agronomy

Article

A Standard Methodology for Evaluation of Mechanical Maize Seed Meters for Smallholder Farmers Comparing Devices from Latin America, Sub-Saharan Africa, and Asia

Jelle Van Loon [1,*], Timothy J. Krupnik [2], Jesús A. López-Gómez [1], Jagadish Timsina [2,3] and Bram Govaerts [1,4]

1. International Maize and Wheat Improvement Center (CIMMYT), Carretera México-Veracruz km 45, El Batán, Texcoco C.P. 56237, Estado de México, Mexico; j.a.lopez@cgiar.org (J.A.L.-G.); b.govaerts@cgiar.org (B.G.)
2. International Maize and Wheat Improvement Center (CIMMYT) Bangladesh, House 10/B, Road 53, Gulshan-2, Dhaka 1213, Bangladesh; t.krupnik@cgiar.org (T.J.K.); timsinaj@hotmail.com (J.T.)
3. Institute for Study and Development Worldwide, Sydney 2140, NSW, Australia
4. Cornell University, Ithaca, NY 14850, USA

* Correspondence: j.vanloon@cgiar.org; Tel.: +52-55-5804-2004

Received: 22 June 2020; Accepted: 20 July 2020; Published: 28 July 2020

Abstract: Precision planting represents an opportunity for farmers to increase income. Seeders and associated seed meters are prerequisite to achieve optimal plant density. However, to assure seed meter performance in smallholder conditions, a comprehensive procedure is lacking. This study develops a methodology for mechanical maize meter evaluation that compares diverse meters in terms of seed singulation, seed damage, and spatial distribution. An experiment assessed 10 m, representing roller types, and inclined, vertical, and horizontal plates collected from various continents and representative of commonly used devices by smallholders. A conveyer-belt setup allowed for seed distribution analysis and the influence of vibration and topography on the seed singulation was determined. Results revealed that a rotational velocity of 20 revolutions per minute (RPM) was optimum for most meters, while all complied with the norm NMX-O-168-SCFI-2009 in terms of seed damage. Independent of the singulation mechanism, devices with the ability to adjust to seed size performed better. The Fitarelli horizontal plate, followed by the BARI-9 inclined plate meter, are considered 'best-bet' performers. Although, considering absolute efficiency, two inclined plate devices worked at near-perfect performance with large seeds. Our study develops a low-cost methodology, easily replicated and implemented, and provides a baseline for continued research on seed meter evaluation.

Keywords: maize seed meters; spatial seed distribution; seed plates; mechanical seed singulation; seeding performance

1. Introduction

Sowing is a crucial step for successful crop production [1]. Working correctly, seeder equipment must perform a series of actions passing over the field. These actions include soil penetration, metering the correct amount of seed to drop at the right location, depositing those seeds in the soil and providing pressure for adequate soil–seed contact [2–4]. Suboptimal planting geometry, due to uneven distribution of seeds along the rows, causes nutrient competition between plants [5,6]. In addition, seeding is usually a very time-sensitive operation—with only a short period offering the right climatic conditions [7,8]—as factors such as soil temperature and moisture are critical for seed germination [5]. In many countries with tropical and sub-tropical climates, delayed planting often results in high temperature stress during crop development causing significant yield losses, especially true for winter-sown maize [8,9]. To complete seed sowing in the narrow time-frame available and ensure successful crop establishment, it is essential to have a reliable seeder [5,10,11]. Besides adequate soil-engaging implements, quality seed meters are essential to provide the required precision, as the latter controls the singulation and flow of seeds and distributes them to the ground. Seed singulation is especially important for big-sized grain crops, like maize or cowpea, which are planted in a spaced, discontinuous fashion in contrast with smaller grains where seeds are deposited continuously [12,13]. Although different pneumatic seeders, equipped with synchronous rotating seed plates and vacuum chambers, can perform seed singulation with high precision and, therefore, are often preferred in highly mechanized farming systems [14,15], mechanical seed meters remain worldwide the most commonly found and the more economical option [16–19]. Indeed, while pneumatic seeders could be a viable option for high-speed planting [20], they are unlikely suitable for smallholder farmers (for mechanized farming schemes and in the context of this study, farms operating a land area from less than 1 and up to 10 hectares can be considered small, although depending the region, this threshold can be significantly lower; in Latin America farm sizes are generally higher, while for many parts of Asia and Africa farms are commonly less than 2 ha, often with many dispersed fields [21]) due to small plots sizes and high maintenance costs [13]. Selection of seeds with uniform size and shape facilitates mechanized sowing. However, due to the higher cost of graded seeds compared to heterogeneous ungraded seed batches, small-scale farmers in developing countries tend to use ungraded seed mixtures [22]. When using mechanical seed meters, heterogeneous seeds can clog the delivery mechanism and damage the seeds, resulting in too few seeds being distributed to the soil, while imprecise metering devices can create undesired skips or multiples within the row [2,3,5]. By contrast, a well-tuned and properly setup device meters seeds precisely and uniformly in variable field conditions without compromising the seed [5,23]. Nonetheless, for smallholder farmers in developing nations, seed-metering equipment should be simple in operation, affordable, and reliable [24,25]. To meet these requirements, mechanical meters are preferred over pneumatic meters.

From this perspective, mechanical seed meters are evaluated, comparing their performance to provide best-bet recommendations that enable good crop establishment in varying conditions. Different types of mechanical meters are used in developing countries depending on seed size and manufacturers' preference. The mass-flow meters, such as fluted rollers and double run seed meters, are generally used for smaller grains (i.e., wheat and barley) where a continuous seed flow is required. For larger grains like maize and beans, which require precise seed deposition to optimize plant geometry and manage higher seed cost, a variety of singulation mechanisms or precision meters exist, including horizontally, vertically or inclined plates, and disc, finger and cell systems that deliver seeds to the ground [3,5]. Although many studies report the design and evaluation of pneumatic and high-speed seed meters for maize [26,27], studies on mechanical maize seed meters commonly used by smallholder farmers are very limited. Furthermore, existing studies focus on the field evaluation of a single manual or hand-pulled seeder but fail to compare tools [13,19,28], with only a handful of studies specifying a comparative evaluation of different seed metering systems [29–32].

None of these studies review the performance of isolated metering systems but as the combined effect of the seed delivery system [33] and hence obscure the variability originating from the seed singulation mechanism [12]. To bridge this research gap, this study develops a methodology for mechanical maize seed meter evaluation that allows comparison of the performance of various types of maize meters. The methodology was developed specifically for ease of implementation without the need of advanced instruments as used in other studies on precision meters [12,31,34,35], as this facilitates replication with additional seed meters and seed types all over the world.

2. Materials and Methods

2.1. Experimental Setup

Experiments were conducted using two test-bench setups (Figure 1A) to assess the performance of 10 seed meters. For the determination of the recommended operating speed (and angle for inclined plates), a fixed-frame test-bench was built on which seed meters can be driven at a desired speed with an electromotor, and an independently driven conveyer belt below allows analysis of the distribution pattern with a fixed trajectory for each seed to reach the belt. This setup was used for seed damage analysis during which the meters were fixed on the frame and seeds were collected in a bag as they left the metering device. Seed distribution analysis was also performed on this bench, where smooth transparent tubes of 30 mm diameter were attached at seed meter exits to guide seeds in straight lines towards the moving conveyer belt.

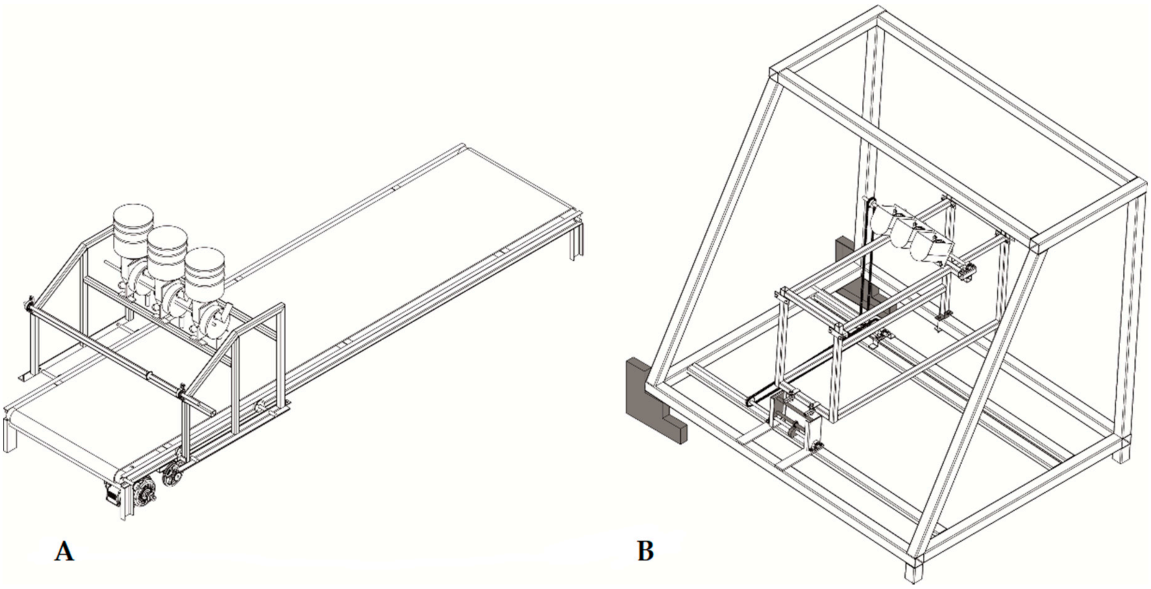

Figure 1. Test-bench setup with a fixed frame over a conveyer belt (**A**) and the seed meters mounted on seeder-like structure that facilitates adding vibration and sideways inclination (**B**).

A second test-bench mimicking field conditions was used to test the influence of vibratory and topography-induced disturbances on the singulation performance of meters (Figure 1B). The vibration is generated by resting the frame on one side on top of a snail-shaped cam with a vertical fall of 20 mm (amplitude) and revolving 132 times per min around its central axle [36], resulting in movement of the frame during operation, while working on slopes was evaluated by inclining the frame to a 10° angle, as prescribed by the Mexican norm NMX-O-168-SCFI-2009 for mechanical seeders [37]. Although smallholder farmers often cultivate crops on sloped terrains, inclinations over 15° are considered steep and pose a risk for tractor overturning and, therefore, are not recommended. Even two-wheel tractors with seeder implements attached become highly unstable on slopes as pronounced as this [38].

Finally, following the Mexican norm NMX-O-168-SCFI-2009 for mechanical seeders [37], the overall working efficiency of the different meters was evaluated. Details of both test-bench setups are provided in the Supplementary Materials.

2.2. Seed Meter Systems

Ten types of mechanical seed meter with different characteristics were selected from across Latin America, Sub-Saharan Africa, and Asia, representative for their availability worldwide and commonly used by farmers in developing countries. These meters generally use gravity and a rotating mechanism to separate seeds, and include horizontal and vertical plate systems, inclined plates, and two roller types including a mass-flow fluted roller commonly used for smaller grains. Representing horizontal plate systems, metering devices with 24 orifices from manufacturing companies Sembradoras del Bajio MR (SDB) in Manuel Doblado, Mexico and Fitarelli (FIT) in Aratiba, Brazil were selected (Figure 2D). Inclined plate meters with 24 seed orifices were represented by devices developed by National Agro Industries (NAT), Ludhiana, India, Sembradoras TIMS (TIMS), Texcoco, Mexico and Bangladesh Agricultural Research Institute (BARI-24) located in Joydebpur, Bangladesh (Figure 2A); the latter also provided the inclined plate system with 9 orifices (BARI-9; Figure 2B). Vertical plate meter systems were represented by a 12 seed cup plate developed for the versatile multi-crop planter by CIMMYT [16] and used in Nepal and Bangladesh (VMP-12; Figure 2C) and a second, generic system from China with 12 seed fingers (SRK; Figure 2E). Finally, the roller systems selected came from Terradonis® company in La Jarrie, France with 9 seed cells (TER; Figure 2F) and a generic sliding fluted roller used in many countries including USA, Mexico, China and Bangladesh (2BGF; Figure 2G). Detailed information on the selected meters is provided in the Supplementary Materials.

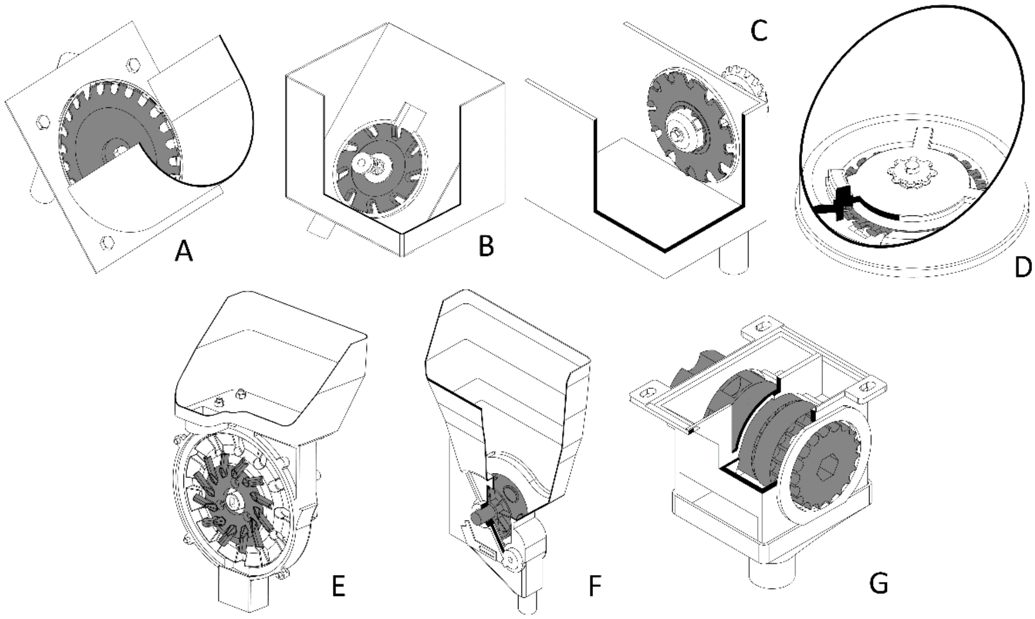

Figure 2. Model representations of the mechanical maize seed meters types evaluated, with (**A**) inclined plate systems with 24 seed orifices for the National Agro Industries, India (NAT), Sembradoras TIMS, Mexico (TIMS) and one of the Bangladesh Agricultural Research Institute meters (BARI-24), (**B**) inclined plate metering device with 9 orifices from Bangladesh (BARI-9), (**C**) vertical plate meter with 12 seed cups for the versatile multi-crop planter seed meter used in Nepal and Bangladesh (VMP-12), (**D**) horizontal plate meters with 24 orifices for the meters from Sembradoras del Bajio MR in Mexico (SDB) and Fitarelli in Brazil (FIT), (**E**) vertical plate system with 12 fingers representing a generic metering device from China (SRK), (**F**) roller system with 9 cells depicting the mechanism from Terradonis® company in France (TER), and (**G**) a generic sliding fluted roller type metering system (2BGF).

2.3. Characterization of Maize Seed Samples

As seed uniformity is of major concern for any metering mechanism, different seed samples were selected with varying size and shape assuming a differential response when passing through the meters and attempting to reflect conditions of using either graded hybrid seeds or heterogeneous open-pollinated seeds. Seed density (i.e., number of seeds per unit mass) is often provided, but companies usually have proprietary graded seeds making them difficult to compare [12], let alone comparison with ungraded farm-sourced seeds as is often the case for smallholder farmers. As such, to determine seed meter performance detailed information on input seeds is required and two parameters to describe the physical characteristics of a seed are size and shape.

Three seed types, obtained from the CIMMYT's Maize Program, were selected for evaluation: CLTHW14003 (origin HXCPV1565BD; medium round; Figure 3A), V13 (origin LXCBA1202SJ01Y; small drop-shaped; Figure 3B) and CLTHW14003 (origin HXCAHA1502RC; large flat; Figure 3C).

Figure 3. The 3 selected seed types, seed type 1—medium round (**A**), seed type 2—small drop-shaped (**B**), and seed type 3—flat and large (**C**).

To determine the size of a certain seed type, the three orthogonal dimensions (L: length, mm; W: width, mm; T: thickness, mm) of 100 random seeds per type were measured using a digital caliper with 0.1 mm precision. The general shape of a seed was determined by seed sphericity (Φ), following Equations (1) and (2) [39]:

$$D_g = (L \times W \times T)^{1/3}/100 \quad (1)$$

$$\Phi = (D_g/L) \quad (2)$$

with D_g an average measure of shape for each seed type. Furthermore, bulk density (ρ_g) was determined according to [40] using Equation (3) as it represents an easy measure to compare seed types and often readily available for commercial varieties.

$$\rho_g = m_g/V_r \quad (3)$$

where m_g is total mass of non-compacted maize seed contained in a one-liter recipient (V_r), determined with an electric scale with a 10^{-4} g precision.

Finally, for each seed type, the mass of 1000 seeds was measured 15 times and averaged for mean seed weight. To determine differences between seed types in terms of average seed shape or sphericity and average weight of 1000 seeds, the Tukey honest significant difference (HSD) test was performed using R package 3.5.0 with 95% confidence level [41].

2.4. Seed Meter Evaluations

For inclined plate meters, the working angle of the plate can be adjusted for optimal results. Because of its smooth manufacturing finish and high resemblance with the other selected inclined plate meters, a preliminary evaluation was done with the seed metering device manufactured by National Agro Industries, India (NAT) and its optimal angle was determined; other inclined plate meters were considered to behave similarly. For this evaluation, the meter was operated for one min at three angles (i.e., 40°, 45° and 50°) with respect to the horizontal plane. Deposited seeds were collected over 30 runs, at three different speeds for all three seed types. The operational speeds were set at 2.7, 4.4 and 5.7 km h^{-1} which, with a fixed virtual plant density goal of 60,000 seeds ha^{-1}, translate to a rotational velocity (revolutions per minute—RPM) of the metering plate of 9, 14.5 and 19 respectively. The optimal angle for the NAT inclined plate meter was determined at 45° and this angle was used for all inclined plate meters as it gave best results for all seed types.

Likewise, the optimal rotational speed, defined here as the maximum RPM at which a meter's main axle turns without deviating more than 5% from the theoretical value of distributed seeds, was determined. The theoretical value or performance was determined by multiplying the number of plates' orifices or seed cells by the rotational velocity and the time of operation (i.e., a seed meter using a plate with 24 seed cells, operating for 2 min at 20 RPM has a theoretical performance of 480 seeds, or a theoretical distribution rate of 240 seeds per min). Most meters came with only one seed plate, which either gave low seed cell-filling rates at any rotational speed, or a high frequency of double or triple seed allocations into the plate cells. For the latter, the recommended RPM was set at an arbitrary operating speed depending on the degree of deviations found for all seed types combined with a maximum of 50 RPM. In all other cases, the recommended RPM was selected as the RPM that approximated most the theoretically calculated metering quantity with the seed type 1.

2.4.1. Mechanical Seed Damage

Due to the mechanical nature of the evaluated seed meter devices, there is a risk of causing seed damage due to friction with or obstruction of the moving parts' seeding mechanisms. Well-designed meters are able to reduce these events to a minimum and, therefore, some manufacturers offer a set of seed plates with varying cell sizes to choose from, in an attempt to broaden the range of crop species and seed types farmers may choose to cultivate. Naturally, options will always be limited and even when the seed plate orifices of the metering mechanism are a near-perfect fit for the seed type used, seeds can be damaged. Logically, for ungraded seed this offers no immediate solution. Nonetheless, in the experiment, when multiple plates were provided, the best match with each seed type was chosen, and this was the case for the Sembradoras del Bajio (SDB) and the Fitarelli (FIT) meters which come with a variety of plates, and the Terradonis (TER) device offering rollers with different cell sizes. For other devices, only one option was available.

Following, the damage caused by passing through the seed meter was determined for each metering device by visually inspecting 10 seed samples (i.e., seeds collected for 30 s at meter exit) at the recommended RPM. Seeds were considered "damaged" when they presented visible cracks or were broken and subsequently, seed damage was determined as the percentage of damaged seed weight to total sample weight. A least significance difference (LSD) test for each seed type was performed on the resulting seed damage percentage, using a 95% confidence level [41].

2.4.2. Spatial Seed Distribution

To determine spatial seed deposit distributions, the greased-belt method, originally described by [42], was used. The rotational speed for each meter was set at the predetermined RPM. A belt section of 2.5 m was analyzed 10 times for each seed type-seed meter combination and the inter-seed distance was measured. As described in the ISO7256/1-1984 [43], the distribution of the seeds in each row was indexed as a series of acceptable (A), double (D) or failed deposits (F) as compared to the theoretical inter-seed distance (χ_{ref}). Inter-seed distances smaller than $0.5\chi_{ref}$ were considered 'doubles' and those larger than $1.5\chi_{ref}$ were considered 'failed' deposits while all others were considered 'acceptable'. A 'triple' deposit (T) was characterized by two consecutive values below $0.5\chi_{ref}$, three consecutive values or more below $0.5\chi_{ref}$ were registered as 'multiple' (M) deposits.

The theoretical value (TV) for the inter-seed distance was calculated as follows: the linear belt velocity (V_b) determined by Equation (4), accounting for the diameter of the belt's pulley (ϑ_r) and the RPM of the conveyer belt axis (RPM_{belt}), while seeds per linear meter (S_m), as a function of cells in the metering plate (P), the plate's rotational velocity (RPM_{plate}) and the linear belt velocity (V_b), was calculated using Equation (5). Finally, TV was calculated by dividing a linear meter by S_m. Constants in Equations (4) and (5) are specific dimensional factors for the test bench.

$$V_b = \vartheta_r \times \pi \times \mathrm{RPM}_{belt} \times 0.06 \quad (4)$$

$$S_m = (P \times \mathrm{RPM}_{plate})/(V_b \times 16.66) \quad (5)$$

With the measured inter-seed distances, a probability density function of expected inter-seed distances was calculated, using a Gaussian kernel density with normal reference rule. This allowed to visually detect deviations of the theoretical spatial distribution and gain insights on metering accuracy.

2.4.3. Determination of Work Efficiencies

On the second test-bench, mimicking field conditions, three identical meters were mounted as they would normally be placed on a seeder implement, either as individual or stand-alone machine components or grouped in series, which potentially influenced freedom of movement and vibration propagation. Furthermore, minor manufacturing differences between seed meters produced by the same manufacturer could be ignored in the analysis as data from the three instantaneous runs were grouped. The overall working efficiency or deposition precision was determined at the specific meters' recommended velocity. As NMX-O-168-SCFI-2009 [37] requires, two additional RPMs were evaluated at −20% and +20% of the recommended RPM, to determine the effect of operating at non-prescribed speeds. The effect of working on slopes was determined by elevating the frame from one side to a 10° angle, and finally the interference of added vibration to the frame was measured. This was performed for all but the SDB meter. For each remaining meter and seed type combination, five treatments combining speed (S), inclination (I), and vibration (V) were tested with the meters running five times for 1 min (Table 1), generating 15 data points for each treatment per meter.

Table 1. Settings for base treatment ($S_1I_0V_0$) of efficiency tests (S_1 as recommended seed plate revolutions per min—RPM).

Seed Meter	RPM(S_1)	Angle (°)	Seed Cells
NAT	20	45	24
BARI-24	20	45	24
TIMS	20	45	24
BARI-9	20	45	9
VMP-12	20	90	12
SRK	30	90	12
FIT	20	0	28 and 43
2BGF	25	N/A	6
TER	20	N/A	6

The absolute work efficiency (E_{abs}) of the meter types was calculated for each treatment as a performance rate around 100% single seeding efficiency, shown in Equation (6). Performance rates above 100% indicate the occurrence of multiple seed deposits, while below 100% indicates failed cell fillings.

$$E_{abs} = 100 - [(\text{Theoretic value} - \text{Measured value}/\text{Theoretic value}) \times 100] \quad (6)$$

After confirming normal distributions and equal variances between treatments, the Student's *t*-test was used in R 3.5.0 for comparison between treatments, using the base treatment ($S_1I_0V_0$) as the starting reference, the -20% and +20% speed treatments ($S_2I_0V_0$ and $S_3I_0V_0$ respectively), and the inclination ($S_1I_1V_0$) and vibration ($S_1I_0V_1$) treatments [41]. The relative efficiency (E_{rel}) for each seed type per meter was defined as the average performance over all treatments. Subsequently, the overall efficiency (E_{ovl}) for each meter was calculated as the average performance for all seed types.

3. Results

3.1. Characterization of Maize Seed

Seed characterization showed that each maize seed type had different dimensions. On average, the second type (i.e., drop-shaped) was not significantly different in shape to the first type (i.e., round-shaped) ($p = 0.605$), while the third type (i.e., large flat) was significantly thinner, broader and flatter ($p < 0.001$) than the other two (Table 2). The drop-shaped seeds were smallest while the round-shaped were the most uniform with minimal differences in length, width and thickness. The weight of 1000 seeds of seed types 1, 2 and 3 was significantly different with light, medium and heavy weights, respectively ($p < 0.001$). Although smaller, seed type 2 was heavier than seed type 1 but its irregular shape caused it to have lower bulk density. This might be important for seed presentation to the metering plate when seeds are compacted under their own weight; seed type 2 would be less compacted within the container.

Table 2. Characterization of maize seed types.

Parameter	Seed Type		
	1 (Medium Round)	2 (Drop-Shaped)	3 (Large Flat)
Average size (mm)			
Length	9.14	7.78	11.86
Width	7.55	6.90	8.98
Thickness	6.59	5.11	4.59
Average shape			
Sphericity	0.84	0.84	0.66
Average weight (g)			
1000 seeds	165.7	288.7	364.7
Density (g cm^{-3})			
Bulk	1.31	1.18	1.33

3.2. Seed Meter Evaluations

3.2.1. Recommended Rotational Velocity

For each meter, the recommended rotational velocity of the seed plate was determined, where a deviation higher than 5% below the theoretical performance was considered unsatisfactory. The maximum velocity that presented deviations smaller than 5% was chosen as the recommended velocity, with a maximum of 50 RPM due to high risk for damage in case of obstruction at higher RPMs. In case the maximum RPM could not be determined unambiguously, the RPMs that achieved the closest approximation to the theoretical value with seed type 1 was selected (Figure 4).

The NAT meter holds a 24-cell plate that matches seed type 1 and this shows from the distribution pattern, following theoretical distribution almost perfectly until 20 RPM. Since seed type 2 showed a high frequency of double fills (32%) and seed type 3 gave an increasingly higher failed fill rate, 20 RPM was set as the recommended velocity. Contrastingly, the BARI-24 plate did not provide a good fit, resulting in distributions above the theoretical value due to double and triple fillings for all seed types; seed type 2 presented 57% of triple cell fillings. Seed type 1 gave best results near 20 RPM, therefore this speed is recommended. The TIMS meter offered two seed plates, offering a decent fit for seed type 2 and 3 and produced overall good distributions for both seed types despite a slight overfilling, especially for higher velocities. The plate was less effective for seed type 1 producing 25% double fills. In general, the best performance was given at 20 RPM, and therefore recommended. Using the BARI-9 meter, seed type 1 presented a tendency for doubles at low RPMs (11% at 30 RPM) and dropped below 95% of its theoretical rate between 30 and 40 RPM. Seed type 3 distributed poorly and increasingly so with higher RPMs, while seed type 2 dropped just below a triple filled 95% performance at about 20 RPM; with even 58% of triple fills at 40 RPM. Since distribution at 20 RPM showed the highest consistency for all seed types, and as seeds would uncontrollably burst out of the container at higher RPMs, once again 20 RPM was set as recommended.

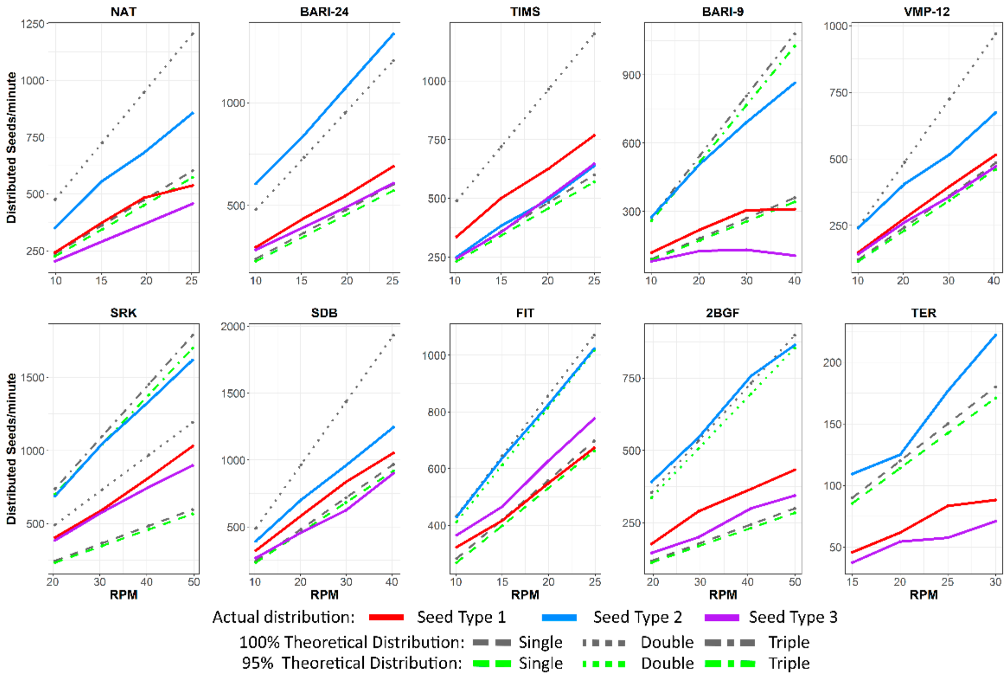

Figure 4. Effect of plate velocity (revolutions per min—RPM) for the different seed meters on actual seed distribution for the three seed types (Seed type 1—medium round, Seed type 2—small drop-shaped and Seed type 3—flat and large), compared with 100% and 95% of the theoretical distribution at three filling rates. Note more detail of the different mechanical maize seed meters given in Figure 2.

The vertical plate meter VMP-12 showed similar results to the BARI-9. Both seed type 1 and 3 behaved consistently with minimum double fillings across settings: an average 11% of doubles for seed type 1 and approximating theoretical performance for seed type 3 at 30 RPM; the absence of reduced performance at higher RPMs likely explained by failed fillings balancing out the doubles. Type 2 performed perfect double metering at 10 RPM and dropped below 95% of theoretical double filling rate at 20 RPM, hence, set as recommended for this meter too. High double (seed type 1 and 3) and triple (seed type 2) frequency was observed for the finger vertical plate meter (SRK), and distribution rates remained stable with increasing RPMs. For type 2, after 30 RPM distribution dropped below 95% theoretical triple filling, while for type 3, distribution slowly stagnated on double delivery after this point. No improvement could be attained above 30 RPM, and therefore determined as recommended velocity. The SDB meter comes with several plates to fit seed size and shape. Nonetheless, with the selected plates, seed type 1 and 2 were distributed abundantly at all RPMs surpassing theoretic values up to 30% and 60%, respectively. Type 3 reached optimal rotations at 20 RPM, subsequently marking the recommended velocity. The FIT meter had better performing plates for seed type 1, with satisfactory distribution from 15 RPM onwards, and seed type 2, maintaining a near perfect (double) distribution overall with a plate containing 43 cells instead of 28. Type 3 was distributed at above theoretical values, averaging on 13% double depositions. Lack of more decisive results suggested the recommendation of 20 RPM for this system too.

As a roller-based meter, the 2BGF can adjust to different seed sizes, but the smallest setting still allowed more than one large-sized seed of type 3 to be allocated in the available slots. Hence, all types showed multiple cell fillings, with type 2 having, on occasion, even four seeds deposited simultaneously. On average, type 1 and 3 distributions resulted in 33% and 14% double droppings, respectively. Similar to others, this meter was difficult to optimize, but to avoid jamming a maximum rotational velocity of 25 RPM was recommended. With the TER celled roller, frequent jams at the bottom of the seed container caused fails, with type 1 and 3 clearly showing unusual low performance for all RPMs (24% of failed fills on average). In contrast, the jamming did not occur with the smaller type 2, resulting in a higher than theoretical deposition rate, with 55% double fillings. Nonetheless, seed type 2 achieved a near perfect distribution rate at 20 RPM and consequently this velocity was recommended.

In summary, although most meters responded differently to different seed types and at times generated serious deviations from the theoretical distribution rate, recommended rotational velocities were suggested, frequently in close vicinity of 20 RPM, with exceptions of the 2BGF (25 RPM) and the SRK vertical plate (30 RPM).

3.2.2. Mechanical Seed Damage

The damage caused to the seed by passing through the meters at their recommended operating speed (see Table 1) showed, for seed type 1, on average 0.75% damaged seed with an LSD-value of 0.47 and with the TIMS meter damaging most (1.2%), although only the TER, BARI-9 and FIT meters produced significant lower seed damages; 0.24%, 0.13% and 0.11%, respectively (Figure 5). Seed type 2 suffered the least damage (0.41% across meters with an LSD-value of 0.41). For this seed type, SDB as the worst performer produced significantly higher damage (0.97%) compared to all the others, while the BARI-9 and TER meters caused significantly lower seed damage (0.14% and 0.12%, respectively). For type 3, similar results were found with SDB causing significantly more damage (1.65%), while the FIT and BARI-9 inflicted significantly the least damage (0.13% and 0.16%, respectively). With 0.51% damage on average and an LSD-value of 0.49, type 3 presented only slightly more damage than type 2 but with most variation among meter devices.

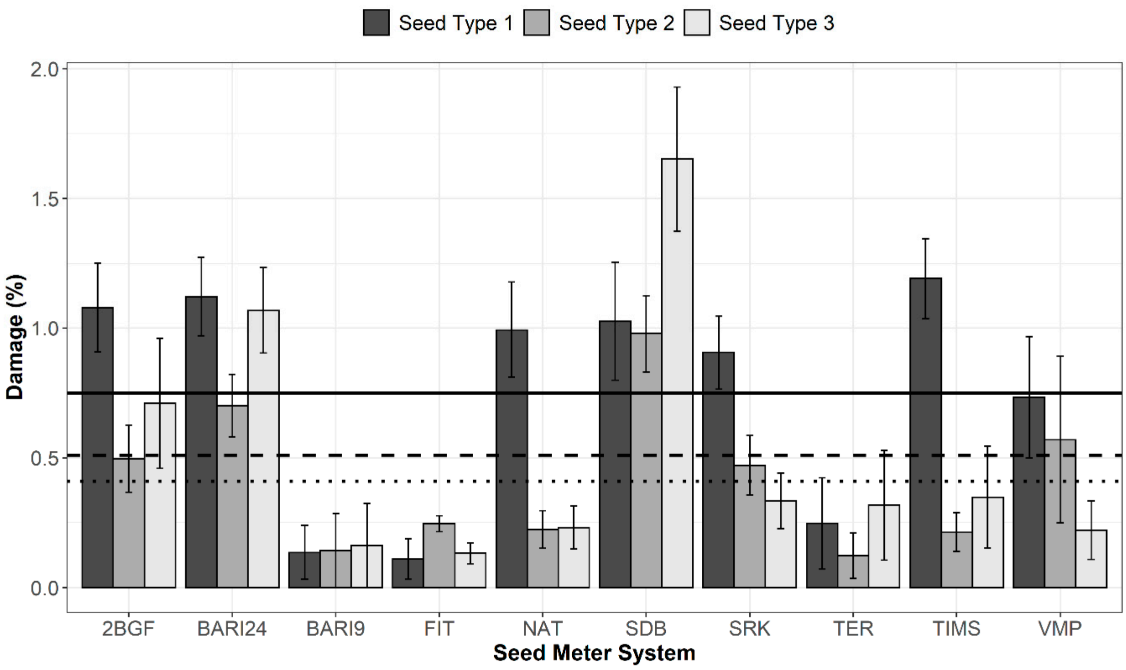

Figure 5. Mean percentage seed damage caused by the different meters for the three seed types (Seed type 1—medium round, Seed type 2—small drop-shaped and Seed type 3—flat and large) and corresponding standard errors. Solid, dotted and dashed horizontal lines show mean level of damage for seed types 1, 2 and 3, respectively.

3.2.3. Spatial Seed Distribution

Ideally, seed depositions on the soil should occur at equal distances. This implies that when measuring the distance between two consecutive seeds in one row, it approximates on average the distance determined during calibration. For example, a seeder calibrated to deposit 85,000 seeds/ha, with an inter-row configuration of 80 cm, should deposit 6.8 seeds per linear meter, which translates to an average inter-seed distance of nearly 15 cm.

Estimated probability density functions for the spatial in-row distribution of the three seed types for each meter helped detect deviations from the theoretical calibration values (Figure 6).

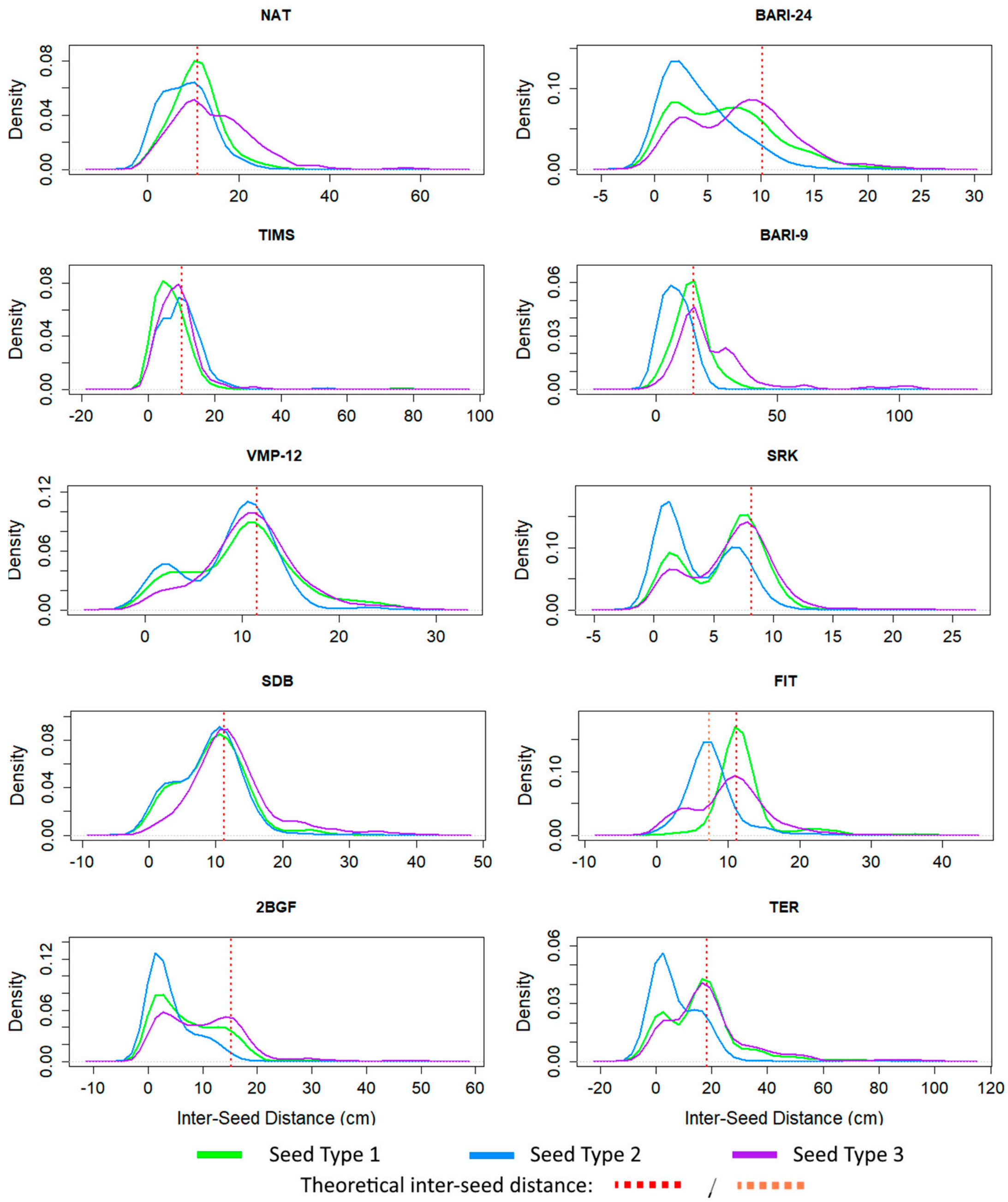

Figure 6. Probability density functions of the spatial in-row seed distances for the three seed types (Seed type 1—medium round, Seed type 2—small drop-shaped and Seed type 3—flat and large) as estimated for each seed meter. The vertical dotted line indicating theoretical inter-seed distance per meter, with the second orange dotted line representing this value for a second plate used with the FIT meter for seed type 2.

A bell-shaped curve around the target value indicates a good and uniform distribution estimate with a high probability of acceptable depositions, while skewed or double bells indicate the likeliness of undesired doubles or failed fillings occurring. Overlap of the density curves for different seed types indicate consistent estimated precision for spatial distribution across seed types. Note that for the FIT meter, two different plates were used, resulting into two vertical expected values and two corresponding bell-shaped curves.

The NAT, TIMS, SDB and VMP-12 meters scored very well with 65.3%, 66%, 75% and 74.6% of acceptable depositions, respectively, averaged for all seed types (Table 3). Only the FIT produced a better average result (i.e., 84% of acceptable depositions) due to usage of two different plates. It appears that double, triple or multiple depositions occur more frequently than failed depositions, as for the less precise meters the curves tend to be skewed towards the left indicating a higher likeliness of short inter-seed distances. Finally, note that failed and multiple deposits could balance each other out in the presented analysis.

Table 3. Spatial deposition precision of seed meters for selected seed types.

Seed Meter	Seed Type	χ_{ref} (cm)	Depositions (%)				
			Acceptable	Failed	Double	Triple	Multiple
NAT	1	10.9	77	9	14	-	-
	2		69	6	19	4	2
	3		50	37	12	1	-
BARI-24	1	10.1	58	3	25	10	4
	2		32	-	10	17	41
	3		67	4	19	7	3
TIMS	1	10	66	4	18	7	5
	2		61	13	14	7	5
	3		71	7	14	6	2
BARI-9	1	15.5	74	9	11	2	4
	2		51	-	29	13	7
	3		57	37	6		-
VMP-12	1	11.5	71	7	18	3	1
	2		74	1	22	3	-
	3		79	8	10	3	-
SRK	1	8.2	68	-	25	5	2
	2		41	-	21	25	13
	3		72	2	21	4	1
SDB	1	11.2	73	4	12	7	4
	2		73	2	18	7	-
	3		79	12	9	-	-
FIT	1	11.2	94	6	-	-	-
	2	7.3	85	8	6	1	-
	3	11.2	73	8	14	3	2
2BGF	1	15.2	45	-	15	20	20
	2		21	-	4	10	65
	3		57	-	17	10	16
TER	1	18.2	60	12	21	7	-
	2		37	1	12	28	22
	3		62	17	15	3	3

3.2.4. Determination of Work Efficiencies

The absolute efficiency for each treatment (i.e., combination of speed, inclination and vibration) was determined together with the relative efficiency for each meter per seed type and subsequently an overall work efficiency per meter was established (Table 4). Comparisons were made only between treatments for one particular meter and seed type, between those that differ only in one parameter value (i.e., $S_1I_0V_0$ with $S_2I_0V_0$ and $S_3I_0V_0$, $S_1I_0V_0$ with $S_1I_1V_0$ and $S_1I_0V_1$), identifying significant differences

($p < 0.05$) with the base treatment for each seed type (marked with different letter superscripts in Table 4).

Table 4. Absolute, relative and overall efficiencies per seed meter device.

Seed Type	Treatment	Absolute Efficiency (E_{abs})								
		NAT	**BARI-24**	**TIMS**	**BARI-9**	**VMP-12**	**SRK**	**FIT**	**2BGF**	**TER**
1	$S_1I_0V_0$	95.5 ^{a}	119 ^{a}	64.2 ^{a}	88.2 ^{a}	267.2 ^{a}	133.1 ^{a}	90.9 ^{a}	373.9 ^{a}	115.8 ^{a}
	$S_2I_0V_0$	92.0 ^{b}	116.5 ^{a}	62.9 ^{a}	92.5 ^{a}	265.6 ^{a}	134.6 ^{a}	88.4 ^{b}	371.6 ^{a}	117.3 ^{a}
	$S_3I_0V_0$	94.4 ^{a}	124.6 ^{a}	50.2 ^{b}	94.4 ^{b}	260.9 ^{a}	173.9 ^{b}	95.0 ^{c}	379.8 ^{a}	115.6 ^{a}
	$S_1I_1V_0$	94.6 ^{a}	119.9 ^{a}	55.4 ^{c}	94.9 ^{a}	261.1 ^{a}	135.1 ^{a}	90.2 ^{a}	367.8 ^{a}	115.3 ^{a}
	$S_1I_0V_1$	73.07 ^{c}	106.43 ^{a}	45.86 ^{d}	89.56 ^{a}	155.67 ^{b}	110.8 ^{c}	89.8 ^{a}	366.5 ^{a}	123.7 ^{b}
	E_{rel} *	89.9	117.3	55.7	91.9	242.1	137.5	90.9	371.9	117.6
2	$S_1I_0V_0$	112.7 ^{a}	231.01 ^{a}	211.7 ^{a}	208.5 ^{a}	271.7 ^{a}	238.6 ^{a}	97.0 ^{a}	374.3 ^{a}	164.1 ^{a}
	$S_2I_0V_0$	107.4 ^{b}	207.6 ^{a}	209.9 ^{a}	181.1 ^{b}	288.2 ^{a}	227.7 ^{a}	96.6 ^{a}	376.4 ^{a}	157.5 ^{b}
	$S_3I_0V_0$	109.4 ^{c}	222.5 ^{a}	212.9 ^{a}	210.4 ^{a}	194.4 ^{b}	313.8 ^{a}	96.5 ^{a}	403.2 ^{b}	168.1 ^{a}
	$S_1I_1V_0$	109.4 ^{d}	205.5 ^{a}	204.3 ^{a}	201.1 ^{a}	187.0 ^{c}	163.2 ^{b}	96.4 ^{a}	391.6 ^{c}	167.2 ^{a}
	$S_1I_0V_1$	128.5 ^{e}	178.8 ^{b}	152.1 ^{b}	183.4 ^{c}	67.9 ^{d}	173.2 ^{c}	97.2 ^{a}	404.5 ^{d}	163.4 ^{a}
	E_{rel} *	113.5	209.1	198.2	196.9	201.8	223.3	96.7	390.0	164.1
3	$S_1I_0V_0$	29.3 ^{a}	96.9 ^{a}	100.9 ^{a}	29.9 ^{a}	186.2 ^{a}	120.6 ^{a}	101.3 ^{a}	267.1 ^{a}	93.9 ^{a}
	$S_2I_0V_0$	27.2 ^{a}	92.0 ^{a}	101.0 ^{a}	22.0 ^{b}	178.9 ^{a}	126.0 ^{a}	105.6 ^{b}	256.4 ^{b}	80.3 ^{b}
	$S_3I_0V_0$	32.7 ^{b}	108.4 ^{b}	98.2 ^{b}	34.7 ^{a}	211.6 ^{b}	163.0 ^{b}	111.0 ^{c}	266.6 ^{a}	90.1 ^{c}
	$S_1I_1V_0$	26.9 ^{a}	100.9 ^{a}	90.8 ^{a}	37.7 ^{a}	204.9 ^{a}	129.6 ^{c}	105.6 ^{d}	256.8 ^{c}	92.0 ^{a}
	$S_1I_0V_1$	46.3 ^{c}	100.1 ^{c}	65.3 ^{c}	40.8 ^{a}	121.9 ^{c}	101.4 ^{a}	102.8 ^{e}	257.9 ^{d}	99.4 ^{a}
	E_{rel} *	32.5	99.7	91.3	33.0	180.7	128.1	105.3	261.0	91.1
	E_{ovl} *	78.6	142.0	115.1	107.3	208.2	163.0	97.6	340.9	124.3

* E_{rel} and E_{ovl} indicate relative and overall efficiencies, $^{a, b, c, d, e}$ indicate significant differences between treatment with different letter superscripts, for each seed meter and seed type.

Measured seed distributions showed that meters often behave significantly different under altering conditions and with different seed types, and that the theoretical distribution value is not likely to be reached (data not shown). The resulting efficiencies for the NAT meter illustrate this; for seed type 1 and 3, the inclination treatment ($S_1I_1V_0$) showed no significant difference from the base treatment ($S_1I_0V_0$) (p = 0.99 and 0.64, respectively), but for type 2 a significant difference was found (p = 0.03). For type 3, significant differences were found between the −20% and +20% speed treatments (p = 0.002 for $S_2I_0V_0$ − $S_3I_0V_0$). For all seed types, the added vibration was generating the largest impact. The non-vibration treatments for type 1 showed an absolute efficiency above 90% indicating an almost perfect fill rate, while the vibration treatment drops below 75%. The relative efficiency of the NAT meter for type 1 averaged out on 89.9% (i.e., 1 in 10 cells remaining unfilled). The E_{rel} for type 2 showed deviating only 13.5 % from perfect performance, due to multiple fillings producing a slightly rich seed deposition instead of failed metering. For type 3, however, poor relative efficiency was achieved (32.5%). In this case, the plate cells seemed to be too small, resulting in failed fillings and unsatisfactory distribution. Hence, despite the good performance of seed type 1 and 2, the overall efficiency E_{ovl} of the NAT meter decreased to 78.6% due to the poor performance of type 3.

Calculated efficiencies for the remaining meters gave comparable results, but also revealed some meters to deliver quite constant precision over all treatments with a particular seed type, like BARI-24 for seed type 1 and FIT for type 2. The 2BGF also showed consistent behavior for type 1, but with E_{rel} of 371.9 presented an undesirable superfluous distribution (i.e., close to four seeds per cell). TIMS and BARI-24 meters performed, for seed type, consistently near double filling rate, excluding the vibration treatment. Finally, BARI-9 and TER meters delivered good performance for three of five treatments; the first presenting occasional failed fills and the latter one producing doubles.

4. Discussion

To our knowledge, this study is the first to evaluate diverse maize seed meters collected from Latin America, Sub-Saharan Africa, and Asia. Meters were chosen as representative models for mechanical systems used by smallholder farmers, including horizontal, vertical and, inclined plate meters, and roller systems. Experiments were performed to gain insights in the overall performance and efficiency. Three seed types were chosen representing common maize seeds, including a large flat-shaped, medium-sized round, and small-sized drop-shaped seeds, the latter representing non-commercial homebred varieties. Preliminary trials with the inclined plate meters showed that the angle of the plate influences distribution, with fewer seeds distributed at smaller angles and higher speeds. We concluded that, without prior knowledge of optimal working angle, 45° was generally a fair choice. However, depending on seed and plate cell sizes, precision could be improved by decreasing the angle compared to this intermediate position.

The recommended rotational velocity for each meter was determined, although as the chosen plates or rollers did not accommodate all seed types adequately, often an optimal RPM remained unclear. Therefore, 20 RPM was chosen for most meters as this velocity achieved closest approximation to the theoretical value with seed type 1, the most uniform type. Exceptions were the SRK vertical plate meter and 2BGF roller for which 30 and 25 RPMs were recommended, respectively. Rotational speeds above 30 RPM resulted frequently in a fast decline in meter performance, as signaled by [5]. It is important to note that meters using seed plates with a higher number of seed cells or plate orifices would in practice be able to operate at lower speeds to achieve the same seeding rate compared to seed plates with fewer cells. It is clear that this can produce a practical advantage, especially at higher tractor operating speeds. Furthermore, depending on the seed type, many meters produced near perfect double or triple seeding rates. Such distributions could be preferred over a failing meter, especially when seed varieties or mixtures are used with lower germination. Indeed, in many traditional maize systems, homebred seeds are planted at much higher rates than recommended to ensure optimal plant establishment [44].

Seed singulation was examined, which is important when seed is expensive or scarce. No seed meter was expected to perform perfectly, but large deviations are undesired. When the primary objective of seeding is for production, understandably, a low increase in double deposits is preferred over a higher fail rate. Beware however, that depending on the methodology used, failed and multiple deposits can balance each other out. In any case, our results suggest that a good match between plates and seed types is essential and meters with a variety of plates or size-adjustable devices are likely to remain the preferred choice offering more flexibility. The ability to work with ungraded seeds and a limited set of seed plates is often suggested as an advantage of pneumatic seed meter systems [5], however studies do report that air flow meters often do not perform adequately with irregular shaped seeds [45,46] and when using seed mixtures often only the larger or smaller seeds are picked up depending on plate orifices' size in combination with air-suction/blowing mechanisms [23,47,48]. This explains once more that for a variety of seeds, in relation to low-tech reliability, mechanical seed meters remain the preferred choice for smallholder farmers.

In addition to distribution or singulation ability, the damage caused to the seeds was also investigated, as damaged seeds reaching the soil represent a net loss. Results revealed that the FIT and BARI-9 devices were the least damaging, while SDB and BARI-24 presented more damaged seeds. Nevertheless, we found for all seed meters that seed damage was very low (i.e., below 2% of total seed weight) and all meters passed the Mexican standard comfortably [37]. These results are in line with earlier studies where in general low damage rates are found [23,46], with an exception for dicots seed where splitting often results into damage rates above 10% [5,49]. Once more, pneumatic seeders are proposed to further reduce seed damage as fewer moving parts are assumed to produce friction with the grains [45,46], and while on occasion successful in doing so [50], seed damage is often not reported on [26,27,33]. Yet so, the potential benefits would not outweigh increased acquisition and maintenance costs for small-scale farm operations [25]. Interestingly, it was the medium sized seed type 1 that presented most damage on average, and not the larger seed type 3 as is generally expected with mechanical seed meters [5]. Note that seed damage was evaluated only at the recommended RPM determined for each seed meter as described above. Although not specifically evaluated, higher speeds would likely result in more seed damage, which in turn reaffirms the rationale behind the methodology used to define the recommended RPM as an upper limit of acceptable performance seed meter velocity.

Furthermore, the meters' ability to deposit seeds at uniform intra-row distances, essential for optimizing field plant density, was investigated on a test-bench isolating the variability originating from the meters instead of the whole seeder delivery system. Results clearly indicate a high probability of double and triple deposits, with all meters presenting below perfect spatial distribution curve estimates. Instead of a bell-shaped probability density function indicating high likeliness of equidistant seed distribution, often a skewed or double curvilinear pattern was found. The FIT system gained the upper hand here as plates could be adjusted to seed size. The VMP-12 and SDB followed with less than 25% non-acceptable depositions. Worst performers were the TER, SRK and 2BGF due to difficulties in compensating for seed size. High double and triple depositions occurrences indicate that single seed deposit regimes might be a technological limitation for mechanical meters. Several studies report this as being an issue, but fail to isolate the meter performance from the whole seeder or seed-delivery mechanisms under review [29,30,32]. This underlines the value of the presented meter assessment methodology as it confirms the importance of the seed metering system over the system that delivers the seed to the soil, as was already alluded to by [23].

Finally, the efficiency of each meter was calculated during variable conditions using the different seed types. Treatments included working at an angle to simulate sloped terrain, adding vibration to simulate terrain roughness, and working at suboptimal speeds. These results confirmed the FIT and the BARI-9 meters as the best-bet performers, the former with minimal failed deposits and the latter with a slightly higher than theoretical distribution rate. Nonetheless, results depended largely on seed type, and different results can be expected when seed types are altered, or new types are added. In terms of absolute efficiencies, best results were found for the BARI-24 and TIMS meters, each working at near-perfect performance with the larger seed type 3 at the recommended RPM. The BARI-24 system appeared to benefit from the added vibration which accommodated seeds better in the plate, while the opposite was found for the TIMS device where the vibration seemed to disturb cell filling. On several occasions, this effect of vibration seems to aid larger seeds accommodate better in the plate cells (i.e., NAT, BARI-9 and TER meter for seed type 3), while for the intermediate-sized seed type this seems to cause more disturbance (i.e., VMP-12 and SRK).

5. Conclusions

Considering calculated overall efficiencies, the FIT meter arises as the best option, likely aided by the fact that several plates were available allowing selection of seed plates per seed type. In the absence of a variety of plates/rollers, the BARI-9 inclined plate meter seemed to be most successful followed closely by the TIMS inclined plate meter. These overall efficiencies give an indication of what more versatile seed meters could be, although for specific conditions one should consider the absolute efficiency values of each meter in addition to the relative efficiencies. With this, the evaluation of the metering systems, mimicking smallholder farm conditions in developing countries, was usefully concluded and a low-cost and easily replicable methodology was developed, offering a firm baseline for continued research where additional devices and a wide variety of seed types or mixtures can be included.

It is ultimately important to point out that the working efficiencies detailed in this study reflect the performance of the individual seed meter devices. When mounted on a seeder implement and attached to a power source, operating ground speed, adequate seeder calibration and chosen seed train configurations will all influence the precision of seed distribution and crop establishment. The insights gained here, however, provide a critical starting point to optimize seeding quality during the research and engineering stage of seed meter development, prior to and as a complement to field testing with complete equipment units and power sources.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4395/10/8/1091/s1, Figure S1: Schematic representation of the fixed-frame test-bench, Figure S2: Bridge set up at CENEMA with steps for adding an angle to the structure and a set of 3 seed meters mounted on a fixed frame during the trails, Figure S3: Schematic of the vibration generation mechanism of the test-bench, Figure S4: The National Agro Industries inclined plate seed meter, Figure S5: The BARI 24-cell inclined plate seed meter, Figure S6: Sembradoras TIMS inclined plate seed meter, Figure S7: The BARI -9-cell inclined plate seed meter, Figure S8: VMP-12 vertical plate seed meter, Figure S9: Finger vertical plate seed meter system, Figure S10: Close up of seed drop position adjustment mechanism of the finger vertical seed meter system, Figure S11: Sembradoras del Bajio horizontal Plate Seed meter system, Figure S12; Fitarelli horizontal plate seed meter system, Figure S13: 2BGF sliding fluted roller seed meter system, Figure S14: The Terradonis celled roller seed meter system.

Author Contributions: Conceptualization, J.V.L and T.J.K.; methodology, J.V.L. and J.A.L.-G.; investigation, J.V.L. and J.A.L.-G.; resources, J.V.L., T.J.K., and B.G.; writing—original draft preparation, J.V.L and J.T.; writing—review and editing, J.V.L., J.T., T.J.K. and B.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was implemented by CIMMYT in collaboration with the Syngenta Foundation for Sustainable Agriculture (SFSA), the Mexican Centro Nacional de Estandarización de Maquinaria Agrícola (CENEMA-INIFAP) and as part of the projects MasAgro Productor, the Cereal Systems Initiative for South Asia (CSISA), and the CGIAR Research Program Maize, made possible with the generous support of the government of Mexico through SADER (Secretaría de Agrícultura y Desarrollo Rural), the Bill and Melinda Gates Foundation, and the United States Agency for International Development (USAID)/Bangladesh. The contents and opinions expressed herein are those of the author(s) and do not necessarily reflect the views of USAID or the United States Government, BMGF, SFSA, the government of Mexico, and shall not be used for advertising or product endorsement purposes.

Acknowledgments: The authors thank G. Martinez, Illescas Salvador, S., Cruz Gallardo R., F. Baudron, Mir Matin and CIMMYT colleagues that provided the necessary support.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Finch-Savage, W.E.; Bassel, G.W. Seed vigour and crop establishment: Extending performance beyond adaptation. *J. Exp. Bot.* **2016**, *67*, 567–591. [CrossRef] [PubMed]
2. Kepner, R.A.; Bainer, R.; Barger, E.L. *Principles of Farm Machinery*, 3rd ed.; AVI Publishing Company Inc.: Westport, CT, USA, 1978; p. 527.
3. Srivastava, A.K.; Goering, C.E.; Rohrbach, R.P.; Buckmaster, D.R. Crop Planting. In *Engineering Principles of Agricultural Machines*, 2nd ed.; Srivastava, A.K., Goering, C.E., Rohrbach, R.P., Eds.; ASABE: St. Joseph, MI, USA, 2006; pp. 231–268.
4. Wankhade, C.; Kotwal, M.R. A review paper on various seed sowing metering devices. *Int. J. Pure Appl. Res. Eng. Technol.* **2014**, *2*, 429–435.
5. Murray, J.R.; Tullberg, J.N.; Basnet, B.B. *Planters and their Components: Types, Attributes, Functional Requirements, Classification and Description*; ACIAR Monograph 121; Australian Centre for International Agricultural Research: Canberra, Australia, 2006; Available online: https://ageconsearch.umn.edu/bitstream/114069/2/121.pdf (accessed on 26 March 2020).
6. Mohammed, S.; Blaser, B.C.; Stewart, B.A. Planting Geometry and Plant Population Affect Dryland Maize Grain Yield and Harvest Index. *J. Crop. Improv.* **2012**, *26*, 130–139. [CrossRef]
7. Timsina, J.; Jat, M.L.; Majumdar, K. Rice-maize systems of South Asia: Current status, future prospects and research priorities for nutrient management. *Plant Soil* **2010**, *335*, 65–82. [CrossRef]
8. Timsina, J.; Buresh, R.J.; Dobermann, A.; Dixon, J. *Rice-Maize Systems in Asia: Current Situation and Potential*; CIMMYT. IRRI: Los Baños, Phillipines, 2011; p. 235.
9. Jahan, M.A.H.S.; Sen, R.; Ishtiaque, S.; Choudhury, A.K.; Akhter, S.; Ahmed, F.; Biswas, J.C.; Manirruzaman, M.; Miah, M.M.; Rahman, M.M.; et al. Optimizing sowing window for wheat cultivation in Bangladesh using CERES-wheat crop simulation model. *Agric. Ecosyst. Environ.* **2018**, *258*, 23–29. [CrossRef]
10. He, J.; Zhang, Z.Q.; Li, H.W.; Wang, Q.J. Development of small/medium size no-till and minimum-till seeders in Asia: A review. *Int. J. Agric. Biol. Eng.* **2014**, *7*, 1–12.
11. Johansen, C.; Haque, M.E.; Bell, R.W.; Thierfelder, C.; Esdaile, R.J. Conservation agriculture for small holder rainfed farming: Opportunities and constraints of new mechanized seeding systems. *Field Crop. Res.* **2012**, *132*, 18–32. [CrossRef]

12. Koller, A.; Wan, Y.; Miller, E.; Weckler, P.; Taylor, R.K. Test method for precision seed singulation systems. *Trans. ASABE* **2014**, *57*, 1283–1290. [CrossRef]
13. Oduma, O.; Ede, J.E.; Igwe, J.E. Development and Performance Evaluation of a Manually Operated Cowpea Precision Planter. *Int. J. Eng. Technol.* **2014**, *4*, 693–699.
14. Mahl, D.; Furlani, C.E.; Gamero, C.A. Efficiency of pneumatic and horizontal perforated disk meter mechanism in corn no-tillage seeders in soil with different mobilization reports. *Engenharia Agrícola* **2008**, *28*, 535–542. [CrossRef]
15. Qi, B.; Zhang, D.; Liu, Q.; Yang, L.; Shi, S.; Cui, T. Design and experiment of cleaning performance in a centralized pneumatic metering device for maize. *Trans. Chin. Soc. Agric. Eng.* **2015**, *31*, 20–27.
16. Haque, M.E.; Bell, R.W.; Islam, A.K.M.; Sayre, K.; Hossain, M.M. Versatile Multi-Crop Planter for Two-wheel Tractors: An Innovative Option for Smallholders. In Proceedings of the 5th World Congress of Conservation Agriculture incorporating 3rd Farming Systems Design Conference, Brisbane, Australia, 26–29 September 2011; Gilkes, R.J., Prakongkep, N., Eds.; pp. 102–103.
17. Hossen, M.; Musabbir, A.; Hossain, M.; Hasan, M.; Islam, M. Improvement of the Seed Metering Device of Power Tiller Operated Zero Till Drill. *Prog. Agric.* **2013**, *24*, 203–210. [CrossRef]
18. Krupnik, T.J.; Santos Valle, S.; Hossain, I.; Gathala, M.K.; Justice, S.E.; McDonald, A.J. *Made in Bangladesh: Scale-Appropriate Machinery for Agricultural Resource Conservation*; International Maize and Wheat Improvement Center: Mexico City, Mexico, 2013.
19. Soyoye, B.O.; Ademosun, O.C.; Olu-Ojo, E.O. Development of a manually operated vertical seed-plate maize planter. *Agric. Eng. Int. CIGR J.* **2016**, *18*, 70–80.
20. Yin, X.; Yang, L.; Zhang, D.; Cui, T.; Han, D.; Zhang, T.; Yu, Y. Design and experiment of balance and low-loss air allotter in air pressure maize precision planter. *Trans. Chin. Soc. Agric. Eng.* **2016**, *32*, 9–17.
21. Lowder, S.K.; Skoet, J.; Raney, T. The Number, Size, and Distribution of Farms, Smallholder Farms, and Family Farms Worldwide. *World Dev.* **2016**, *87*, 16–29. [CrossRef]
22. Almekinders, C.J.M.; Louwaars, N.P. The Importance of the Farmers' Seed Systems in a Functional National Seed Sector. *J. New Seeds* **2002**, *4*, 15–33. [CrossRef]
23. Babeir, A.S. Evaluation of the Seed Metering System of an Airseeder. Master's Thesis, Iowa State University, Ames, IA, USA, 1982.
24. Van Loon, J.; Speratti, A.; Gabarra, L.; Govaerts, B. Precision for Smallholder Farmers: A Small-Scale-Tailored Variable Rate Fertilizer Application Kit. *Agriculture* **2018**, *8*, 48. [CrossRef]
25. International Rice Research Institute. Small Farm Equipment for Developing Countries. In Proceedings of the International Conference on Small Farm Equipment for Developing Countries: Past Experiences and Future Priorities, Los Baños, Philippines, 2–6 September 1986; International Rice Research Institute: Los Baños, Philippines, 1986.
26. Liu, Q.; Cui, T.; Zhang, D.; Yang, L.; Wang, Y.; He, X.; Wang, M. Design and experimental study of seed precise delivery mechanism for high-speed maize planter. *Int. J. Agric. Biol. Eng.* **2018**, *11*, 61–66. [CrossRef]
27. Miller, E.A.; Rascon, J.; Koller, A.; Porter, W.M.; Taylor, R.K.; Raun, W.R.; Kochenower, R. Evaluation of Corn Seed Vacuum Metering Systems. In Proceedings of the American Society of Agricultural and Biological Engineers Annual International Meeting 2012, Dallas, TX, USA, 29 July–1 August 2012; ASABE: St. Joseph, MI, USA, 2012; Volume 1, pp. 815–825.
28. Kumar, D.; Tripathi, A. Development and performance evaluation of a manually operated cowpea thresher. *Int. J. Curr. Microbiol. Appl. Sci.* **2017**, *6*, 2984–2996. [CrossRef]
29. Kocher, M.F.; Coleman, J.M.; Smith, J.A.; Kachman, S.D. Corn Seed Spacing Uniformity as Affected by Seed Tube Condition. *Appl. Eng. Agric.* **2011**, *27*, 177–183. [CrossRef]
30. López Gómez, J.A.; Van Loon, J. Agrotechnical evaluation of manual implements for corn planting. *Rev. Mex. Cienc. Agric.* **2018**, *21*, 4258–4269.
31. Panning, J.W.; Kocher, M.F.; Smith, J.A.; Kachman, S.D. Laboratory and field testing of seed spacing uniformity for sugarbeet planters. *Appl. Eng. Agric.* **2000**, *16*, 7–13. [CrossRef]
32. dos Reis, Â.V.; Forcellini, F.A. Functional analysis in the evaluation of four concepts of planters. *Ciência Rural* **2002**, *32*, 969–975. [CrossRef]
33. Li, Y.; Yan, B.; Yu, Y.; He, X.; Liu, Q.; Liang, Z.; Yin, X.; Cui, T.; Zhang, D. Global overview of research progress and development of precision maize planters. *Int. J. Agric. Biol. Eng.* **2016**, *9*, 9–26.

34. Önal, O.; Önal, I. Development of a computerized measurement system for in-row seed spacing accuracy. *Turk. J. Agric. For.* **2009**, *33*, 99–109.
35. He, X.; Ding, Y.; Zhang, D.; Yang, L.; Cui, T.; Wei, J.; Liu, Q.; Yan, B.; Zhao, D. Design and evaluation of PID electronic control system for seed meters for maize precision planting. *Trans. Chin. Soc. Agric. Eng.* **2017**, *33*, 28–33.
36. Secretaría de Economía. *Tractores, Implementos Agrícolas-Sembradoras Neumáticas De Precisión-Especificaciones y Método De Prueba*; NMX-O-222-SCFI-2004; Secretaría de Economía: Ciudad de México, Mexico, 2004.
37. Secretaría de Economía. *Tractores, Implementos, Sembradoras Unitarias, Fertilizadoras Accionadas Mecánicamente, Con Dosificador De Semilla De Disco Y Métodos De Prueba En La Maquinaria Agrícola*; NMX-0-168-SCFI-2009; Secretaría de Economía: Ciudad de México, Mexico, 2009.
38. Abubakar, M.S.; Ahmad, D.; Akande, F.B. A Review of Farm Tractor Overturning Accidents and Safety. *Pertanika J. Sci. Technol.* **2010**, *18*, 377–385.
39. Mohsenin, N.N. *Physical Properties of Plant and Animal Materials*, 2nd ed.; Gordon and Breach Science Publisher: New York, NY, USA, 1986; p. 891.
40. Tarighi, J.; Mahmoudi, A.; Rad, M.K. Moisture-dependent engineering properties of sunflower (var. Armaviriski). *Aust. J. Agric. Eng.* **2011**, *2*, 40–44.
41. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2018; Available online: https://www.r-project.org (accessed on 12 March 2020).
42. Smith, J.A.; Palm, K.L.; Yonts, C.D.; Wilson, R.G. *Seed Spacing Accuracy of Sugarbeet Planters*; No. 91-1551; ASAE: St. Joseph, MI, USA, 1991.
43. *Sowing Equipment—Test methods—Part I: Single Seed Drills (Precision Drills)*; 7256-1. International Organization for Standardizations: Geneva, Switzerland, 1984. Available online: https://www.iso.org/standard/13910.html (accessed on 18 February 2020).
44. Anderson, W.K. Optimizing plant population, crop emergence and establishment. In *Explore On-Farm: On-Farm Trials for Adapting and Adopting Good Agricultural Practices*; Rawson, H.M., Rawson, A., Gabrielli, A., Eds.; FAO: Rome, Italy, 2003; p. 84.
45. Shi, S.; Zhang, D.; Yang, L.; Cui, T.; Zhang, R.; Yin, X. Design and experiment of pneumatic maize precision seed-metering device with combined holes. *Trans. Chin. Soc. Agric. Eng.* **2014**, *30*, 10–18.
46. Hunt, D.; Wilson, D. Seeding Machines. In *Farm Power and Machinery Management*, 11th ed.; Waveland Press, Inc.: Long Grove, IL, USA, 2016; pp. 113–124.
47. Liu, J.; Cui, T.; Zhang, D.; Huang, S.; Shi, S. Experimental study on pressure of air-blowing precision seed-metering device. *Trans. Chin. Soc. Agric. Eng.* **2011**, *27*, 18–22.
48. Yang, L.; Shi, S.; Cui, T.; Zhang, D.; Gao, N. Air-suction corn precision metering device with mechanical supporting plate to assist carrying seed. *Trans. Chin. Soc. Agric. Mach.* **2012**, *43*, 48–53.
49. Nave, W.R.; Paulsen, M.R. Soybean seed quality as affected by planter meters. *Trans. ASAE* **1979**, *22*, 739–745. [CrossRef]
50. Ibrahim, E.J.; Liao, Q.X.; Wang, L.; Liao, Y.T.; Yao, L. Design and experiment of multi-row pneumatic precision metering device for rapeseed. *Int. J. Agric. Biol. Eng.* **2018**, *11*, 116–123.