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氧传感技术在板栗种子活力检测中的应用

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摘 要:【目的】探讨氧传感技术在板栗种子活力快速测定中的应用效果。【方法】分别采集板栗'浙早1号''浙早2号'各5个母株的种子材料,通过老化处理0、24、48 h,分别获得各品种3个活力梯度的15份种子样品,然后进行氧传感测定以及室内标准发芽和田间出苗比较试验。【结果】经老化处理后,板栗种子活力开始下降,老化时间越长下降幅度越大。相关分析表明,氧气消耗指数(O_{CI})、氧气消耗速率(O_{CR})与'浙早1号'板栗种子的标准发芽率、杭州及温州田间出苗率均呈显著相关,O_{CI}、理论萌发时间(T_{GT})与'浙早2号'板栗种子的3个发芽指标均呈显著相关。【结论】O_{CI}是评价2个板栗品种种子活力的最佳指标,并在贮藏种子的活力检测中得到了验证。

关键词:板栗;种子活力;氧传感技术;氧气消耗指数(O_{CI})

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Application of oxygen sensing technology in seed vigor testing of *Castanea mollissima*

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Abstract:【Objective】*Castanea mollissima* has a growing history of over 2 000 years in China and plays an important role in the economy. It is also one of the oldest edible seeds in the northern hemisphere, which has been extensively consumed in the past, suggesting that chestnut is a good source of bioactive substances including levels of vitamins, fibers, essential fatty acids and minerals. There is increasing evidence that the consumption of chestnuts is becoming more important in human nutrition due to the health benefits provided by the presence of antioxidants. Its seed vigor reflects field emergence performance and it is one of the most important indices of seed quality. Nowadays, standard germination experiments are still the unique determination method for seed vigor of *C. mollissima*. However, the germination test takes a very long time (up to 35 days). Oxygen-sensing technology is a new tool for seed vigor testing based on oxygen consumption during seed germination. Oxygen-sensing testing can be completed when the radicle breaks through the testa. Our objective was to find the relationships among oxygen-sensing indices and germination performances under laboratory and field conditions and then build a rapid seed vigor determination method for *C. mollissima*.【Methods】Two varieties of *C. mollissima*, 'Zhezao No.1' and 'Zhezao No.2' were used for our experiment. For each variety, seeds of five mother plants were collected from Zhuji Forestry Institute in Zhejiang, China. Fifteen samples of 3 vigor levels were obtained by artificial aging treatments (0 h, 24 h, 48 h). An oxygen-sensing machine developed by the Netherlands ASTEC Global Company was employed to measure the oxygen contents during seed germination of *C. mollissima* in a darkened closed system at 25 ℃. Four oxygen metabolism indices were calculated: oxygen consumption index (O_{CI}), oxygen consumption rate (O_{CR}), critical oxygen concentration (C_{OC}) and theoretical germination

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time (T_{GT}). In addition, laboratory standard germination tests and filed emergence tests were conducted as the most direct indices of seed vigor were determined to be in Hangzhou and Wenzhou.【Results】Seed vigor of *C. mollissima* began to decrease after seeds were subjected to artificial aging treatments. Germination rate, emergence rate and oxygen metabolism indices used to describe seed quality of both cultivars were ranked in descending order as: aging for 0 h > aging for 24 h > aging for 48 h. Furthermore, seeds of the variety 'Zhezao No.1' generally had higher quality than did seeds of 'Zhezao No.2', except for the C_{OC} value. The oxygen metabolism indices, except the T_{GT} value and the C_{OC} value, were significantly correlated with the three germination indices of *C. mollissima* variety 'Zhezao No.1'. The O_{CR} value showed a significant positive correlation with the germination rate, whereas it was not significantly correlated with the emergence rates at both field locations. However, for the *C. mollissima* cultivar 'Zhezao No.2', the O_{CI} value and the T_{GT} value were significantly correlated with the three germination indices. The O_{CI} value showed a significant positive correlation with the germination rate, but it was not significantly correlated with the emergence rate at both field locations, which was the same as 'Zhezao No.1'. The C_{OC} value was significantly correlated with the germination rate, whereas it was not significantly correlated with the emergence rates at both locations. In general, only the O_{CI} value was significantly correlated with the three germination indices of both varieties and it was used to further evaluate seed quality during storage. The germination rate of *C. mollissima* variety 'Zhezao No.1' initially decreased with increasing storage time in all four storage conditions. The germination rate was 77.0% after low-temperature sand storage for 2 months. After low-temperature sand storage for 4 months, the germination rate decreased to 60.0%. Seeds stored at room-temperature in dry storage had the lowest germination rate. After room-temperature dry storage for 1 month, seed germination peaked at 62.0%, while the germination rate decreased to 6.0% after three-months of storage. The change trend of the germination rate was similar for the seeds treated with low-temperature dry storage and room-temperature sand storage. After seeds were stored under low temperature and dry environmental conditions for 1 month, seed germination peaked at 69.0%, whereas the germination rate decreased to 17.0% after three-months of storage. After seeds were treated with room-temperature sand storage for 2 months or 4 months, the germination rate decreased to 63.0% and 20.0%, respectively. In addition, the effects of different storage treatments on the O_{CI} value of the 'Zhezao No.1' variety showed similar changes as those for the germination rate. The O_{CI} value of 'Zhezao No.1' gradually decreased with prolonged storage time under the four storage conditions, suggesting that the seed respiration of *C. mollissima* always reduced after storage. Furthermore, seed respiration under the conditions of dry storage rapidly decreased while seed respiration under the conditions of sand storage was slowly reduced. All the above results suggest that the optimal method is low-temperature sand storage for *C. mollissima*. Above all, the results of the correlation analysis showed that O_{CI} and O_{CR} were significantly correlated with standard germination rates and field emergence rates in Hangzhou and Wenzhou of 'Zhezao No.1', and O_{CI} and T_{GT} were significantly correlated with the above three indices of 'Zhezao No.2'. More importantly, the seed vigor of *C. mollissima* needs to be determined for 35 days by a standard germinations test, while only 10 days are required for the oxygen-sensing test. The determination time of the new technology was greatly shortened.【Conclusion】The results of variance analysis showed that through field emergence percentages, the O_{CI} value could significantly distinguish the seed vigor of 'Zhezao No.1' and 'Zhezao No.2' into 3 levels, respectively. In a word, the O_{CI} value was the optimal index to assess seed vigor of both varieties of *C. mollissima*, which was validated in vigor monitoring of stored seeds. Compared with the standard germination test, the seed vigor detection time of *C. mollissima* was greatly shortened by the O_{CI} value and about 25 days were saved.

Key words: *Castanea mollissima*; Seed vigor; Oxygen-sensing technology; Oxygen consumption index (O_{CI})

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国内外种子活力测定研究更多倾向于农作物种子，对林木特别是一些具有较高经济和食用价值的果树种子研究较少[1-4]。板栗（*Castanea mollissima*）又名栗子，是原产于我国的世界著名干果，可食用、药用，也可供观赏用，具有较高的经济和药用价值[5]；分布于北半球的亚洲、欧洲、美洲和非洲，现已广泛栽培；板栗营养丰富，品质优良，富含淀粉、蛋白质和粗脂肪；其中维生素C含量比西红柿高，是苹果的十几倍；矿物质尤其含钾量是苹果的3倍多，有“休闲果品”之王、“铁杆庄稼”之誉；故发展板栗产业具有重要的经济、生态和社会价值[6-8]。

板栗种子是典型的生理后熟种子，在自然条件下脱落后，种胚约需经过3个月的发育过程才具备萌发能力。了解板栗在繁育过程的出苗效果须首先对其种子质量进行评价。目前评价板栗等特色果木种子质量的主要方法是种子发芽率的测定。种子活力是衡量种子质量的重要指标，甚至有人把它作为种子质量的同义词，它决定了种子在田间的出苗情况；但迄今仍未见板栗种子活力检测方法研究的报道[4,9-10]。鉴于板栗种子发芽测定周期较长，因此，研究板栗种子活力快速测定方法具有非常重要的理论意义与实际应用价值。

目前，关于种子活力的检测方法主要集中在生理、生化、物理、组织化学、种子形态特征等方面[4,11-16]。氧传感技术是荷兰ASTEC Global公司基于荧光猝灭原理开发的，通过测定种子萌发早期过程中的耗氧量来反映种子的质量和活力状况，一般在种子萌动之前，即胚根伸出前即可结束，具有直接、快速、真实、可靠等特点，在种子活力检测的基础研究和商业应用中具有划时代的意义[4,17]。然而，ASTEC Global公司仅开发了甜菜等小粒种子的氧传感测定方法，至于大粒果木种子如板栗等，目前还没有专门的测定标准[4,17]。笔者通过测定不同品种、不同活力梯度板栗种子萌发过程中的耗氧情况，探讨氧传感测定指标与发芽测定指标的相关性，为板栗及其他大粒特色果木种子活力的快速测定和生产经营提供理论依据和技术参考。

1 材料和方法

1.1 材料

板栗品种‘浙早1号’和‘浙早2号’均采自各品种纯林，树木年龄约8 a（年），待其果实7~8分成熟时开采，地点位于浙江省诸暨市林业科学研究所板栗林品种基地30°阳坡的中段处（N29°71′，E120°25′；海拔110 m；年平均气温16.3 ℃，年均日照约1 887.6 h；年平均降雨量约1 373.6 mm，相对湿度约82.0%；具有典型的丘陵山地气候特征）。采摘经脱外果皮后的种子均置于含水量10.0%沙中于4 ℃下贮藏备用（沙子过2 mm筛孔，然后用双氧水消毒，最后于180 ℃下烘干1 h）。

1.2 方法

所用的板栗种子在7~8分成熟时赴浙江诸暨进行现场采摘，并经过常温条件下3个月发育过程（后熟）具备较好的萌发能力后用于以下试验。

1.2.1 种子老化处理 在40 ℃和95.0%相对湿度下，将以上各品种贮藏种子分别在老化箱（LH-150S型，杭州托普公司）中处理0、24、48 h后获得3种活力梯度种子，这样共获得种子样品6份。

1.2.2 种子氧传感测定 便携式氧传感检测仪（荷兰ASTEC Global公司提供）用于板栗种子氧传感测定。含有感光材料的荧光物质喷涂在试管的上部，试管委托荷兰ASTEC Global公司生产。本试验在浙江农林大学中荷种子技术研发中心进行，首先根据种子大小和耗氧情况，确定种子萌发所需试管的大小为25 mL，然后往试管基部加入5 mL 0.50%（φ）琼脂溶液，待凝固后，每个试管加入1粒种子，其中1个试管不加种子作为空白对照管，最后拧紧盖子，于25 ℃下培养。将检测仪与电脑相连，然后将光纤传导线与检测仪发光部位相连，启动测定软件（3.0版）。将温度设定为25 ℃，将连续测定的次数设定为4次，将每个试管间测定间隔时间设定为6 s，每天同一时间测量1次，直至10 d，自动获得实时测定的氧气浓度信息。每样品取10粒种子，5次重复。

1.2.3 种子室内发芽试验 随机选取50粒种子，进行室内标准发芽试验，砂子过2 mm孔径筛孔，然后于烘箱中180 ℃高温消毒1 h，冷却后用蒸馏水将砂子湿度调至10.0%，置于20 cm×30 cm自制发芽盒中，使基部沙子厚度达到6 cm，放入种子后覆砂2 cm，于25 ℃黑暗下培养，35 d后统计发芽种子数并计算发芽率，3次重复。

1.2.4 种子田间出苗试验 每样品种子50粒，条播，覆土2 cm，行距20 cm，株距10 cm，35 d后统计出苗数并计算田间出苗率，3次重复。试验地分别在

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浙江省临安市浙江农林大学官塘农场和浙江省温州市农业科学院创业园进行，环境条件参照Zhong等[4]的设置。

1.2.5　种子贮藏试验　分别采用4种方式（室温干藏法、室温沙藏法、低温干藏法、低温沙藏法）贮藏种子8个月。贮藏前经测定‘浙早1号’板栗种子的含水量为53.4%，发芽率为90.0%。不同贮藏方式具体操作参照Zhong等[4]的方法。

1.2.6　数据处理　根据以上获得的氧气浓度测定绝对值，首先计算试管内每天氧气浓度的相对值（oxygen relative value，O_{RV}）/%，即：实际氧气浓度/空管氧气浓度×100。在此基础上，计算4个氧代谢值：氧气消耗指数（oxygen consumption index，O_{CI}）、氧气消耗速率（oxygen consumption rate，O_{CR}）、临界氧气浓度（critical oxygen contentration，C_{OC}）、理论萌发时间（theoretical germination time，T_{GT}）。以上4个氧代谢值的计算公式如下（其中T为测定的时间）：

$$O_{CI} = \Sigma[O_{RV(T-1)} - O_{RV(T)}] / T \quad (1)$$

$$O_{CR} = \Sigma[O_{RV(T-1)} - O_{RV(T)}] / 10 \quad (2)$$

$$C_{OC} = O_{RV(6)} \quad (3)$$

$$T_{GT} = \Sigma[(O_{RV(T-1)} - O_{RV(T)}) \times T] / \Sigma[O_{RV(T-1)} - O_{RV(T)}] \quad (4)$$

用SAS 8.2和SPSS 22.0统计软件进行相关数据的方差分析和相关分析。

2　结果与分析

2.1　板栗种子活力氧传感检测方法的建立与分析

氧传感技术通过种子萌发过程中的耗氧情况来反映种子的活力状况，为验证板栗不同老化处理之间及标准发芽、室内和田间种子发芽试验的相关性，以便对种子活力进行精确评估，笔者还进行了杭州和温州2地的田间发芽试验。结果表明，经老化处理后板栗种子活力开始下降，老化时间越长下降幅度越大。

同时，根据测定计算的30粒种子萌发过程中氧气的相对浓度，绘制了板栗种子的耗氧曲线（图1）。从图1可以看出，板栗种子的耗氧曲线呈逐渐下降的趋势，分别在萌发6 d后试管内氧气浓度基本趋于稳定，此时胚根已突破种皮萌发，对应的氧气相对浓度O_{RV}值即为C_{OC}值。10 d后板栗种子不再耗氧，此时检测即可结束。通过标准发芽试验测定板栗种子活力需要35 d。

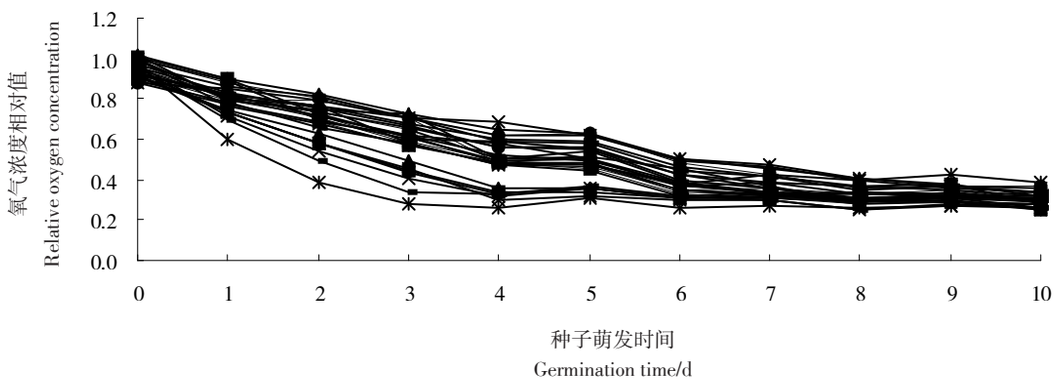

图1　板栗种子萌发过程的耗氧曲线

Fig. 1 Oxygen consumption curves of *Castanea mollissima* during seed germination

2.1.1　板栗种子活动测定候选指标　根据板栗种子萌发过程中的氧气浓度测定，通过计算可以获得多个氧代谢指标。O_{CI}为种子耗氧量与当天时间商的累加值，O_{CR}是种子单位时间内的耗氧量[单位：%（φ）·d^{-1}]，C_{OC}是种子耗氧趋于稳定时氧气浓度的临界值[单位：%（φ）]，T_{GT}是根据氧传感检测推测的萌动时间（即吸胀到胚根突破种皮的时间）（单位：d）。

2.1.2　板栗种子活力测定候选指标与其发芽测定指标的相关分析　由表1可知，O_{CI}和O_{CR}与其发芽测定指标呈正相关关系，T_{GT}和C_{OC}与其发芽测定指标呈负相关关系。‘浙早1号’板栗种子的O_{CI}、O_{CR}与3个发芽测定指标间均呈极显著正相关；T_{GT}、C_{OC}与室内标准发芽率间也呈显著负相关，但它们与2个田间出苗率间相关关系不显著。‘浙早2号’板栗种子的O_{CI}与室内标准发芽率间相关关系极显著，与2个田间出苗率间相关关系显著；O_{CR}虽与室内标准发芽率

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表 1 板栗种子氧传感测定指标与其发芽测定指标的相关系数

Table 1 Correlation coefficients between oxygen metabolism indices and germination data of seeds from two cultivars of *Castanea mollissima*

	氧气消耗指数 Oxygen metabolism index, O_{CI}		氧气消耗速率 Oxygen metabolism rate, O_{CR}		理论萌发时间 Theoretical germination time, T_{GT}		临界氧气浓度 Critical oxygen pressure, C_{OC}	
	浙早1号 Zhezao No.1	浙早2号 Zhezao No.2	浙早1号 Zhezao No.1	浙早2号 Zhezao No.2	浙早1号 Zhezao No.1	浙早2号 Zhezao No.2	浙早1号 Zhezao No.1	浙早2号 Zhezao No.2
室内标准发芽率 Germination rate, G_R	0.752**	0.664**	0.781**	0.603*	−0.518*	−0.786**	−0.557*	−0.534*
杭州田间出苗率 Emergence rate in Hangzhou, H_{ER}	0.719**	0.613*	0.747**	0.511	−0.467	−0.662**	−0.451	−0.496
温州田间出苗率 Emergence rate in Wenzhou, W_{ER}	0.746**	0.598*	0.757**	0. 453	−0.486	−0.695**	−0.462	−0.513

注：*表示在 $P < 0.05$ 显著；**表示在 $P < 0.01$ 显著。

Note: * or ** is significantly different at $P < 0.05$ or $P < 0.01$, respectively.

之间呈显著相关，但与2个田间出苗指标间的相关关系不显著；T_{GT}值与3个发芽指标间均呈极显著负相关；C_{OC}虽与室内标准发芽率之间呈显著负相关，但与2个田间出苗指标间的相关关系不显著。由此可见，板栗种子的氧代谢值与其室内和田间发芽指标间均存在一定的相关关系。

以上结果表明，O_{CI}是评价2个板栗品种种子活力的理想指标，但不同品种板栗种子活力的氧传感检测最佳指标略有差别；O_{CR}对评价‘浙早1号’板栗种子活力具较理想效果，而T_{GT}则是评价‘浙早2号’板栗种子活力的理想指标。

2.2 O_{CI}值在贮藏种子活力检测中的验证

2.2.1 不同贮藏方式对种子发芽的影响 以‘浙早1号’板栗品种为例，挑选饱满大小一致的种子，贮藏前测定其种子的含水量（ω）为53.4%，发芽率为90.0%；采用前面4种方式（室温干藏法、室温沙藏法、低温干藏法、低温沙藏法）贮藏4个月后，对其不同贮藏方法的耗氧特征，以及呼吸代谢与种子活力的关系进行比较研究（图2、图3）。

由图2可知，随着贮藏时间的延长，4种贮藏方法的‘浙早1号’板栗种子的发芽率逐渐降低，但是降低幅度各不相同；降低幅度从小到大依次是低温沙藏法、室温沙藏法、低温干藏法、室温干藏法。贮藏效果最好的是低温沙藏法，贮藏2个月后仍保持较高活力（发芽率为77.0%），4个月后的发芽率仍可达60.0%。贮藏效果最差的是室温干藏法，贮藏1个月后发芽率即降低为62.0%，3个月后发芽率降为6.0%，基本失去发芽能力，4个月后完全失去发芽能

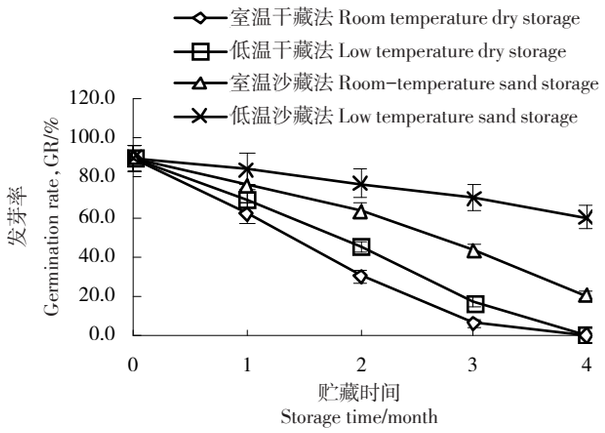

图 2 ‘浙早 1 号’板栗种子贮藏时间与发芽率的关系

Fig. 2 Relationship between storage time and germination rate of ‘Zhezao No.1’

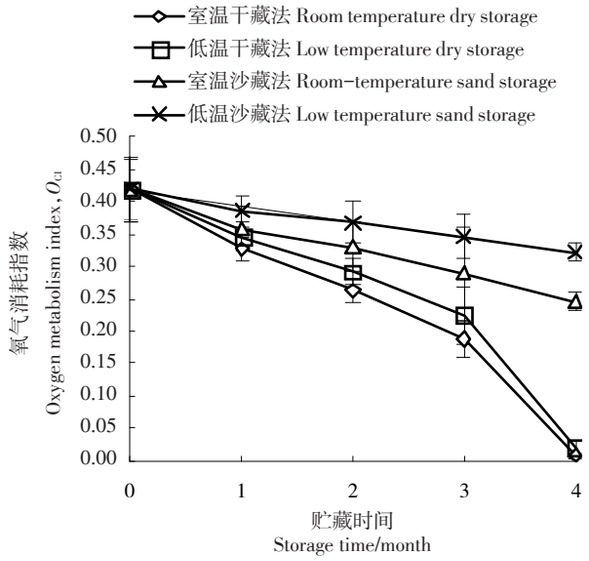

图 3 ‘浙早 1 号’板栗种子贮藏时间与呼吸代谢的关系

Fig. 3 Relationship between respiratory metabolism and germination rate of ‘Zhezao No.1’

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力。室温沙藏法贮藏2个月后发芽率降低到63.0%，4个月后发芽率降低到20.0%。低温干藏法贮藏1个月后发芽率降低到69.0%，3个月后发芽率降低到17.0%，4个月后完全失去发芽能力。

2.2.2　不同贮藏方式对种子耗氧关系的影响　为深入探讨种子贮藏过程中耗氧量的生理机制，试验采用氧传感技术测定了不同贮藏方式与过程中的种子呼吸代谢水平。由表1可知，'浙早1号'板栗种子活力氧传感检测的最佳指标是O_{CI}值。由图3可知，O_{CI}值若处在0.35~0.42 %·d^{-1}，'浙早1号'板栗种子则可保持较高的活力（发芽率约80.0%）。

同时，在'浙早1号'板栗种子贮藏过程中利用氧传感技术分析其呼吸代谢水平。结果表明，氧传感检测指标O_{CI}值随着贮藏时间的延长而逐渐降低，与发芽率呈显著正相关（图3）。这说明，板栗种子随着贮藏时间的延长，其呼吸强度逐渐降低。但4种贮藏方法略有区别，室温干藏法和低温干藏法贮藏的种子呼吸代谢强度下降幅度较大，室温沙藏法和低温沙藏法贮藏的种子呼吸代谢强度下降幅度较小。

2.2.3　O_{CI}值与种子发芽率的关系分析　以上结果表明，在4种贮藏方式下，随着贮藏时间的延长，'浙早1号'板栗种子的O_{CI}值与其发芽率的变化规律基本一致。进一步的相关分析结果表明，O_{CI}值与其发芽率之间的直线相关系数为0.909，达到了极显著水平。以O_{CI}值为自变量，发芽率为因变量，建立了一元二次回归方程$y=959.36x^2-138.22x+1.03$（图4），可对发芽率进行预测。

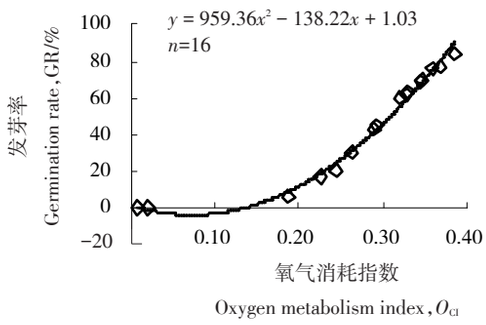

图4　'浙早1号'板栗种子O_{CI}值与发芽率的回归关系

Fig. 4 Regression relationship between O_{CI} and germination rate of 'Zhezao No.1'

3　讨　论

种子活力是一个复杂的性状指标，它反映了种子的田间出苗表现，种子活力评价最直接的指标是其发芽能力；而面对广泛的田间条件，如何精确地测定种子活力是一个值得深入探讨的课题。自20世纪50年代，科学家发现种子活力决定了种子的田间出苗能力以及对后续的农林业生产有重大影响后，世界各国对种子活力的研究与检测新方法层出不穷[17-18]。而国内则直到上世纪80年代郑光华才首次提出种子活力的概念，他认为种子活力就是种子的健壮度，包括种子迅速、整齐发芽的潜力和生长、生产潜力[18-19]。因此，种子活力指标与室内标准发芽率相比，更能客观准确地反映其质量状况。

当前果树种子特别是大粒种子活力评价的主要方法仍然以发芽试验为主，生理生化指标的应用较少，先进技术在果树种子活力检测中的应用更罕见[18-20]。基于发芽试验，Wang[20]最先采用幼苗生长测定法评价红松种子的活力，随后成为一个普遍使用的方法被沿用至今。电导率测定法在小粒林木种子上应用较多，如杉属、松属等的种子[21-23]；但电导法受水质、种子本身含水量、机械损伤程度等多种因素的影响。目前，氧传感技术已在水稻和小粒林木种子的活力水平检测中有所应用[4,23]，而在种子的氧代谢指标与其田间出苗指标的相关性研究，尤其是大粒种子中，应用较少[4]。为验证它们之间的相关性和对种子活力进行精确评估，笔者还补充完成了室内和田间发芽试验，结果表明，经老化处理后板栗种子活力开始下降，老化时间越长下降幅度越大，这与经典理论相符[17,23]。更为重要的是，标准发芽试验测定板栗种子活力需要35 d，但通过氧传感测定仅需10 d，检测时间大大缩短。

本研究结果表明，物种不同乃至物种内品种的差异，种子活力评价的最佳指标亦不同。与其他氧代谢指标相比，T_{GT}和O_{CR}分别是评估杉木、银杏和马尾松种子活力的最佳指标[4,23]。而本研究，O_{CI}值是评价板栗'浙早1号''浙早2号'种子的理想指标；O_{CR}值不仅是评价'浙早1号'和'浙早2号'板栗种子室内发芽水平的理想指标，而且也是评价'浙早1号'板栗种子杭州、温州田间出苗水平的理想指标；T_{CT}值不仅能较好地评价'浙早2号'板栗种子3个指标间的出苗水平，也是评价'浙早1号'板栗种子室内发芽水平的理想指标；C_{OC}值则不适合评价板栗'浙早1号''浙早2号'的两地田间出苗水平。以上结果充分说明，种子活力的氧传感测定方法存在物种甚至品种间的差异性，基因型可能是影响不同指标表

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现差异的主要原因。此外，笔者提出可通过一元二次回归方程来预测板栗种子的发芽率。但需要注意的是，仅当O_{CI}值在0.01~0.39之间取值时，可靠程度比较高；如果氧传感测定数值不在上述范围内，则需要通过更多的试验数据进一步验证，以提高其预测的可靠性。笔者不建议采用O_{CI}值的回归方程来预测板栗种子的田间出苗率，因决定系数（表1中相关系数r的平方值）仅为0.358~0.557。

贮藏方法的正确性及贮藏条件的适宜性，均关系到种子的活力，进而影响种子的品质。但生产上却常因贮藏条件和贮藏方式的不当造成种子活力下降，以致浪费大量的优质种子，给生产、经营带来较大的损失。本试验条件下，贮藏后的种子，随着贮藏时间的延长，4种贮藏方法贮藏种子的发芽率均会表现出一定程度的降低趋势，贮藏效果最好的是低温沙藏法。原因可能是低温沙藏法一方面可以让种子水分得到及时补充，保持种子的旺盛生命力；另一方面也为种子的萌发提供了条件，让其呼吸强度仍保持较高的水平，能较好地保持种子的活力。因此值得推广应用。

在‘浙早1号’板栗种子贮藏过程中采用氧传感技术分析其呼吸代谢水平，结果表明氧传感检测指标O_{CI}值随着贮藏时间的延长而逐渐降低，与发芽率呈正相关。这说明，板栗种子随着贮藏时间的延长，其呼吸强度逐渐降低，原因可能是刚收获的种子活力最高。但随着贮藏时间的延长，种子开始慢慢老化，活力逐渐降低，呼吸代谢强度逐渐减弱。且4种贮藏方法又略有区别，以室温沙藏法和低温沙藏法贮藏的种子呼吸代谢强度下降幅度最小。其原因可能是干藏法随着贮藏时间的延长，顽拗型板栗种子含水量越来越低，从而导致种子脱水死亡；而沙藏法可以使种子的水分得到及时补充，种子能够保持其生命力，同时也为种子的萌发提供了条件：因此低温沙藏法种子的呼吸强度仍保持较高的水平。这也说明板栗种子适合于随采随播或应用低温沙藏法贮藏后于早春再播种，这与生产实际相吻合。

种子质量是提高农作物和果树产品产量、品质的基础，是种子种苗企业的生命，是促进农林业生产发展的重要保证。种子活力是决定种子在发芽和出苗期间活性水平和行为的种子特性的综合表现[24]。若应用单一的种子活力测定方法较难准确全面地反映其活力的真实水平，通常可同时采用几种方法综合评定[25]。李淑贤等[26]按照平均生化指数法将电导率、丙二醛含量、硝酸还原酶活性、超氧物歧化酶活性、发芽指数、发芽值、壮苗率等活力指标的数据进行处理，所形成的活力综合值与田间出苗率相关程度很高。因此，若能将传统检测方法与氧传感检测方法结合起来将更能准确地反映板栗种子的活力水平，为农林业生产提供更准确的参考数据。

4 结 论

O_{CI}、O_{CR}是评价‘浙早1号’板栗种子的理想指标，O_{CI}、T_{GT}是评价‘浙早2号’板栗种子的理想指标，建议通过O_{CI}快速评价板栗种子的活力水平，相比标准发芽时间测定可节省25 d。

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