Laboratory Tests to Assess Optimal Agricultural Residue Traits for an Abrasive Weed Control System

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Abstract

One of the biggest challenges to organic agricultural production and herbicide resistant crops in industrialized countries today is the non-chemical control of weed plants. Studies of new tools and methods for weed control have been motivated by an increased consumer demand for organic produce and consumer and regulatory demands for a reduction in environmentally harmful herbicide use. The objective of this study is to assess different agricultural residues as gritty weed-abrading materials that are delivered through condensed-air machinery. This is a new weed control technology based on highly-directed air-propelled, innocuous, abrasive grit. Laboratory equipment was designed to calculate the angle of repose of seven different agricultural residues (crushed olive seed, walnut shell, maize cob, poultry manure, soybean seed, almond shell and grape seed). Color, digital, high-speed computer vision analysis of the motion and energy of the air-propelled particles was conducted. The high-speed video analysis determined the capability of each grit to damage a reference surface and kill weeds (species of *Amaranthus, Centaurea, and Chenopodium*) at different growth stages. A preliminary laboratory trial showed that walnut shell grit has great potential to damage/break the reference surface when it was propelled at 600, 700 and 800 kPa air pressure. Abrasive-weeding reduced final weed biomass by 80% compared with the weedy control at early growth stages. Field research tests are needed in different cropping systems to improve the technical and economic efficiency of this novel system before on-farm adoption.

Keywords: Alternative weed control, precision farming, non-chemical application, abrasion, organic farming.

1. Introduction

The most widely used practice for weed control in conventional agriculture is still spraying of an entire field with selective or non-selective herbicides at differents times during the growing season (e.g., boom sprayer). During the last decade some research groups have been devoted to the development of precision spray application systems that actuate spray valves independently in different sprayer sections to provide application accuracy based on detailed weed infestation maps (Christensen et al., 2009) and GNSS/Vision technology (Pérez-Ruiz et al., 2011). Researchers, farmers and society are aware that pesticide use represent a heavy economic burden for the agricultural sector and a substantial chemical load for the environment, and it increases the risks of undesirable side effects on human health. Agricultural systems require safe, effective and efficient weed control operations to ensure the success of crop production (Gutjahr & Gerhards, 2010).

Conversations with stakeholders have given new insight on the advantages and disadvantages of various weed control techniques. Some of the limitations of certain methods that must be taken into account are: (i) manual hand hoeing to remove weeds during early competitive growth from specialty cropping systems can be up to five times the cost of conventional cultivation techniques (Slaughter, 2008), (ii) if herbicides are used as a weed control method, their persistence in the soil can negatively affect the next crops in the rotation as a result of soil residues, (iii) European legislation aims to limit the use of synthetic plant protection products in agriculture, and (iv) consumer demand continues to drive the increase in organic food markets.

Weed management remains the single most important agronomic issue in organic cropping systems according to farmer surveys (Walz, 1999). Both, mechanical weed control and hand hoeing (intensive labor, time consuming, and speed and accuracy are restricted by the skills and experience of the crew) are the most commonly used weed control methods in organic agricultural sistems. Extensive research has been conducted to address this issue, and alternate techniques to hand weeding have been developed to control weeds growing in the crop row (Jørgensen et al., 2007; Nørremark et al., 2008; Van Evert et al., 2011). However, precise systems of intra-row weed control typically depend upon tillage. Reduced and no-tillage techniques in arable cropping systems are known to protect soil form erosion, increase soil orgnaic matter and increase C sequestration, but increase pernnial weed infestations. Tillage also impacts release of nitrous oxide (N_2O), another greenhouse gas, indirectly through modification of microclimate and substrate availability (Johnson et al., 2005). Thus, despite good intentions, the C-N footprint (Williams et al., 2006) left by organic agriculture, as currently practiced, likely is comparable to that of conventional agriculture (Qin et al., 2010).

One of the biggest challenges to row crops and orchard production in industrialized countries today is the non-chemical control of weeds within the crop row (i.e., intra-row weed control). In recent years many research groups have worked diligently on this issue. For example, methods like flaming (Ulloa et al., 2010), grit-abrasion (Forcella 2012) and mechanical cultivation uisng a RTK-GNSS based crop plant map with minimun soil disturbance (Perez-Ruiz et al., 2012) have been demonstrated to control weeds effectively in the row crop, but their complete system costs are not well documented. While simple and economical equipment is available to control the inter-row (i.e., between row) weeds, intra-row (i.e., within-row) weed control still requires costly hand weeding for organic and small-scale farmers (Sivesind et al., 2009). For manual weed control the operation in many cases causes the worker to be stooped and work in uncomfortable bending postures over long periods, which may cause serious chronic health issues for workers and, therefore, increased costs for growers and society due to lost work time and increased health costs.

A new method that has been gaining attention in recent years as chemical-free alternative, has been the use of of air-propelled abrasive grit. The grit abrades small weed seedlings within the crop row and leaves the crop plants essentially unscathed. Various innocuous grits derived from agricultural residues possibly can be used for post-emergence control of small seedlings of broadleaf and grass weeds generally (Forcella 2009a) and even selectively within corn (Forcella 2012a), soybean (Forcella 2013), pepper and tomato (Wortman 2014, 2015). Indeed, Wortman's studies show that organically-approved fertilizers can work effectively as weed-abrading grits in vegetable crops.

The objectives of this study were to:

i) Determine the angle of repose for seven different agriculutural residues and investigate its relationship to the ability to damage a reference surface material when the residue is propelled by pressurized air.

ii) Test laboratory applications of the differing abrasive grits on seedlings of the three common weeds (species of *Amaranthus retroflexus, Chenopodium murale, and Centaurea cyanus*).

2. Materials and Methods

2.1. Agricultural residues angle of repose (AoR)

When granular material is poured onto a surface, its forms a conical. Figure 1 shows seven heaps of agricultural residues used in this work. In particular, a cohesive agricultural residue yields a high value of the repose angle and strong deviations from the conical shape (Ryck et al., 2005; Ileleji and Zhou, 2008). Therefore, a precise measurement of heap shape offers some useful information regarding interactions between the particles.

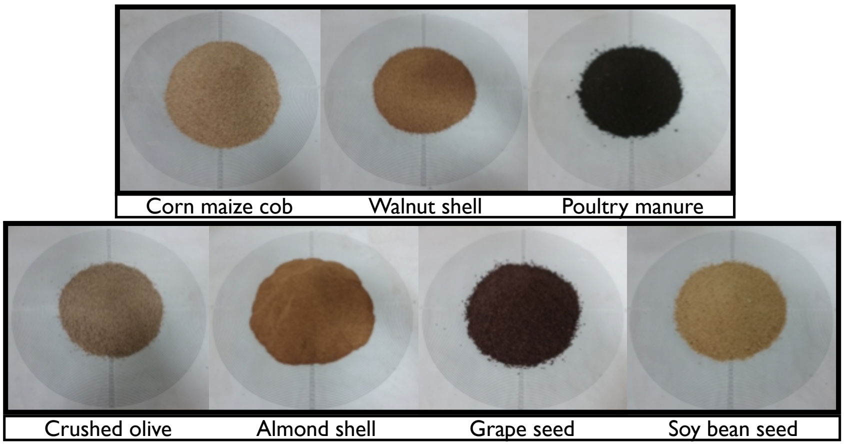

Figure 1. Seven heap shapes.

The AoR test is very sensitive to the method used to create a heap. After heap formation, the measurement of the repose angle is not obvious. As shown in Figure 1, the shape of a heap has to be analysed carefully. Therefore, the classical method, which consists of measuring the heap height h on a circular support of diameter b and calculating the angle with the relation tan (alfa)=2h/b, is subject to caution.

To determine the AoR for each sample of agricultural residue, laboratory equipment was designed and fabricated in a shop located at the University of Sevilla. The equipment consisted of a platform and a frame height of 60 mm, the top of which supported an electric screwdriver, a rheostat, an electric motor with a pulley and a methacrylate cylinder (Figure 2). The screwdriver (BLACK & DECKER model) was driven rom 116 rpm to 1.66 rpm and was reduced by a rheostat. To reduce the input, the electric motor was attached to the pulley so that this system could allow for ascending and descending cylinder speed of 0.001162 ms^{-1}, with a height of 150 mm an outer diameter of 80 mm and an inner diameter of 74 mm.

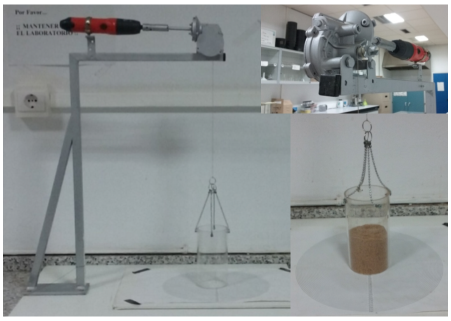

Figure 2. Lab equipment for determining the angle of repose.

The methacrylate cylinder was centred on the platform, whose dimensions were 495 x 340 mm. This platform was marked with concentric circles of known measurement scaled from 5 to 5 mm with a maximum diameter of 280 mm and a minimum diameter of 40 mm. Moreover, in the frame, it was necesary to perform the height measurement.

The experimental design involved 4 repetitions with three mass weights, i.e., 100, 150 and 200 grams, for each agricultural residue. A priori, the mass is an independent parameter of friction angle; thus, different volumes were taken to verify that this was the case, and a total of 12 repetitions for each residue was conducted. Initially, we started with 10 repetitions for each of the fixed masses; however, these were decreased to four because the data were quite homogeneous. Moreover, the maximum weight was 200 g because the residue of corn cob occupies much volume, and the weight for the same maximum weight, which was introduced into the cylinder, was taken. The minimum weight of 100 g indicated that enough time had passed for the proper formation of a cone, even though 50 g appeared adequate.

2.2. Condensed-air machinery

A small laboratory portable grit applicator, similar to a sand blaster in functionality, was designed to characterize and study adjustments of pressure, speed, flow and direction. The system consists of a grit tank, air pressure system and a specific nozzle connected by high-pressure rubber hoses. One hose is for grit intake and draws from a reservoir tank of grit; the second hose is for air intake and is coupled to an air compressor. Once the nozzle is open, compressed air passes over the top of the grit hose and through the nozzle, thereby creating a vacuum that draws grit from the tank through the grit hose and out of the nozzle. This system allows for a wide range of easily repeatable laboratory tests. Monitoring pressure (kPa), exit velocity of grit particles (m/s) and flow (kg/h) through the nozzle are basic features of the system, for which engineering knowledge is as important as residue consumption.

2.3. Referenced test

A first screening of agricultural residues was conducted to gain prior knowledge of the behaviour of the residues before the efficacy test on weed plants. To perform this experiment, a test material was needed that offered resistance but still is easily damaged; the results were taken as reference, and the starting point of the experimental design. The material selected for the test was white tissue paper. For this test, a pistol-type handheld sandblaster (SpeedBlaster ZENDEX model) connected to a compressor was used.

This device used gravity to feed grit into the sandblaster. The material fell into a hardened steel mixing chamber where compressed air forced the particles to pass, at an extraordinary speed, through a ceramic nozzle with top grade aluminium. To operate the pistol, it simply needed to be connected to the compressed air and have the trigger pulled. An outlet valve regulated the flow of material. To perform all tests, the valve was in the same position, i.e., maximum opening.

Table 1. Specifications of the handheld sandblaster gun

Specifications	
Operating pressure	60-100 PSI
Working pressure	70-100 PSI
Air consumption	10CFM-100PSI
Min. Air Compressor	3 HP
Fitting Size	1/4 NPT
Container Capacity	26 Oz. (Vol.)
Max. Particle Size	14 grit

First, several tissue papers were put in a frame 25 cm in diameter and kept it as tight as possible. This frame was fastened with a clamp attached to a lab stand so that the frame was vertically arranged at an angle of 90° with the ground, as shown in Figure 3. All this was performed on a tray to collect all possible and reusable material.

(a)

(b)

Figure 3. a) Laboratory application and b) papers penetrated by the residue

Then, the pistol, with a full storage tank was pointed at the frame at approximately 30 cm and shot for 3 seconds while pointed at the centre of the paper mounted on the frame for 3 seconds.

This operation for each material continued with increasing numbers of tissue papers until the residue did not penetrate all the papers. Each shot was properly labelled with a code, with 3 parts corresponding to the number of papers, residue and pressure used. In the example of Figure 3b, the label on the top indicates that the number of papers was 9, the residue was walnut and the pressure was 700 kPa.

The experiment was performed at three different pressures (600, 700 and 800 kPa) for each of the agricultural residues.

The maximum number of penetrated papers was counted, considering breakage to be positive when all papers were penetrated by the residue (Figure 3b); the shot was considered as failed when one of the papers was not totally punctured. In addition the diameter of the damaged area that formed after each shot was recorded and average diameter calculated.

2.4. Determination of the success rate of eliminating weeds

Seeds of the three weed species were sown in 70x70x80 cm pots filled with 0.24 L of a fine-grained substrate ($ø \leq 0.1$ (mm) ≤ 10) and grown in a growth chamber (under controlled conditions with alternating night/day cycles of 9/16 hours, 23/25°C, and 45/60% relative humidity. Photosynthetically active radiation was 22 W m^{-2}. When seedlings were at the 2- to 3-leaf stages of growth they were exposed to grit propelled at 800 kPa for 1 s. For each type of residue, 10 seedlings (5 s) of each species were tested. Damage was assessed visually at 0, 1, 2, 3, 7 and 14 d after exposure to grit.

To predict the success rate *(P)* or probability of removing a weed species under the action of a particular residue, multiple binary logistic regression with a categorical independent variable was used [Eq. 1].

$$logit\,(P) = \ln\frac{P}{1-P} = \alpha + \sum_{i=1}^{8}\beta_i \cdot Z_i + \sum_{j=1}^{2}\lambda_j \cdot Z'_j + \sum_{j=1}^{2}\sum_{i=1}^{8}\theta_{ij} \cdot Z_i \cdot Z'_j \quad (1)$$

where *logit (P)* is the logical function, defined as the natural logarithm of the ratio between the probability of success *(P)* and failure *(1-P)* for a given species (represented in the model by Z'_j, with 3 levels) and a particular type of residue (represented by Z_i, with 9 levels). For modeling in addition to the artificial set of variables Z'_j and Z_i, their interactions are used to explain possible variations in the elimination of species for the same residue. These artificial variables are used in this study to define the various categories of weed species and type of residue, taking a value of 1 if the observation corresponds to the specified category and 0 otherwise.

The covariates were considered individually significant in the model if the p-value of the estimate was less than 0.01. The G^2 (deviance) statistic was used to test the null hypothesis of the fit of the model to the sample, being distributed according to $X^2_{n-(k+1)}$, where n is the number of observations and k is the number of covariates in the model.

For the evaluation of the modelling capacity *(P)* of the logistic regression model, a comparison was made between the observed and predicted frequencies for each group. A measure of the goodness of fit of the response rate was also predicted correctly by assigning a value of 1 to the estimated probabilities greater than 0.5 and a value of 0 otherwise (Wooldridge, 2013).

The relative success rate (TER) [Eq. 2] is defined as the ratio of the odds of success with a particular residue against a standard or reference residue, which may be more common in the area. Keep in mind that olive (Olea europaea L.), with an approximate 2.5 Mha, is the most common woody crop in Spain, constituting 53% of the total area of woods nationally (Ministry of Agriculture, Food and Environment, 2015). For this reason, olive was chosen as the reference residue, as expressed in Eq. [2].

$$TER_{residuo\,i} = \frac{P_{residuo\,i}}{P_{crushed\ olive}} \tag{2}$$

In those cases where the rate of removal of the model also depends on the species, the TER is particularized for each of them.

Statistical models have been made with the use of R (R Core Team, 2015).

3. Results and Discussion

3.1. Agricultural residues angle and penetration ability in tissue papers

The data in Table 1 show the mean and standard deviation values for the agriculture residue angles of repose for the 100, 150, and 200-g samples. The variation of the angle of each weight level was less than 10%, as is logical because the weight of the sample must not have influence on the cone formed by the residue.

Table 1. Angles of repose for nine types of experimental abrasive grits.

	Sand		**Olive seed**		**Walnut shell**		**Maize cob**		**Poultry manure**	
Weight	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
100	27.0	±0.39	30.7	±0.74	31.7	±0.66	32.0	±0.24	33.0	±0.81
150	29.1	±0.65	30.9	±0.52	32.1	±0.54	31.5	±0.58	32.5	±0.40
200	28.7	±0.39	30.1	±0.40	32.0	±0.63	32.6	±0.34	32.8	±0.67
Average	**28.3**		**30.6**		**31.9**		**32.0**		**32.8**	
	Soybean meal		**Almond shell (1-1.05 mm)**		**Almond shell (0.5-0.2 mm)**		**Grape seed**			
Weight	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**		
100	34.0	±0.45	34.6	±0.26	37.1	±0.45	40.5	±0.57		
150	34.1	±0.36	33.7	±0.56	38.4	±0.36	39.0	±0.41		
200	33.9	±0.62	35.0	±0.17	38.6	±0.62	39.6	±0.40		
Average	**34.0**		**34.4**		**38.0**		**39.7**			

The results can be assembled into four groups. In the first of these residues obtained by the larger angles such as grape seed, which had the largest friction angle (39.7°) followed by almond shell with a particle size between 0.5 to 0.2 mm. A second group, with angles of about 34°, included soybean meal and almond shell with particle size of 1-0.5 mm. The third group, with angles of about 32°, comprises poultry manure, maize cob and walnut shell. Finally, the residues with the smallest angles were the olive seed and sand, 30.6° and 28.3°, respectively.

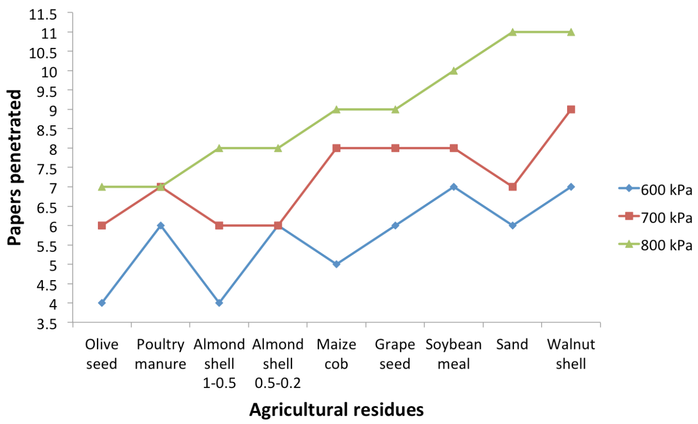

Figure 4. Number of layers of tissue paper penetrated by residues at three air pressures.

Figure 4 shows the ability of penetration of each agricultural residue at 600, 700 and 800 kPa. Walnut shell was the residue that penetrated more reference papers (7, 9, and 11 papers at 600, 700, and 800 kPa, respectively). The olive seed was the residue that least penetrating power. At this point, we cannot confirm that the angle of repose was associated with the penetration ability of the residues.

3.2. Success rate of eliminating weeds

Frequencies of success or elimination of the various combinations of weeds x grit residue are shown in Table 2, with percentages ranging from 30 to 100%, except for the control treatment. In only 3 of 24 cases in which abrasive grit was applied was the effectiveness less than 80% (Figure 1). The lowest success rate occurred for sand in Chenopodium (30%), compared to the 90% achieved by the remaining species with the same residue.

The resulting estimates of the parameters of the global model, which initially comprised all residues and species [Eq. 1], are shown in Table 3. The null hypothesis model adequacy, according to the significance of G2 (p = 0.9), is accepted. All the coefficients associated with the residues were associated with p values $<10^{-4}$, indicating significant differences among them. Sometimes, however, the coefficients were not relevant at the practical level, as evidenced by the frequencies in Table 2. Only the interaction that was significant was that of the behaviour of Chenopodium with sand (p = 0.0027).

The fact that significant results have only the coefficients associated with the types of residue (Table 3) indicates that the susceptibility of each plant to weeding with abrasive grit is constant and independent of the weeds on which the application was performed. This finding is very interesting because it suggests a uniform replacement by each residue (Table 2), with the exception of the sand, as reflected in the significance of the coefficient associated with covariate $Z_1 Z'_2$ (Table 3).

Errors in success rates were generally small and rarely higher than 0.15 (absolute value) (Table 2); thus, we consider that the model has good predictive ability. These errors are somewhat greater in those cases in which some sample variability occurred between species, e.g., almond shell and grape seed (Table 2).

Table 2. Comparison between frequencies of removed weeds model and tests

Treatment	*Weed*	*Fitted probability*	*Trial probability*	*Error*	*Mean (treatment)*	*TER*
Sand	*Amaranthus*	*0.90*	*0.90*	*0.00*		*0.98*
	Chenopodium	*0.30*	*0.30*	*0.00*		*0.33*
	Centaurea	*0.90*	*0.90*	*0.00*	*0.70*	*0.98*
Olive seed	*Amaranthus*	*0.92*	*0.90*	*0.02*		
	Chenopodium	*0.92*	*1.00*	*-0.08*		
	Centaurea	*0.92*	*0.80*	*0.12*	*0.90*	*1*
Walnut shell	*Amaranthus*	*0.97*	*1.00*	*-0.03*		
	Chenopodium	*0.97*	*0.90*	*0.07*		
	Centaurea	*0.97*	*1.00*	*-0.03*	*0.97*	*1.05*
Maize cob	*Amaranthus*	*0.93*	*1.00*	*-0.07*		
	Chenopodium	*0.93*	*0.90*	*0.03*		
	Centaurea	*0.93*	*0.90*	*0.03*	*0.93*	*1.01*
Poultry manure	*Amaranthus*	*0.90*	*1.00*	*-0.10*		
	Chenopodium	*0.90*	*0.80*	*0.10*		
	Centaurea	*0.90*	*0.90*	*0.00*	*0.90*	*0.98*
Soybean meal	*Amaranthus*	*0.84*	*0.80*	*0.04*		
	Chenopodium	*0.84*	*0.80*	*0.04*		
	Centaurea	*0.84*	*0.90*	*-0.06*	*0.83*	*0.91*
Almond shell	*Amaranthus*	*0.87*	*0.90*	*-0.03*		
	Chenopodium	*0.87*	*1.00*	*-0.13*		
	Centaurea	*0.87*	*0.70*	*0.17*	*0.87*	*0.95*
Grape seed	*Amaranthus*	*0.73*	*0.90*	*-0.17*		
	Chenopodium	*0.73*	*0.50*	*0.23*		
	Centaurea	*0.73*	*0.80*	*-0.07*	*0.73*	*0.79*
Control	*Amaranthus*	*0.08*	*0.00*	*0.08*		
	Chenopodium	*0.08*	*0.00*	*0.08*		
	Centaurea	*0.08*	*0.22*	*-0.15*	*0.08*	*0.09*

Table 3. Estimated logistic regression model

Coefficient	*Estimate*	*Standard error*	*p-value*	*Associated parameter*	*Covariate*
α	-2.485	0.736	0.0007	-	-
β_1	4.682	1.048	$<10^{-5}$	Sand	Z_1
β_2	4.927	1.042	$<10^{-5}$	Crushed olive	Z_2
β_3	5.852	1.255	$<10^{-5}$	Walnut shell	Z_3
β_4	5.124	1.038	$<10^{-5}$	Corn maize	Z_4
β_5	4.682	1.047	$<10^{-5}$	Poultry manure	Z_5
β_6	4.143	0.916	$<10^{-5}$	Soybean	Z_6
β_7	4.357	0.911	$<10^{-5}$	Almond shell	Z_7
β_8	3.496	0.844	$<10^{-4}$	Grape seed	Z_8
θ_{21}	-3.046	1.016	0.0027	Sand x Chenopodium	$Z_1 \cdot Z_2'$

Globally, of the 246 seedlings, the model correctly classified 216 (88% of all observations). With all coefficient estimates of β being positive, the higher the value, the more they indicate a higher probability of success of the residue. Thus, walnut shell, maize cob and olive seed are the most efficient, with β equal to 5.85, 5.12 and 4.92, respectively, which correspond to proportionate control values above 0.9 (Figure 5). The first of those (walnut shell) controlled almost all of the treated weeds (29 pots out 30) and has a TER of 1.05 from the standard residue.

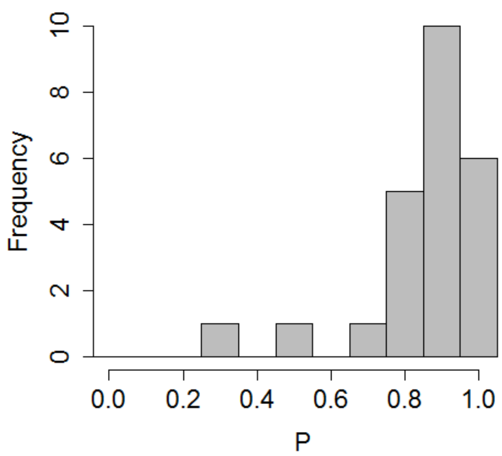

Figure 5. Frequencies of proportionate control by all residue types.

4. Conclusions

Weed control is mostly based on cropping systems coupled with chemical and mechanical techniques. The need for alternative weed control management practices has been constantly rising. This desire has occurred after several environmental, sustainability, and health issues have emerged among the scientific world, as well as the general public. One form of alternative weed control is the use of abrasive grit. This paper is a first laboratory approach to examine the physical nature of agricultural residues that can be used in this new weeding technique.

Walnut shell was the residue that penetrated more reference papers and was the residue that removed almost all of the treated weeds (29 pots out 30) and has a TER of 1.05 from the standard residue. Thus, considering that these preliminary tests were conducted at weed growth stages recommended for applications (2- to 3-leaf seedlings) (citation), walnut shell is the material most recommended for removing weeds via mechanical impact by air-propelled abrasive grit. Nevertheless, these are preliminary tests. Examining a greater number of weed species and understanding the properties of grits that promote better control would enable more consistent generalizations.

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