Germination behavior of *Jatropha curcas* L. after diffrent imbibition times

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# Abstract

*Jatropha curcas* is a important specie for production of bio fuel and his seeds oil content require less water. The plant can survive on infertile and under drought condition. For an adequate establishment in the field is necessary that seed have good quality in vigor and viability. We studied the seed water relation for aim these objective was performed an experiment with different imbibition time from 0 to 24 hours in deionized water. Imbibed seeds were sown in aluminium containers with 1200 g of sand. The germination was recorded every day for 25 days. Seed with 1 cm radicle under the soil was considered as germinated. To determinate seed water relation were weighed 10 seeds in fresh, turgid and dry weight (104 °C for 24 hours). Our results show that exist decrease in the germinability of the seeds according to a increase in seed imbibition time. The seed water content was about 8-10% and after 24 hours the seeds water content were around 60% . This study suggest that *J. curcas* don’t need previously water imbibition in order to improve germination percentage in seed with a initial water moisture less than 8%.

**Key words:** bio fuel — seed water content - seed moisture - germinability

# Introduction

*Jatropha curcas* L. belongs to the family Euphorbiaceae and is native to the American tropics (Abhilash, Srivastava, Jamil, & Singh, [2010](#ref-Abhilash_2010)). It is a small tree but it can reach 6 meters or more. *J. curcas* is a seed-bearing plant and can produce 1-2 kg of seed per plant/year when the plant is 2-3 years old (Mukherjee, Varshney, Johnson, & Jha, [2011](#ref-Mukherjee2011Jatropha)) and can be propagated both by seeds and stem cuttings.

More than 95% of the oil produced for biodiesel purposes comes from edible oils, which can have a negative impact on food production (khan et al., [2014](#ref-khan_2014)). *J. curcas* seeds are a good source of oil and It has great economic potential as an alternative to oil bio fuel. The decorticated seeds contain 40-60% oil (Kumar, Makkar, Amselgruber, & Becker, [2010](#ref-Kumar2010Physiological); SHAH, [2005](#ref-SHAH2005Extraction)) and is a non-edible, eco-friendly, non-toxic, biodegradable fuel-producing plant has attracted worldwide attention as an alternate sustainable energy source for the future (Mukherjee et al., [2011](#ref-Mukherjee2011Jatropha)).

The seeds of *J. curcas* have a short viability period and they are more sensitive to salinity at germination (Elhag & Gafar, [2014](#ref-elhag2014effect); Moncaleano-Escandon et al., [2013](#ref-Moncaleano2013Germination)). *J. curcas* is drought tolerant (Luz Costa et al., [2015](#ref-da_Luz_Costa_2015)) and perhaps also as salinity tolerant it can be cultivated on marginal and salt affected areas, without competing with crop food production (Elhag & Gafar, [2014](#ref-elhag2014effect); Heller, [1996](#ref-heller1996physic)). Seed deterioration is a natural and irreversible process, even under ideal storage conditions. Dry seeds suffer a variety of biochemical and metabolic changes, including lipid peroxidation, enzyme inactivation and rupture of cellular membranes (Bewley, Bradford, Hilhorst, & Nonogaki, [2012](#ref-Bewley_2012)).

In arid environments, the water needed for germination is available for only short periods and consequently, successful crop establishment depends not only on rapid and uniform germination of the seed, but also on the ability of the seed to germinate under low water availability (L. Windauer, Altuna, & Benech-Arnold, [2007](#ref-Windauer2007Hydrotime)). The speed and uniformity of seed germination are prominent parameters especially for field crop seeds to compete with weed seeds (Ruttanaruangboworn, Chanprasert, Tobunluepop, & Onwimol, [2017](#ref-Ruttanaruangboworn_2017)). Water uptake is the fundamental requirement for the initiation and completion of seed germination (Koornneef, Bentsink, & Hilhorst, [2002](#ref-Koornneef2002Seed)). Studies on germination and seedling establishment which are the critical stages in the plant life cycle. In these important species have not been conducted so far. Knowledge of the capacity of the species to complete this stage successfully is fundamental for crop production (L. B. Windauer, Martinez, Rapoport, Wassner, & Benech-Arnold, [2011](#ref-Windauer2011Germination)). Considerable variation was registered in *J. curcas* for seed germination, seedling growth and biomass parameters. The small value of error or environmental variances of the seedling growth traits suggests that majority of characters are under genetic control (Ginwal, Phartyal, Rawat, Srivastava, & others, [2005](#ref-ginwal2005seed)).

The main objective of this study was to evaluate the behavior of *J. curcas* seeds under different imbibition time, seed water relation and aspects about germination.

# Materials and methods

## Plant material

The experiment was carried out with *Jatropha curcas* commercial seeds (Commun Variety, BRSEEDS , Brazil). The seeds presented 72% viability and they were collected in 2013 and stored around 9% humidity with any pesticide treatment.

## Seed imbibiton test and water relation

The seeds was distributed in 52 cups (400 ml) with 25 seed for each experimental unit in a controlled room at 25 °C. For each cup was applied 100 ml deionized water according to the imbibition treatment (0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22 and 24 hours). The pH (W3B, Bel Engineering , Italy) and electrical conductivity (CD-4306, Lutron, Taiwan) were evaluated with 20 ml of soaking solution for each treatment. For seed water content 52 cups (100 ml) was applied 50 ml deionized water and were added 10 seed previously weight in a analytic scale (ATY224, Shimadzu, Japan) according to different imbibition time. After each treatment was take the seeds imbibition weight and putted in papers bags for oven at 104 °C for 24 hours and determinate seeds dry weight.The water relation variables were calculated according the following formulas: and . Where , Seed moisture; Seed Water content; , Seed dry weight; , Seed fresh weight and , Seed turgid weight.

## Germination test

The 25 seed from each treatment was sowing in aluminium trays content 1000 g of river sand at field capacity (1300 g). The seed was distributed in the tray and covered with 200 g sand. The germination experiment was carried out in greenhouse condition with average temperature of 27.48 °C and 78.05% relative humidity. Seed germination was evaluated daily according to agronomic criteria consider germinated seed when the radicle had emerged about 1 cm above the surface of sowing media. When no germination was observed in all treatments at least in five consecutive days, the germination was considered completed (Moncaleano-Escandon et al., [2013](#ref-Moncaleano2013Germination)).

## Data analysis

The experimental was carried out in a completely randomized design with 13 treatments of imbibition times (0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22 and 24 hours) with four replications with seeds of *J. curcas*. The germination variables was calculated according the GerminaR R package (Lozano Isla, Benites Alfaro, & Pompelli, [2017](#ref-R-GerminaR)). Statistical analysis and generation of graphs were performed in the statistical software R (R Core Team, [2017](#ref-R-base)). The analysis of variance (ANOVA) was performed to evaluate the differences between the factors and the comparison of the means with the Student-Newman-Keuls test (p <0.05) (de Mendiburu, [2017](#ref-R-agricolae)). For the multivariate analysis, correlation analysis was performed (de Mendiburu, [2017](#ref-R-agricolae); Wei & Simko, [2017](#ref-R-corrplot)) and principal components analysis were made (Husson, Josse, Le, & Mazet, [2017](#ref-R-FactoMineR)).

# Results

## Electrical conductivity and pH

The water solution from the soaked seeds show variation under the imbibition time for electrical conductivity (EC) and pH, Figure 1 A-B. The pH range had a variation from 7.7 to 5.13 showing difference between the different imbibition time with a reduction of the pH in the time (r = -0.88, p<0.05), Figure 1 A. While the EC show a increase in relation to imbibition time (r = 0.80, p<0.05) with value ranges from 0.021 to 0.69 ds.m−1, Figure 1 B. According the correlation analysis exits a negative correlation between EC and pH (r = -0.74, p<0.05).

## Seed water relation

The seed moisture was 7.93% at the begging of the experiment and during the time line it arrive until 9.50% , Figure 1 C. The seed moisture show a strong positive correlation with the imbibition time (r = 0.89, p<0.05). While the seed water content show a fast increase until the first two hour of imbibition the seed arrives to 25.67% of water content, afterwards these moment the water content in the seeds increase continuously to arrive around 59.23% in 24 hours, Figure 1 D. There was an increase in the water content around 6.5 times from initial moisture it is represented for a high correlation between imbibition time with the water content (r = 0.93, p<0.05). While the correlation between both variables is 0.96 (p<0.05).

## Seed germination analisys

Germinability of the seeds of *Jatropha curcas* had a significant decrease since the 2 hours of imbibition with a initial germinability of 85% for seed without imbibition treatment at 00 hours. After that the range of germinability were between 68 to 44% from 02 to 24 hour of imbibition (Figure 2 A). Germinability show a strong negative correlation with imbibition time (r = −0.72, p<0.05). The mean germination time in seed without imbibiton has a major value with 4.8 day in comparative with the other treatment with values around 5.89 to 7.06 day for germination between 02 to 24 hours of imbibition (Figure 2 B). Seed germinability presented a negative strong correlation with a mean germination time (r = −0.88, p<0.05). The germination synchrony show values from 1.86 to 2.34 without difference between the imbibition times (Figure 2 C). The maximum value for the uncertainty in germination for the experiment was 4.64 bits an the results don't show any trend according the imbibition time. The germination uncertainty had values from 1.86 to 2.34 bits. The germination synchrony show a high correlation with the germination uncertainty (r = −0.92, p<0.05).

## Multivariate analisys

The principal component analysis according to the studied variables explain 75.03% of the variance between the first and second dimension. In the first dimension exist high positive correlation between ELC (r = 0.97, p<0.05), SWC (r = 0.96, p<0.05), SMT (r = 0.91, p<0.05), STW (r = 0.91, p<0.05), IBTH (r = 0.87, p<0.05), MGT (r = 0.82, p<0.05) with a negative correlation with the GRP (r = -0.92, p<0.05) while in the second dimension SFW (r = 0.77, p<0.05), SDW (r = 0.71, p<0.05) present positive correlation in contrast with HPT (r = -0.75, p<0.05) with negative correlation.

# Discussion

This study found that exist a reduction in the seed germinability of *J. curcas* according to water imbibiton. It is suppose that seeds precise a mount of water for promote the germination but in these case the seeds submitted to water imbibition had a decrease in germination and an increase in the mean germination time parameters related to the seed vigor (S. Matthews & Hosseini, [2006](#ref-Matthews_2006)). Also is observed during the time line of the experiment there was a increase in EC that reflect in lost the seed germinability from seed steeping in water from 02 to 24 hours.

The seeds used in this experiment were stored dry and hence have very low levels of metabolism. During imbibition of water, they swell and metabolic activity increases. Hydration of tissue components during imbibition takes place in a not controlled way so that the reconstruction of internal structures of the cells and organelles was affected. So leakage of stored materials and enzymes, colouring, cracking or absence of cotyledons, and overall damage to the hypocotyl may occur during germination (Hobbs & Obendorf, [1972](#ref-Hobbs1972Interaction); Pollock, Roos, & Manalo, [1969](#ref-pollock1969vigor)). The amount of the constituents of the leaked depended unequivocally on the initial water content of seeds; the lower moisture in seed at the initial water content show more leakage that no occur with seeds with the initial water content of 24.2% (ISHIDA, KANO, KOBAYASHI, HAMAGUCHI, & YOSHIDA, [1988](#ref-ISHIDA1988relationship)). This damage takes place in the early stages of imbibition (Parrish & Leopold, [1977](#ref-Parrish1977Transient)). This indicates that membrane functions are restored, even though the activities of respiration and metabolism are restricted. Water molecules are semi bound and that mobile water necessary for metabolism is deficient for moisture contents between 12-24% (Koizumi et al., [2008](#ref-Koizumi2008Role)). According to these the lost of viability can be explain for the initial seed water content of the seeds used in these experiment because they had an initial moisture around 8%. It is low water content according to moisture in harvest that is around 18% (M. F. Pompelli et al., [2010](#ref-Pompelli_2010)). Also in other crops like soybean seeds water content is usually 10 to 20% at harvest and falls further during storage, seed water contents below 10% were shown to be desirable for long period storage because seeds stop their biological activities and the stored materials are consumed at a minimum level (L. Windauer et al., [2007](#ref-Windauer2007Hydrotime)). *J. curcas* seeds after 24 hour of imbibition arrive 6.5 times initial moisture as reported by (ISHIDA et al., [1988](#ref-ISHIDA1988relationship)), dried seeds is elevated to a certain level, two or three times the dry weight of seeds, and this rapid increase of water is often accompanied by some deterioration of the tissues, called imbibitional damage. These damage is expressed as a reduced rate of germination and reduced yield of surviving plants. It can be the reason in decrease in the germination percentage in these research. It was reported that soybean seeds with the water content below 13% suffered seriously from imbibitional damage while those above 17% did not, where respiration and metabolic activity rapidly increase with the increase of moisture content (ISHIDA et al., [1988](#ref-ISHIDA1988relationship); Vertucci & Leopold, [1984](#ref-Vertucci1984Bound)). Imbibition damage results from the rapid entry of water into the cotyledons during imbibition, leading to cell death and high solute leakage from the seeds (POWELL & MATTHEWS, [1978](#ref-POWELL1978Damaging)) and the extensive loss of cellular material and enzymes from the seeds (Duke & Kakefuda, [1981](#ref-Duke1981Role); POWELL & MATTHEWS, [1981](#ref-POWELL1981Physical)) indicates extensive membrane disruption. The electrical conductivity was related with seed water content and the germination for these reason EC tests has been applied to detect vigor differences in many other grain legumes and indeed some other species (Hampton & TeKRONY, [1995](#ref-hampton1995handbook)). The conductivity will increase as the laboratory germination falls, in addition to the reduced ability of germination seeds to retain cell contents (Stan Matthews & Powell, [2006](#ref-matthews2006electrical)). In many reports on peas, the EC readings for lots have been found to relate significantly to field emergence (POWELL & MATTHEWS, [1981](#ref-POWELL1981Physical); THORNTON, POWELL, & MATTHEWS, [1990](#ref-THORNTON1990Investigation)).

To alleviate of the effects of soaking injury as a result of the increase in the moisture content of seeds before imbibition is related to the reduced binding energy of water molecules and the appearance of respiratory activity (Vertucci & Leopold, [1984](#ref-Vertucci1984Bound)). Slow and controlled hydration is essential as the first step in the reactivation of metabolic processes in the dry seed,leading to germination and growth. The EC would be developed and standardized for these species (Abdullah, Powell, & Matthews, [1991](#ref-Abdullah1991Association); POWELL, OLIVEIRA, & MATTHEWS, [1986](#ref-POWELL1986Role); Yaklich & Kulik, [1979](#ref-Yaklich1979Evaluation)). Furthermore was reported than the relationship between field emergence and EC turned out to be not only interesting, but useful in practical seed technology (S Matthews & Bradnock, [1967](#ref-matthews1967detection)) as present in these work for *J. curcas*.

# Conclusions

The initial water content in *J. curcas* seeds should be consider because It will be alter the seed germinability according to the imbibition time. The measurement of EC could be have a role alongside ageing based vigor tests, like the accelerated ageing and controlled deterioration tests, by giving a measure of viability following ageing in 24 hours in place of a germination test around 15 to 30 days or longer in *J. curcas*.

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# Figures & tables

## Figures

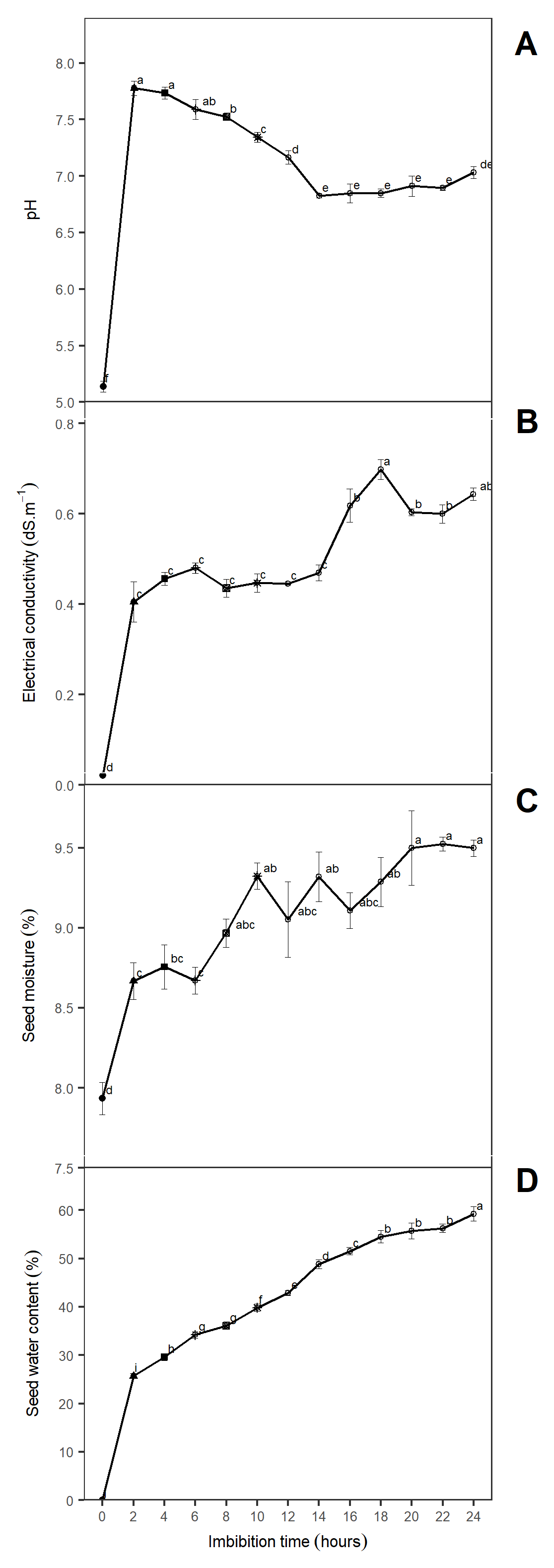


Figure 1 Response of *Jatropha curcas* seeds after different imbition time. (A) Electrical conductivity; (B) pH; (C) Seed moisture and (D) Seed water content. The letter represent the mean difference with Student-Newman-Keuls test (p = 0.05). Means are represent with (±SE). n = 4.

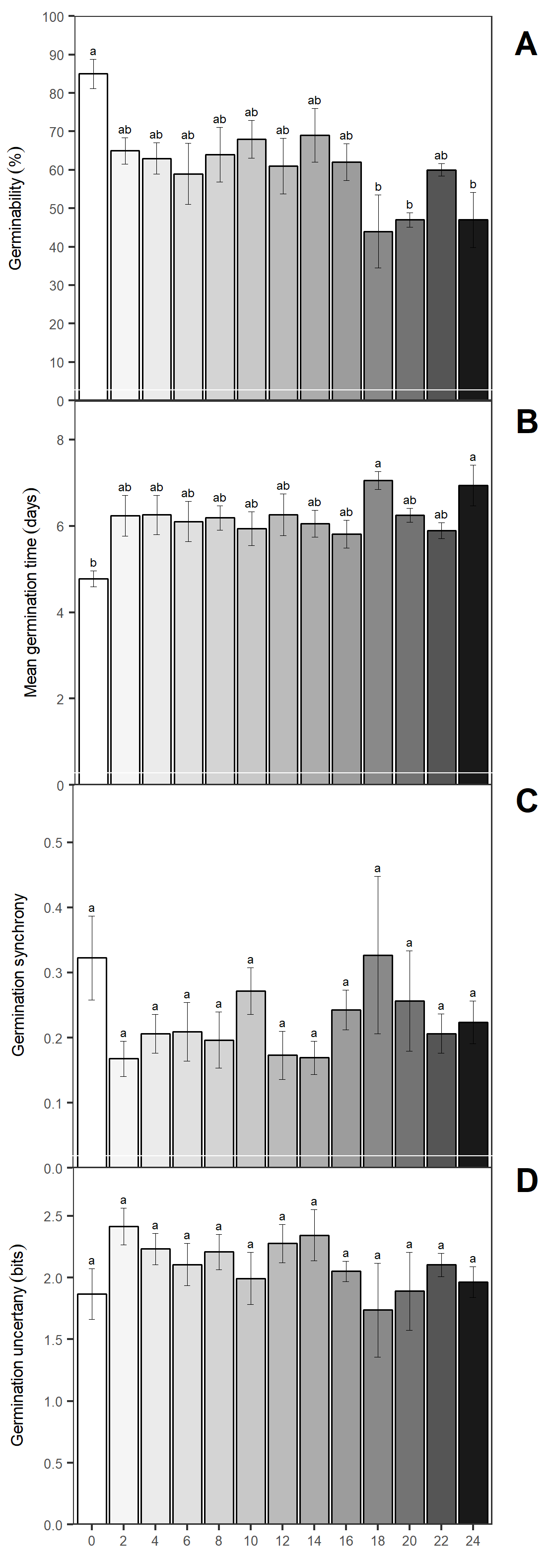


Figure 2 (A) Germination (%); (B) Mean germination time (days); (C) Germination synchrony and (D) Germination uncertany (bits) in *Jatropha curcas* seeds after different imbition times. The letter represent the mean difference with Student-Newman-Keuls test (p = 0.05). Means are represent with (±SE). n = 4.

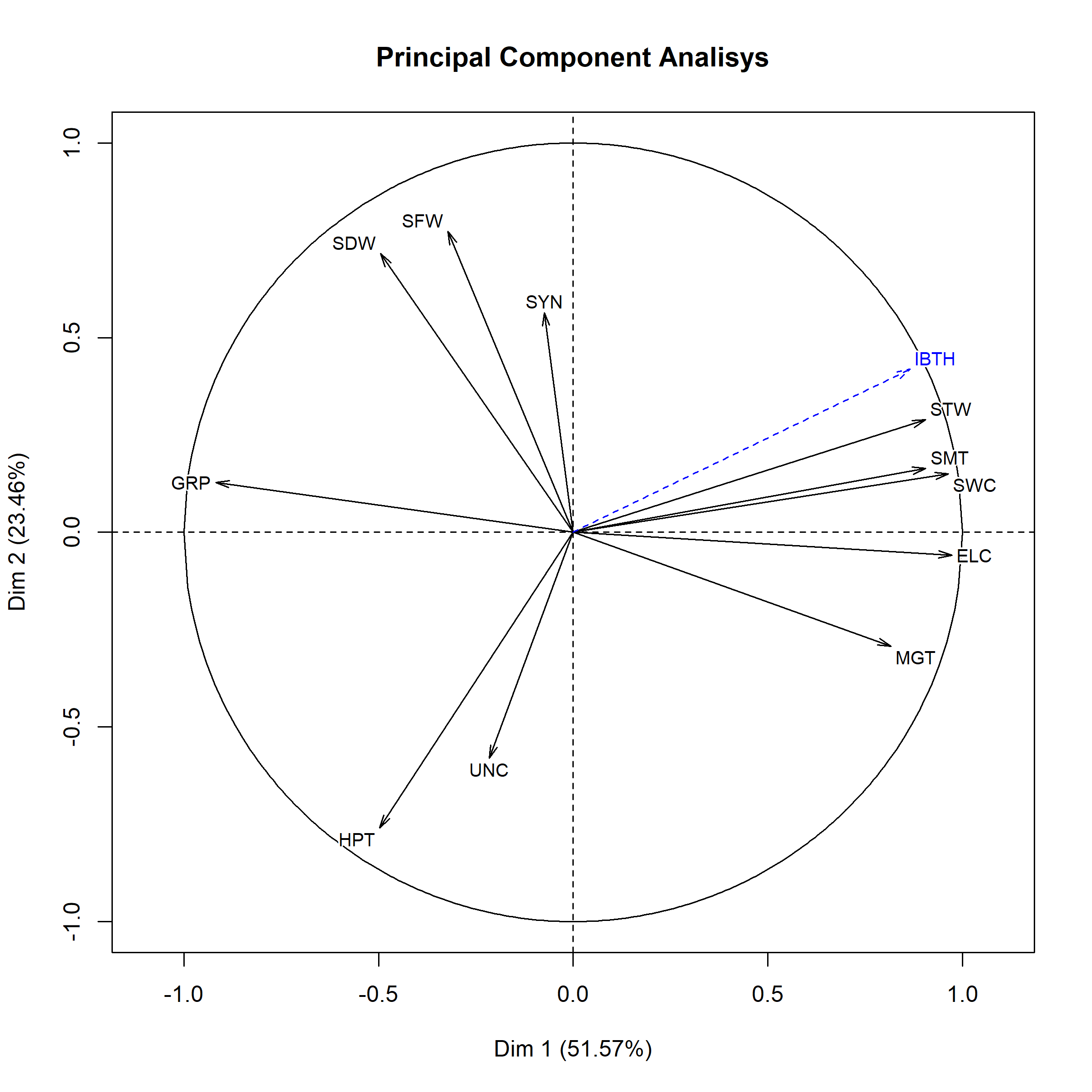


Figure 3 Principal Component Analysis from the variables in *Jatropha curcas* seeds after different imbition times. Where: IBTH, imbibition time; GRP, germination percentage; MGT, mean germination time; SYN, germination synchrony; pH, potential of hydrogen; EC, electrical conducntivity; SWC, seed water content; SMT, seed moisture.

# References

Abdullah, W. D., Powell, A. A., & Matthews, S. (1991). Association of differences in seed vigour in long bean ( vigna sesquipedalis) with testa colour and imbibition damage. *The Journal of Agricultural Science*, *116*(02), 259. <https://doi.org/10.1017/s0021859600077662>

Abhilash, P. C., Srivastava, P., Jamil, S., & Singh, N. (2010). Revisited jatropha curcas as an oil plant of multiple benefits: Critical research needs and prospects for the future. *Environmental Science and Pollution Research*, *18*(1), 127–131. <https://doi.org/10.1007/s11356-010-0400-5>

Bewley, J. D., Bradford, K. J., Hilhorst, H. W. M., & Nonogaki, H. (2012). *Dormancy and the control of germination* (pp. 247–297). Springer New York. <https://doi.org/10.1007/978-1-4614-4693-4_6>

de Mendiburu, F. (2017). *Agricolae: Statistical procedures for agricultural research*. Retrieved from <https://CRAN.R-project.org/package=agricolae>

Duke, S. H., & Kakefuda, G. (1981). Role of the testa in preventing cellular rupture during imbibition of legume seeds. *PLANT PHYSIOLOGY*, *67*(3), 449–456. <https://doi.org/10.1104/pp.67.3.449>

Elhag, A. Z., & Gafar, M. O. (2014). Effect of sodium chloride on growth of jatropha (jatropha curcas l.) young transplants. *Universal Journal of Plant Science*, *2*(1), 19–22.

Ginwal, H., Phartyal, S., Rawat, P., Srivastava, R., & others. (2005). Seed source variation in morphology, germination and seedling growth of jatropha curcas linn. in central india. *Silvae Genetica*, *54*(2), 76–79.

Hampton, J. G., & TeKRONY, D. M. (1995). *Handbook of vigour test methods.* The International Seed Testing Association, Zurich (Switzerland).

Heller, J. (1996). Physic nut. jatropha curcas l. promoting the conservation and use of underutilized and neglected crops. 1. *Roma: IBPGR*.

Hobbs, P. R., & Obendorf, R. L. (1972). Interaction of initial seed moisture and imbibitional temperature on germination and productivity of soybean1. *Crop Science*, *12*(5), 664. <https://doi.org/10.2135/cropsci1972.0011183x001200050033x>

Husson, F., Josse, J., Le, S., & Mazet, J. (2017). *FactoMineR: Multivariate exploratory data analysis and data mining*. Retrieved from <https://CRAN.R-project.org/package=FactoMineR>

ISHIDA, N., KANO, H., KOBAYASHI, T., HAMAGUCHI, H., & YOSHIDA, T. (1988). The relationship between imbibitional damage and initial water content of soybeans. *Agricultural and Biological Chemistry*, *52*(11), 2771–2775. <https://doi.org/10.1271/bbb1961.52.2771>

khan, T. Y., Atabani, A., Badruddin, I. A., Badarudin, A., Khayoon, M., & Triwahyono, S. (2014). Recent scenario and technologies to utilize non-edible oils for biodiesel production. *Renewable and Sustainable Energy Reviews*, *37*, 840–851. <https://doi.org/10.1016/j.rser.2014.05.064>

Koizumi, M., Kikuchi, K., Isobe, S., Ishida, N., Naito, S., & Kano, H. (2008). Role of seed coat in imbibing soybean seeds observed by micro-magnetic resonance imaging. *Annals of Botany*, *102*(3), 343–352. <https://doi.org/10.1093/aob/mcn095>

Koornneef, M., Bentsink, L., & Hilhorst, H. (2002). Seed dormancy and germination. *Current Opinion in Plant Biology*, *5*(1), 33–36. <https://doi.org/10.1016/s1369-5266(01)00219-9>

Kumar, V., Makkar, H. P., Amselgruber, W., & Becker, K. (2010). Physiological, haematological and histopathological responses in common carp (cyprinus carpio l.) fingerlings fed with differently detoxified jatropha curcas kernel meal. *Food and Chemical Toxicology*, *48*(8-9), 2063–2072. <https://doi.org/10.1016/j.fct.2010.05.007>

Lozano Isla, F., Benites Alfaro, O., & Pompelli, M. F. (2017). *GerminaR: Germination indexes for seed germination variables for ecophysiological studies*. Retrieved from <https://CRAN.R-project.org/package=GerminaR>

Luz Costa, J. da, Silva, A. L. L. da, Bier, M. C. J., Brondani, G. E., Gollo, A. L., Letti, L. A. J., … Soccol, C. R. (2015). Callus growth kinetics of physic nut (jatropha curcas l.) and content of fatty acids from crude oil obtained in vitro. *Applied Biochemistry and Biotechnology*, *176*(3), 892–902. <https://doi.org/10.1007/s12010-015-1618-y>

Matthews, S., & Bradnock, W. (1967). The detection of seed samples of wrinkle-seeded peas (pisum sativum l.) of potentially low planting value. *International Seed Testing Association*, *32*, 553–563.

Matthews, S., & Hosseini, M. K. (2006). Mean germination time as an indicator of emergence performance in soil of seed lots of maize (zea mays). *Seed Science and Technology*, *34*(2), 339–347. <https://doi.org/10.15258/sst.2006.34.2.09>

Matthews, S., & Powell, A. (2006). Electrical conductivity vigour test: Physiological basis and use. *Seed Testing International*, *131*, 32–35.

Moncaleano-Escandon, J., Silva, B. C., Silva, S. R., Granja, J. A., Alves, M. C. J., & Pompelli, M. F. (2013). Germination responses of jatropha curcas l. seeds to storage and aging. *Industrial Crops and Products*, *44*, 684–690. <https://doi.org/10.1016/j.indcrop.2012.08.035>

Mukherjee, P., Varshney, A., Johnson, T. S., & Jha, T. B. (2011). Jatropha curcas: A review on biotechnological status and challenges. *Plant Biotechnology Reports*, *5*(3), 197–215. <https://doi.org/10.1007/s11816-011-0175-2>

Parrish, D. J., & Leopold, A. C. (1977). Transient changes during soybean imbibition. *PLANT PHYSIOLOGY*, *59*(6), 1111–1115. <https://doi.org/10.1104/pp.59.6.1111>

Pollock, B., Roos, E., & Manalo, J. (1969). Vigor of garden bean seeds and seedlings influenced by initial seed moisture, substrate oxygen, and imbibition temperature. *Journal of the American Society for Horticultural Science*, *94*, 577–584.

Pompelli, M. F., Rocha Gomes Ferreira, D. T. da, Silva Cavalcante, P. G. da, Lima Salvador, T. de, Hsie, B. S. de, & Endres, L. (2010). Environmental influence on the physico-chemical and physiological properties ofJatropha curcasseeds. *Australian Journal of Botany*, *58*(6), 421. <https://doi.org/10.1071/bt10102>

POWELL, A. A., & MATTHEWS, S. (1978). The damaging effect of water on dry pea embryos during imbibition. *Journal of Experimental Botany*, *29*(5), 1215–1229. <https://doi.org/10.1093/jxb/29.5.1215>

POWELL, A. A., & MATTHEWS, S. (1981). A physical explanation for solute leakage from dry pea embryos during imbibition. *Journal of Experimental Botany*, *32*(5), 1045–1050. <https://doi.org/10.1093/jxb/32.5.1045>

POWELL, A. A., OLIVEIRA, M. D. A., & MATTHEWS, S. (1986). The role of imbibition damage in determining the vigour of white and coloured seed lots of dwarf french beans (phaseolus vulgaris). *Journal of Experimental Botany*, *37*(5), 716–722. <https://doi.org/10.1093/jxb/37.5.716>

R Core Team. (2017). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from <https://www.R-project.org/>

Ruttanaruangboworn, A., Chanprasert, W., Tobunluepop, P., & Onwimol, D. (2017). Effect of seed priming with different concentrations of potassium nitrate on the pattern of seed imbibition and germination of rice ( oryza sativa l.). *Journal of Integrative Agriculture*, *16*(3), 605–613. <https://doi.org/10.1016/s2095-3119(16)61441-7>

SHAH, S. (2005). Extraction of oil from jatropha curcas l. seed kernels by combination of ultrasonication and aqueous enzymatic oil extraction. *Bioresource Technology*, *96*(1), 121–123. <https://doi.org/10.1016/j.biortech.2004.02.026>

THORNTON, J. M., POWELL, A. A., & MATTHEWS, S. (1990). Investigation of the relationship between seed leachate conductivity and the germination of brassica seed. *Annals of Applied Biology*, *117*(1), 129–135. <https://doi.org/10.1111/j.1744-7348.1990.tb04201.x>

Vertucci, C. W., & Leopold, A. C. (1984). Bound water in soybean seed and its relation to respiration and imbibitional damage. *PLANT PHYSIOLOGY*, *75*(1), 114–117. <https://doi.org/10.1104/pp.75.1.114>

Wei, T., & Simko, V. (2017). *Corrplot: Visualization of a correlation matrix*. Retrieved from <https://CRAN.R-project.org/package=corrplot>

Windauer, L. B., Martinez, J., Rapoport, D., Wassner, D., & Benech-Arnold, R. (2011). Germination responses to temperature and water potential in jatropha curcas seeds: A hydrotime model explains the difference between dormancy expression and dormancy induction at different incubation temperatures. *Annals of Botany*, *109*(1), 265–273. <https://doi.org/10.1093/aob/mcr242>

Windauer, L., Altuna, A., & Benech-Arnold, R. (2007). Hydrotime analysis of lesquerella fendleri seed germination responses to priming treatments. *Industrial Crops and Products*, *25*(1), 70–74. <https://doi.org/10.1016/j.indcrop.2006.07.004>

Yaklich, R. W., & Kulik, M. M. (1979). Evaluation of vigor tests in soybean seeds: Relationship of the standard germination test, seedling vigor classification, seedling length, and tetrazolium staining to field performance1. *Crop Science*, *19*(2), 247. <https://doi.org/10.2135/cropsci1979.0011183x001900020019x>