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Research Article

Electrical Conductivity Estimates of Normal Germination Percentages of Seed Lots Belong to The Same and Different Cultivars in Cabbage

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Abstract: Electrical conductivity testing is a widely used, rapid, and non-destructive method to assess seed vigor and predict germination potential. This study investigated the potential of electrical conductivity to predict normal germination percentages in cabbage (*Brassica oleracea* L.) seed lots of varying genetic backgrounds and storage histories. A total of 30 seed lots produced between 2006 and 2024, with moisture contents ranging from 6.1% to 7.3%, were analysed. Normal germination percentages varied from 0% to 99%, reflecting differences in seed age and storage conditions. Electrical conductivity values were consistently higher in seed lots with low normal germination and lower in lots with high normal germination across single-cultivar, multiple-cultivar, and hybrid seed groups. Boxplot analyses showed visible differences in normal germination and electrical conductivity distributions, but Kruskal–Wallis tests indicated no significant group-wise differences. Strong negative correlations were observed between electrical conductivity and normal germination in all groups (Spearman $\rho = -0.82$, $P < 0.001$), with linear regression explaining 84% of normal germination variation ($NG = -0.15 \times EC + 120.4$, $R^2 = 0.84$, $P < 0.001$). Electrical conductivity thresholds corresponding to the minimum commercial germination standard of 75% were estimated between 280 and 322 µS cm^{-1} g^{-1}, suggesting that electrical conductivity measurement is a reliable predictor of cabbage seed quality, independent of cultivar type or seed lot origin.

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1. Introduction

Standard laboratory germination tests take several days to complete, with duration varying between species. For cabbage (*Brassica oleracea* L var. capitata), final counts of normal seedlings are made after 10 days (ISTA, 2020). Shorter testing times would be helpful to seed producers who have to make quick decisions about seed sale for individual seed lots during pre and post storage management. Moreover, germination testing a large number of seed lots requires considerable work. Therefore, methods that predict germinability in a shorter time i.e. about 24 h are potentially advantageous for seed producers/salers.

Several approaches have aimed to estimate differences in normal germination more quickly than a full time germination test period. These include assessment of leakage from seeds using electrical conductivity measurement (Steere et al., 1981; Mirdad et al., 2006; Matthews et al., 2009; Mavi et al., 2016). The electrical conductivity (EC) test measures the amount of electrolytes that leak from seed lots into the soaking water. Originally developed as a seed vigor assessment, it provides an indication of the field emergence potential of seed lots with high germination capacity. The EC test has been standardized by ISTA for several species, including radish and four grain legumes-garden peas, Phaseolus beans, soybeans and chickpeas (ISTA, 2020). Because legumes have large cotyledons, they are considered well-suited for the EC test in predicting field emergence potential (Matthews and Powell, 2006).

Measurements of electrolyte leakage into soak water from bulk seed samples have been linked to standard laboratory germination assessments in artificially aged seeds of various species. Studies have shown that seeds failing to germinate or producing abnormal seedlings exhibited higher EC values in cabbage and cauliflower (Mirdad et al., 2006). Similarly, commercial seed lots with greater proportions of seeds that either failed to develop a radicle or produced abnormal seedlings displayed elevated EC levels in bulk tests across several species, including cabbage (Demir et al., 2008), oilseed rape (Wagner et al., 2012), radish (Demir et al., 2012), garden cress (Ozden et al., 2017), and native species (Marin et al., 2018). Furthermore, Mavi et al. (2016) reported a strong relationship between EC values after 1, 3, 5, and 24 hours of soaking and the proportion of non-germinating seeds in radish seed lots.

Several researchers have identified a strong correlation between the loss of seed viability and increased (EC) in studies conducted on peppers (Demirkaya, 2013) and onion seeds (Demirkaya and Sivritepe, 2011). As seeds undergo ageing, cellular leakage increases, resulting in higher EC values, which reflect increased cell membrane permeability. Moreover, as EC increased, the mean germination time-an important indicator of seed quality-also increased, indicating a decline in seed quality.

Cabbage culture has great cultivar variation and more recently hybrids are getting more widely used in this species and other vegetables due to their higher yield and some other beneficial features (Balkaya et al., 2025). Cabbage seeds are particularly susceptible to lose germinability, due to their major constituent is lipids, which increase the seeds' predisposition to ageing (Priestley, 1986) which may be affected by genetic and physiological potential of seeds, interacting with environmental factors, determine seed germination potential prior to storage (Bewley and Black, 1994). For seed producers it is important to identify normal seed germination percentages of heterogeneity in within and among the cultivars that originated due to different growing environments in the same cultivar (genetically the same) and different cultivars (genetically different) including F1 hybrids. Studies conducted on EC and normal seed germination percentages were mainly done on artificially aged seed lots that produced from a single cultivar in the same species as in radish, cauliflower and cabbage (Mirdad et al., 2006; Matthews et al., 2009; Demir et al., 2012; Mavi et al., 2014; Mavi et al., 2016), or just in two different cultivars in cabbage (Demir et al., 2008). The prediction of the germination of naturally aged seed that had been harvested, stored and transported to the point of sale in seed lots belong to the same and different cultivars has yet to be done. Moreover, seed coat structure and seed chemical components can be altered due to the different genetic background among the lots and cultivars (i.e. F_1 hybrids). Our question then arises as how cultivar/lot differences affect EC and normal seed germination percentages that already set up in cabbage?

The objectives of the present work were to examine the relationship between EC of the soak water of cabbage seed lots belong to (i) the same cultivar (ii) different cultivars (iii) F_1 hybrid cultivars.

2. Materials and Methods

2.1. Seed material

Thirty seed lots were obtained from various sources. Eleven lots belonged to the single cultivar (Yalova-1), nine lots to the different cultivars, and ten lots to F_1 hybrid cultivars of cabbage (Table 1) were obtained from seed market or cabbage (*Brassica oleracea* cv. *capitata*) breeders (Hybrid cultivars).

Production year of the seeds and the minimum and maximum normal seed germination percentages of seed lots in each group were given in Table 1.

Table 1. Number of the seed lots, production year, and normal germination percentages belong to the same, different cultivars that used in the study

	Lot number	Production year	Germination (%)
Lots in single cultivar			
Yalova -1	11	2010-2022	45-86
Multiple cultivars in the species			
Mohrenkoph (4), Brunswick (2), Zencibaş, Ethiopian, Bafra	9	2006-2021	0-91
Hybrid cultivars	10	2022-2024	12-99
Total	30	2006-2024	0-99

Seeds were hermetically (air and watertight) sealed in aluminium foil packets and stored at 5°C until use. Initial seed moisture contents (m.c.), which were determined by the low temperature oven method, ranged between 6.1and 7.3% based on fresh weight.

2.2. Normal germination test

Three replicates of 50 seeds for each lot were placed in between three filter papers (20x20 cm, Filtrak Made in Germany) moistened with 20 ml distilled water. Seeds were placed between three layers of filter paper (one layer above and two layers below the seeds. The papers were rolled and were placed in plastic bags in order to prevent water loss during the test and held at 20 ± 1 °C in the dark (ISTA, 2020). Filter papers were wetted as required during the test. Seed germination was determined at 5 and 10 days. A seed was scored as germinated when it had produced a normal seedling (well-developed seedling and shoot structure). Germination was expressed as percentages.

2.3. Electrical conductivity (EC) test

Two replicates of 25 seeds from each lot were weighed (0.0001 g) and kept at 100% relative humidity over 2 hours to prevent occurrence of imbibition injury. Then each sample was soaked in 40 ml distilled water at 20 °C and EC was measured after 24 hours using a conductivity meter (Schott-Gerate GmbH, Hofheim) and expressed as µS cm^{-1} g^{-1} seed weight (Demir et al., 2008).

2.4. Statistical analysis

All statistical analyses were performed using (IBM SPSS Statistics 26.0 / R software version 4.4). The normality of the data was checked using the Shapiro–Wilk test. Since the data did not meet the assumption of normality, a non-parametric Kruskal–Wallis test was applied to compare the normal germination (NG) percentages among different groups.

The relationship between EC and NG was assessed using Spearman's rank correlation coefficient (ρ). Furthermore, a simple linear regression model was fitted to evaluate the predictive ability of EC for NG, and the coefficient of determination (R^2) was used to estimate the proportion of variance in NG explained by EC. Statistical significance was considered at $P < 0.05$ for all tests.

Boxplots for NG and EC values across seed lot groups (single-cultivar, multiple-cultivar, hybrid, and all combined) were generated using [Python 3.11 (Matplotlib/Seaborn)]. For each group, the median, interquartile range (IQR), minimum and maximum values (whiskers), and outliers were displayed. White circles within each box represent mean values, while the horizontal line inside each box indicates the median.

3. Results

The cabbage seed lots that were used in the study produced between 2006 and 2024, their m.c. upon receipt were between 6.1 and 7.3% which are acceptable for commercial seed lots for sale. They had normal germination percentages ranging between 0 and 99%. Seeds were obtained from the market and some seed lots were stored for many years under ambient storage conditions. Therefore, the germination values in some of them were found very low. This enabled the detection of changes in EC values across a wide range of normal germination percentages, despite seed lots exhibiting germination levels above the minimum threshold required for commercial sale.

Across seed lots belonging to the same cultivar (genetically identical), different cultivars (genetically distinct), and hybrid cultivars (showing heterosis), consistent trends were observed (Figures 1–3). Seed lots with lower NG consistently exhibited higher EC values, whereas lots with higher germination percentages showed lower EC values in all three groups. When all seed lots were analysed together, EC values ranged from 141 to 785 µS cm^{-1}g^{-1}, corresponding to NG values between 0 and 99% (Figure 4).

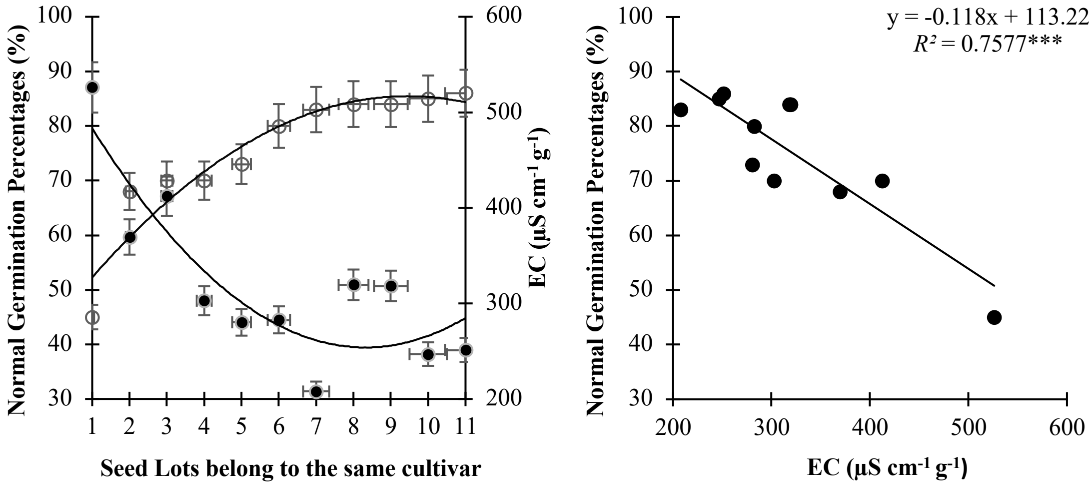

Figure 1. Changes in EC (●) and proportion of seeds showing normal germination percentages (○) for eleven commercial seed lots belong to the same cultivar (Yalova-1) during 24 hours soaking at 20°C. EC and normal germination values are mean±s.e. Relationship between EC and percentage of normal seed germination (***: $P< 0.001$).

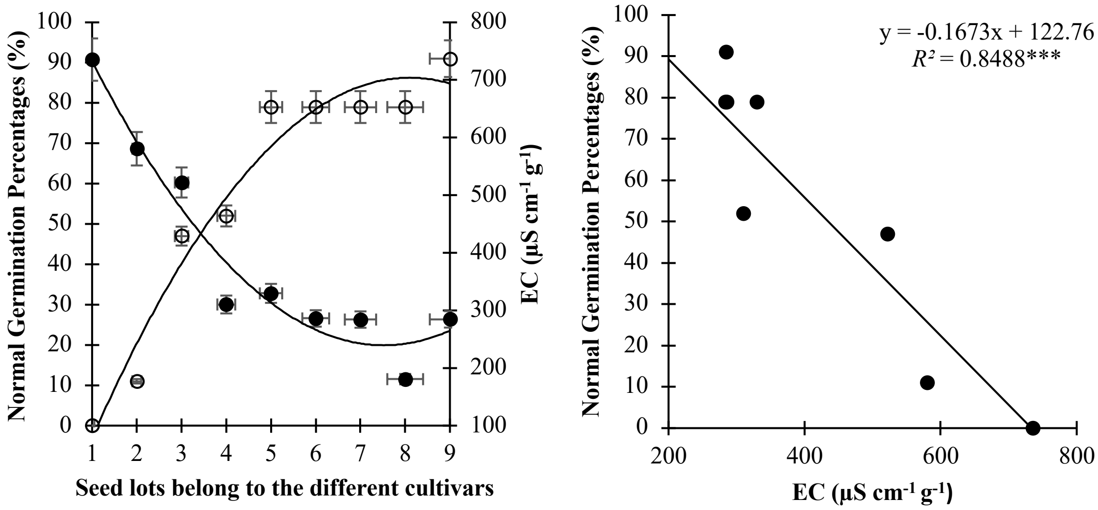

Figure 2. Changes in EC (●) and proportion of seeds showing normal germination percentages (○) for nine commercial seed lots belong to the different cultivar during 24 hours soaking at 20°C. EC and normal germination values are mean±s.e. Relationship between EC and percentage of normal seed germination (***: $P< 0.001$).

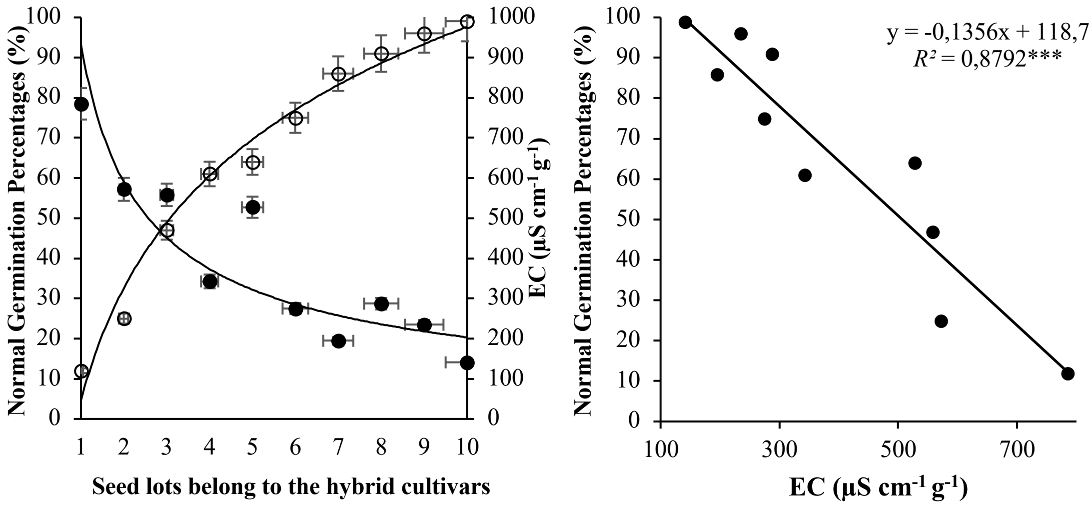

Figure 3. Changes in EC (●) and proportion of seeds showing normal germination percentages (○) for ten hybrid seed cultivars during 24 hours soaking at 20°C. EC and normal germination values are mean ± s.e. Relationship between EC and percentage of normal seed germination (***: $P< 0.001$).

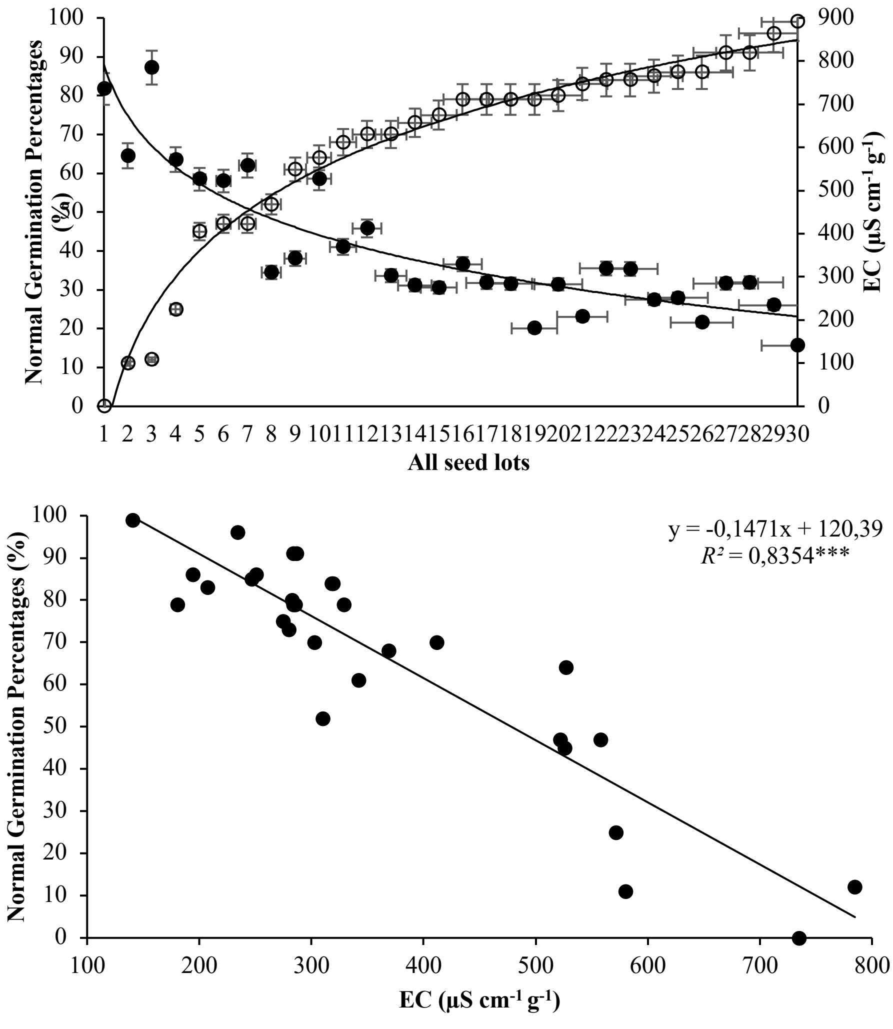

Figure 4. Changes in EC (●) and proportion of seeds showing normal germination percentages (○) for 30 commercial seed lots belong to the same and different cultivars during 24 hours soaking at 20°C. EC and normal germination values are mean ± s.e. Relationship between EC and percentage of normal seed germination (***: $P< 0.001$).

The boxplots (Figure 5) illustrate the variation in NG and EC across the three seed lot groups and all seed lots combined. Although median NG values appeared highest in single-cultivar lots and lowest in multiple-cultivar lots, the Kruskal–Wallis test revealed no statistically significant differences among groups (H= 1.38, P= 0.709). Similarly, EC values showed no significant group-wise differences despite visible variation in distribution ranges (Table 2).

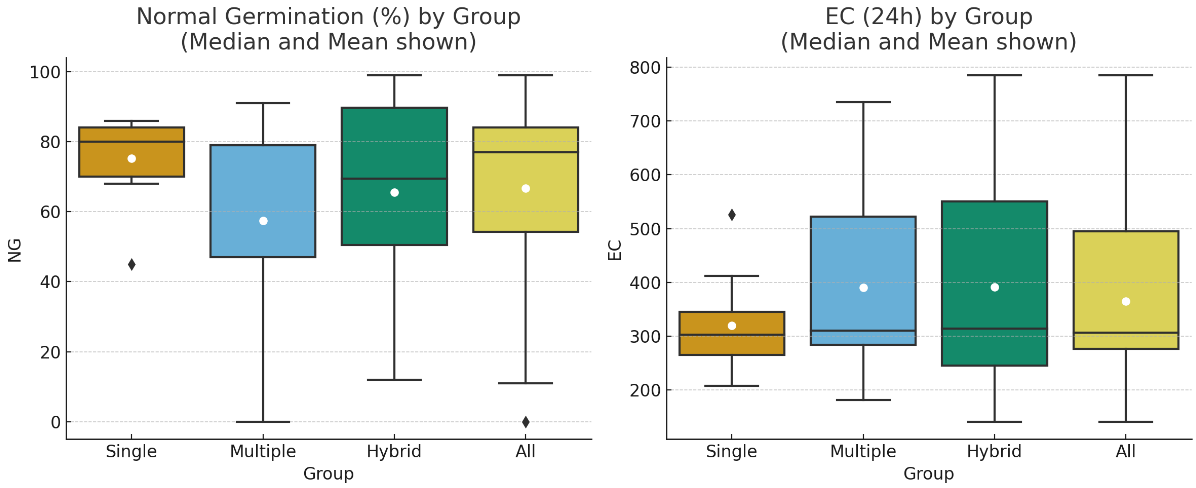

Figure 5. Boxplots of NG and EC values across seed lot groups.

Table 2. Associations between EC and NG

Test	Result	p-value	Interpretation
Kruskal–Wallis (NG)	H = 1.38	0.709	No significant difference among groups.
Spearman Correlation	ρ = -0.82	< 0.001	Strong and significant negative correlation: as EC increases, NG decreases.
Regression Analysis	y = -0.15x + 120.4	R^2 = 0.84	EC explains 84% of the variation in NG.

Strong and highly significant relationships were identified between EC and NG in the same-cultivar seed lots (R^2 = 0.75, P < 0.001; Figure 1), different-cultivar seed lots (R^2 = 0.84, P < 0.001; Figure 2), hybrid seed lots (R^2 = 0.87, P< 0.001; Figure 3), and across all lots combined (R^2 = 0.84, P< 0.001; Figure 4).

Spearman's correlation analysis confirmed a strong negative association between EC and NG across all groups (ρ = −0.82, P< 0.001). As EC increased, NG decreased sharply. Linear regression further supported this relationship, yielding the equation:

$$NG = -0.15 \times EC + 120.4 \ (R^2 = 0.84, P < 0.001) \quad (1)$$

This indicates that approximately 84% of the variation in NG can be explained by EC values. The minimum NG percentage required for commercial sale in cabbage is 75%. Regression models developed for each seed group predicted that EC values corresponding to 75% NG ranged from 280 to 322 µS cm⁻¹ g⁻¹. These findings suggest that an EC threshold of approximately 280–320 µS cm⁻¹ g⁻¹ can serve as a reliable indicator of commercially acceptable seed germination, regardless of seed lot origin (Table 3).

Table 3. Changes in EC values corresponding to 75% of normal germination percentages in the lots in the same and different cultivars and all lots. R^2 values, significance level and regression formula were also given for each group

	EC (75% NG)	R^2	Significance	Regression
Lots of Single Cultivar	314-321	0.75	*P <0.001*	y = -0.118x+113.2
Multiple cultivars in species	280-285	0.84	*P <0.001*	y = -0.167x+122.7
Hybrids	315-322	0.87	*P <0.001*	y = -0.135x+118.7
All lots	302-308	0.84	*P <0.001*	y = -0.15x+120.4

4. Discussion

The high correlation between EC values and germination percentages of normal seedlings in cabbage cultivars suggests that electrical conductivity readings can be used in testing seed quality instead of or supporting of a standard laboratory germination test. The basic feature of EC is a rapid test and can be an alternative to the germination test which requires 7-42 days according to ISTA (2020) rules depending on the species when particularly quick information is required about any lot. Our conclusion in this work agrees with the reports for cabbage and cauliflower (Mirdad et al., 2006; Demir et al., 2008), radish (Demir et al., 2012; Mavi et al., 2014) wall-rocket (Lazar et al., 2014), Passiflora L. (Mira et al., 2015), leek (Ozden et al., 2017), Tagetes (Gülöksüz et al., 2025), groundnut (Akuo et al., 2025). The relationship varies among species. Demir et al. (2008) found differences in leakage readings between red and white cabbage cultivar seeds. Similarly, Mira et al. (2015) and Ermis (2022) reported differences in EC measurements in different species of Passiflora and French Bean. Thus, variation in cultivar and species should be considered in use of EC for prediction of germination. Genotypic variation in seed storability and vigour-related traits has also been reported in soybean following accelerated ageing (Maesaroh et al., 2021), further indicating that genetic background should be considered when evaluating seed deterioration and vigour. In this work we proposed the EC variation among the cultivars i.e. open pollinated or hybrids. Information about germination levels of commercial seeds belong to the various cultivars that harvested, grown in different regions and stored for various times, can be obtained within 24 hours compared with the 10 days needed for a complete germination test in cabbage (ISTA, 2020). Regression relationships were established between solute leakage and normal germination percentages (0–99%) in naturally aged seed lots. These findings suggest that EC can detect large and small normal germination differences in wide range of germination. Our results indicate that dead seeds and seeds producing abnormal seedlings (i.e. missing roots, cotyledons) contribute most of the total solute leakage and so, seed samples with a low normal seedling percentage have higher EC values than those with higher values. This was detected by Khajeh-Hosseini et al. (2010) reported that EC averages of a single oilseed rape seed at 24 hours soaking were 4.9, 6.9 and 15.1 µS cm^{-1} g^{-1} in seeds which produced normal and abnormal seedlings or dead seeds, respectively. We used bulk conductivity test in our study. So we evaluated the seeds as a group rather than individual evaluation. We assumed that seed lots are uniformly matured and harvested at optimum period. This method was used in various studies (Matthews et al., 2009; Mavi et al., 2014; Marin et al., 2018). Individual seed leachate measurement can be another option to get more reliable results. EC of a single seed leachate was taken as a physiological index of seed germination and vigour in legume and maize seeds (Steere et al., 1981; Davidson et al., 1994). The evaluation of single-seed conductivity was also suggested as a method for assessing seed viability, following the development of an instrument capable of simultaneously measuring the leachate conductivity of 100 individual seeds. Individual seed EC measurement can be a good option in those seed lots that exhibit non-uniform maturation. However, such instrument does not adjust readings to take account of seed weight. While different seed weights occurred due to pre-harvest practices as maturation stages of silique Brassica (i.e cabbage) may also affect amount of leakage. Weighing of seeds (50-100) prior to EC assessment and referring this EC value to seed weight expressed in gram (0.0001) is a generally accepted experimental procedure for many decades (Hepburn et al., 1984). Use of bulk conductivity was found appropriate to predict germination quality and common practice in artificially aged cabbage and cauliflower (Mirdad et al., 2006), naturally aged cabbage seed lots (Demir et al., 2008, Matthews et al., 2009), chickpea (Khajeh-Hosseini and Rezazadeh, 2011), radish (Mavi et al., 2014) and some native species (Marin et al., 2018).

The leakage observed in low-germinating seeds is primarily attributed to membrane deterioration caused by either artificial or natural ageing. Seed ageing and the resulting loss of membrane integrity are key factors contributing to this leakage (McDonald, 1999; Matthews and Powell, 2006). The adverse effects of seed ageing on germination and subsequent seedling performance have also recently been demonstrated under accelerated ageing conditions (Ozden et al., 2017; Bagheri et al., 2026). In our work we collected seed lots from the seed market and they were naturally aged in retailer's point basically on the bench in uncontrollable environment room temperature. In majority of the studies that EC was used to predict normal germination artificially aged seed lots produced at high seed moisture and temperature were used in various crop seeds (Mirdad et al., 2006; Matthews et al., 2009; Mavi et al., 2014; Pontes et al., 2025). Ozden et al. (2017) compared the natural and artificial ageing and EC relationship in leek seed lots. Regardless of ageing types, EC was found highly predictive ($P < 0.001$) to normal germination percentages. This is consistent with McDonald (1999), who proposed that lipid peroxidation, leading to reduced membrane integrity and increased leakage, may vary between artificial ageing conditions (high seed moisture and temperature) and natural ageing conditions (low seed moisture and temperature). Highly significant correlation coefficients established between predicted germination by EC measurements made in accelerated aged seeds and actual germination scored by standard germination test in commercial seeds provide further evidence that both ageing types have a similar physiological basis. This assumption has been discussed by Powell and Matthews (1977) and Ellis and Roberts (1981) in light of the hypothesis that the intensity of expression of the majority of ageing symptoms in a seed sample is a continuous rather than a step function. These authors deduced that seed deterioration may be regarded as a linear process, where physiological and biochemical changes follow a similar trend and extended depending on the severity of ageing conditions, as shown by increased solute leakage changes in both types of deterioration.

The present study clearly demonstrates that EC measurements are strongly and inversely related to NG percentages in cabbage seeds. The observed strong negative correlation ($\rho = -0.82$) and high coefficient of determination ($R^2 = 0.84$) indicate that seeds with higher solute leakage, as reflected by elevated EC values, exhibit reduced germination capacity.

This finding suggests that the EC test could serve as a reliable and rapid predictor of seed vigour, allowing early identification of seed lots with diminished physiological quality. The lack of significant differences in NG among seed groups implies that the EC–NG relationship is independent of cultivar type, supporting its broader applicability for seed quality assessment.

Our findings indicate that predictive regression equations are very similar for different cultivars within the same species. This indicates that general EC value readings after 24 hours can be successful to predict germination percentages in seed analytical work.

Conclusion

The EC test has potential for detecting cabbage seed lots with varying germination levels in naturally aged open-pollinated and hybrid cultivars. This method could help the seed industry efficiently determine the optimal time for renewing seed lots stored under natural, non-cooled conditions at retail points. Moreover, EC assessment can serve as a routine test to evaluate the germination quality of unsold seeds from previous years before marketing or when further storage is required.

In addition, the consistent EC–NG relationships observed across open-pollinated and hybrid cultivars indicate that electrical conductivity testing can be applied broadly in cabbage seed quality evaluation without substantial influence from cultivar differences. The close agreement between EC threshold values among seed groups further supports the practical use of a common EC reference range for commercial seed testing. Therefore, EC measurement offers seed companies and testing laboratories a rapid, simple, and cost-effective tool for monitoring seed deterioration and supporting storage and marketing decisions.

Ethical Statement

Ethical approval is not required for this study.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Artificial Intelligence Declaration

The authors declare that no generative artificial intelligence tools were used at any stage of the preparation of this manuscript, including the writing, editing, or refinement of the text, or the creation of any images, figures, graphics, tables, or related titles.

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Author Contributions

N.E. concept; design; resources; data collection and processing; validation. A.H.D. data collection; literature search; materials; validation. E.Ö. design; interpretation; writing; analysis; validation; review and editing. İ.D. interpretation; writing; funding acquisition; critical reviews; review and editing.

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