Santalla, E. (2003). Physical properties of quinoa seeds. *Biosystems Engineering*, *86*(1), 59–65. https://doi.org/10.1016/S1537-5110(03)00114-4

Wang, K., Hu, X., Li, S., Li, X., Li, D., Bai, J., … Hua, H. (2018). Racemicindole alkaloids from the seeds of *Peganum harmala*. *Fitoterapia*, *125*, 155–160. https://doi.org/10.1016/j.fitote.2018.01.008

Yilar, M., & Altuntas, E. (2017). Determination of some physical properties of the annual and perennial sage (*Salviaviridis* L., *Salvia cryptantha* Montbret et Aucher) varieties seeds. *Mediterranean Agricultural Sciences*, *30*(2), 137–141. https://dergipark.org.tr/tr/download/article-file/333228

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