



土壤通气性与加氧灌溉研究进展*

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摘 要 水、肥、气、热是保障土壤肥力的四大要素, 传统的灌溉方式往往忽视了气这一重要因素。土壤通气性不足, 四个因素之间的平衡被打破, 土壤理化性质变差, 对作物生长造成不利影响, 进而引起减产。良好的土壤通气性是作物正常生长发育的保证。加氧灌溉通过采用合理的方法改善土壤通气状况, 协调土壤四大要素之间的关系, 提高土壤肥力, 满足作物生长的需要。研究表明, 加氧灌溉可提高作物产量、改善作物品质。本文从根区低氧胁迫的影响分析入手, 评述了土壤通气性的量化指标、测算方法和控制标准, 综述了加氧灌溉技术及其应用, 总结了加氧灌溉研究中存在的问题, 探讨了加氧灌溉对土壤通气性的改善作用, 提出了加氧灌溉与土壤通气性研究展望, 以期今后的研究提供参考。

关键词 低氧胁迫; 加氧灌溉; 溶解氧; 土壤通气性; 评价指标

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土壤通气性对作物正常的生长发育至关重要^[1-3]。土壤通气性是土壤中气体和大气之间不停地进行气体互换的功能; 由于互换的气体主要是氧气与二氧化碳, 故又称为土壤呼吸作用。土壤呼吸作用主要由土壤微生物呼吸和根系呼吸组成。根系呼吸作用不但为植物生命活动供给能源, 而且呼吸作用的中间代谢产物为植物的物质合成提供了原料^[4]。通过微生物呼吸作用完成底物的分解和细胞物质的合成, 实现了土壤养分的循环与转化^[5]。为了保持正常的土壤呼吸作用, 土壤中必须富含空气。土壤氧气浓度较低时会造成根区低氧胁迫, 进而影响作物正常的生理代谢和生长发育^[6]。低氧胁迫是由于土壤紧实或者地下水位较高或者不合理灌溉导致的土壤通气性不畅, 根系及微生物呼吸作用减弱, 作物呼吸作用和生长发育表现异常的现象^[7]。低氧胁迫会对作物产生一些不利的影响, 包括: (1) 作物的新陈代谢速率下降, 生长和发育进程延缓^[8-9], 植物有氧呼吸受阻或者中断,

呼吸作用产生的三磷酸腺苷(ATP, 高能磷酸化合物)水平下降^[10]。(2) 低氧胁迫下作物根系进行无氧呼吸, 一些根系死亡, 植物地上部分则表现为叶片萎缩^[11]。由于根系缺乏足够的氧气供应, 作物水分和养分利用效率下降, 作物鲜重和干重显著下降^[12-14]。(3) 低氧胁迫下作物根区无氧呼吸酶活性显著提高^[15], 土壤微生物数量下降, 土壤动物的正常生理活动受到阻碍^[7]。为缓解低氧胁迫对作物造成的不利影响, 应提高土壤中氧气的浓度^[8], 改善土壤通气性。土壤通气性是表征土壤透气性和土壤中氧含量的综合指标, 也是表示土壤肥力的综合指标之一^[1-2], 反映了土壤生物耗氧和二氧化碳产生过程及其与土壤与大气之间的气体传输过程之间的相互关系^[16]。加氧灌溉是地下滴灌技术(Subsurface drip irrigation, SDI)的改进, 至今有20多年的历史。加氧灌溉通过地下滴灌系统将氧气或者含氧物质输送到作物的根区, 满足根系生长发育的需要改善土壤通气性, 协调土壤

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水、肥、热条件,促进作物生长发育^[17-18],有效提高作物产量和品质^[19-20]。本文在系统论述土壤通气性与加氧灌溉研究的基础上,探讨土壤通气性与加氧灌溉研究中存在的问题,提出未来的研究热点与方向。

1 土壤通气性研究

1.1 土壤通气性的作用

研究表明,氧气在水中和空气中的扩散系数差异较大,氧气在空气中的扩散速率近似于水中的10 000倍^[3]。灌溉过程中随着土壤湿度的不断升高,土壤孔隙中的空气被水所驱替,直至整个土壤孔隙全部被水填充。由于土壤中氧气扩散速率的下降,空气中的氧气进入到土壤中的部分与灌水之前相比变得很少。因作物根系持续消耗氧气,所以灌溉过程中土壤氧气浓度快速下降、二氧化碳含量呈现升高趋势,根系有氧呼吸作用受到抑制。同时,根区的微生物与根系争夺氧气;缺氧条件下,作物根部无氧呼吸产生的乙醇对植物有害,ATP和一些呼吸代谢产物供应不足影响植物的生物合成^[4]。根系氧气浓度持续低下,有氧呼吸受阻,厌氧微生物得到繁殖,根系生长出现异常,严重时作物死亡,造成农业减产。土壤通气性对作物种子萌发至关重要^[21],土壤通气性对土壤微生物的活性和养分的转化也有影响^[17]。土壤通气性对土壤中元素的氧化还原状况有重要影响,如氮、硫、铁等在通气不良时产生一些还原性物质,对植物生长发育极为不利^[22]。

良好的土壤通气性可保障土壤空气质量,有利于作物生长发育,保持较高的土壤肥力^[23]。土壤通气不畅,作物生长发育受到抑制^[24],产量大幅度下降。土壤通气性改善促进了作物干物质积累,增加了块根的产量^[25]。提高土壤氧气浓度,协调土壤水、肥、气、热状况,是解决水稻氮素利用效率低下的有效途径^[26]。根际土壤通气可有效提升作物水分和养分利用效率,促进作物生长潜力的发挥,提高作物根鲜重、根干重和根系活力,增强呼吸作用速率和气孔导度,改善光合作用,提高作物产量^[27-28]。

1.2 土壤通气性量化指标

土壤中气体的扩散包括气体在土壤剖面的宏观

扩散以及因土壤空间变异导致的微观扩散和气体透过水膜到达根表的扩散两个过程。Stepniewski等^[22]认为,气体的扩散直接依赖于土壤气体扩散系数,土壤气体扩散系数由充气孔隙度状况,即土壤水分数量及土壤孔隙的连通状况决定;土壤气体扩散间接依赖于土壤紧实度、耕作、灌溉和排水等其他影响因素。描述土壤通气性的过程指标包括:土壤气体扩散系数、土壤透气性、土壤充气孔隙度和土壤气体组成等4个方面。但是这4个方面的指标很少能成功刻画与作物生长的关系^[29]。这是因为土壤通气性过程中氧的供应包括三个连续的环节,首先,氧气从大气扩散到土壤孔隙中,其次,氧气以溶解氧方式通过根外水膜扩散到根系表面,最后,是氧气由根系表面扩散到根组织内^[30]。土壤通气性指标可归为三类^[31]:第一类为容量指标,气体填充土壤孔隙的体积比例(简称为土壤充气孔隙度);第二类为强度指标,孔隙中的氧气分压或土壤溶液中的氧气含量(Dissolved oxygen, DO);第三类为传输速率,氧气向土壤中某点的供应速率。第三类指标又可分为扩散指标及对流指标两类。氧气扩散速率(Oxygen diffusion rate, ODR)最能反映原位土壤中的氧气水平,它与植物的生理反应、营养特性和植物生长密切相关;对流指标可通过对流测量氧气仪准确测量进入土壤的质量通量,或者直接测定大气与土壤之间的空气压力梯度来计算。通常,土壤通气性的具体指标包括土壤充气孔隙度^[32-33]、土壤氧气浓度或土壤溶解氧浓度(DO)^[34-35]、氧气扩散速率(ODR)、土壤透气性(Ka)、土壤气体扩散系数(Ds)等^[36-37]。

Lemon和Erickson^[30, 38]实验证实,铂金微电极可模拟土壤溶液向根系供氧的速率,因为铂金微电极通过电化学反应消耗氧气。Stolzy和Letey^[39]对ODR与植物生长响应之间进行了综述,得出ODR与植物生长具有良好的响应关系。Feng等^[37]通过对不同质地土壤多个通气性指标的同时监测发现,土壤通气性容量指标不能有效反映与植物生长的关系;ODR直接反映了氧气对植物的有效性,是最具代表性的土壤通气性指标。Wolińska和Stepniewska^[40]研究表明,土壤充气孔隙度、土壤氧气扩散速率与土壤氧化还原电位(ORP, Oxydation-Reduction Potential的缩写,也称为Eh)



呈显著负相关；土壤含水量下降，土壤氧化性加强，土壤通气性得到改善。氧化还原电位表征介质氧化性或还原性的相对程度，土壤中的物理、化学和生物学过程共同导致了氧化还原电位的变化^[41]。土壤中常见的氧化还原离子对有 $\text{NO}_3^-/\text{NO}_2^-$ 、 $\text{Fe}^{3+}/\text{Fe}^{2+}$ 和 $\text{Mn}^{4+}/\text{Mn}^{2+}$ ，反映了土壤的氧化还原状况。ORP是土壤通气性的重要参数，与底物的可利用性和能量转化相关，在调节土壤微生物数量、多样性和群落结构方面发挥着重要作用^[42]。田间条件下影响ORP的因素很多，并且ORP存在着较高的变异性，这些阻碍了ORP成为土壤质量和土壤综合条件的有效评价指标^[43]。土壤透气性是反映气体透过土壤孔隙能力的一个重要物理性质。它既包括单位时间透过单位面积气体的数量，也包括土壤空气交换率对土壤特性的总体影响。土壤透气性能全面地反映土壤质地、结构、紧实度、干湿状况。首先，土壤透气性对土壤氧含量存在显著影响，而且还受土壤质地和容重的影响。其次，灌溉可能会影响土壤的渗透性。土壤透气性的影响因素包括质地、容重、含水量和土壤孔隙度^[44]。气体的相对扩散系数（ D_s/D_0 ， D_0 为大气中空气的扩散系数， D_s 为土壤气体扩散系数）与含气孔隙率之间的关系与气体种类无关，仅仅由土壤性质决定，因此，当讨论土壤气体扩散时常用相对扩散系数来代替扩散系数，以此来消除具体气体的理化性质对扩散系数的复杂影响^[45]。相对扩散系数通常通过模型计算获得^[46]。对 D_s 及 D_s/D_0 的同时测算也可验证变化土壤水分条件下相对扩散系数变化特征及其准确性^[45]。Uteau等^[47]研究了三种不同作物的根系构型对土壤结构和通气性的影响，建立了空气扩散系数、土壤透气性和含气孔隙率与作物种类及种植时间的关系。

土壤具有一定数量的充气孔隙，这些孔隙中充满着气体。因此，只要采集到土壤气体样本，便可确定土壤氧气浓度。通常用特制的空心圆筒钢管垂直深入土壤样品中抽取土壤中的空气^[17]。对于ODR的测量，由于氧气扩散速率在空气中较在水中快得多，土壤中存在可以被作物吸收利用的水分，因此根区供氧的限制可能就是土壤中围绕根区的水膜^[48]。Lemon和Erickson^[30, 38]介绍了一种利用铂电极测量的方法，用一个铂电极和一个参考电极，同时插入土壤中，与土壤水分保持良好接

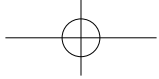
触时，对两电极之间施加一定的电势；在通电的情况下，铂电极附近的氧被快速消耗，几分钟之内，其中的氧被土壤周围的氧取代，并且达到平衡。土壤透气性的测量方法有稳态测量方法和瞬态测量方法，又可分为一维测定方法和三维测定方法等多种^[49-51]。土壤气体扩散系数一般通过实测或者模型估算得到^[52]。

1.3 土壤通气性指标的临界值

根系呼吸速率随着土壤氧气浓度的增大而增加，而根系细胞在二氧化碳浓度2%的条件下4 h就会死亡^[53]。当土壤浓度不能满足作物正常呼吸作用的需要时，一些植物就会减缓生长甚至停止生长^[54]，而且，较低浓度的氧气会破坏土壤微生物群系，厌氧微生物也会更加活跃，并且毒害植物^[55]。所以存在这样一个临界值，即临界氧气浓度，由于氧气浓度限制了根系的呼吸作用，根部的生长活动受到限制，植物生长受到影响^[56]。作物不同生长阶段的低氧胁迫氧气浓度临界值在3%至0.5%之间，最大的临界氧气浓度可能超出15%^[57]。对ODR和ORP而言，同样也存在着临界值。不同的植物对氧气的吸收利用速率不同。对植物生长而言，氧气的供应速率越快，作物呼吸速率也就越快，植物生长和营养物积累速率也越快，所以相对于氧气浓度指标而言，氧气供应速率要重要得多。Stolz和Letey^[39]研究指出，对大多数植物根区而言，临界ODR为 $20 \times 10^{-8} \text{ g cm}^{-2} \text{ min}^{-1}$ ，对一般植物生长而言，ODR为 $40 \times 10^{-8} \text{ g cm}^{-2} \text{ min}^{-1}$ 就可以满足需要。不同的作物临界ORP值不同。pH为7时土壤氧化还原电位通常位于414 ~ 120 mV之间，高于414 mV时为好氧状况，低于120 mV时为缺氧或厌氧状况^[43]。当土壤ORP为350 mV时，土壤中仅含有极少的氧气或根本没有氧气^[58]。Glinski和Stepniewski^[59]指出，相对氧气扩散速率（ D_s/D_0 ）的下限值为0.005，此时土壤呼吸速率达到最低值；上限值为0.02，此时呼吸速率达到最高值。

1.4 提高土壤通气性的方法

目前提高土壤通气性常用的方法有：（1）改良土壤质地和结构。由于砂质土通气性较好，壤土次之，黏土较差，砂土中掺入黏土或者淤泥，黏土中掺入沙子或砂土，可以改变土壤质地，有利于改善土壤通气性^[17]。（2）进行耕作管理，深翻改土。通过翻土，可以改变土壤紧实的状况，降低



土壤容重,增加孔隙含量,提高土壤通气性^[60]。

(3) 秸秆还田。合理的秸秆还田措施能增加土壤腐殖质,疏松土体,提高孔隙率,有利于土壤生物和植株根系的生长^[61]。(4) 加氧灌溉。加氧灌溉提高了土壤氧气浓度,增强了土壤呼吸,改善了土壤通气性^[1, 17]。这些方法对应于作物生长的不同阶段,在种植作物之前,可以进行耕作深翻,还可以在土壤中掺入不同性质的成分来改善土壤通气性。在作物生长阶段,加氧灌溉是适宜有效的方法,在作物收成之后,利用秸秆还田技术不仅可以改善土壤通气性,还能减少秸秆污染,增加有机质,提高肥力。

2 加氧灌溉研究

2.1 灌溉水加氧方法

加氧灌溉的方法包括机械通气、化学加氧、文丘里空气射流器加氧等方法。机械通气是利用空气压缩机对灌溉土壤进行通气的灌溉方法^[62-63]。化学加氧是利用过氧化氢等化学物质进行加氧的方法^[20]。文丘里空气射流器加氧是通过文丘里空气射流器的水流在入口段流速变缓、压力减小而吸入空气或者氧气的方式^[64]。Mazzei空气射流器加氧是文丘里空气射流器加氧的一种^[20]。关于不同加氧灌溉方式的部分研究结果列于表1。

2.2 加氧灌溉的生物效应与效益

加氧灌溉改善了作物根区的生长环境^[65, 69],提高了作物的光合作用效率^[1, 70],增加了作物生长速率,促进根系生长^[64],增加了棉花的产量、提升棉花品质和水分利用效率^[66],利用Mazzei空气射流器对根区加氧,提高根区土壤通气状况,有利于菠萝生长,提高果实产量和品质^[18]。通气灌溉可改善作物根系生长环境,它首先提高了根系的生长速度和水肥的吸收利用^[71],增加叶绿素含量和提高产量^[14]。当土壤水吸力超过进气值时玉米根系伸长速率达到最大^[72],根冠比显著增大^[64]。相对于常规滴灌,采用增氧滴灌可以快速缓解作物根区缺氧状况,根系代谢速率加快^[63, 73]。通过对作物水肥气一体化控制灌溉,可提高肥料利用效率,实现作物高产^[74]。

土壤微生物是土壤中物质转化的驱动力,直接影响着土壤氧化、硝化、氨化、固氮等过程,促进土壤有机质的分解和物质的转化^[5]。加氧灌溉

过程中土壤ORP升高,对提高过氧化氢酶活性有明显作用^[75]。作物生长发育与土壤环境密切相关,在土壤水分和养分供应充分的条件下,加氧灌溉提供了充足的氧气,改善了土壤通气性,促进了土壤微生物数量的增加和活性的提高,有利于根系吸收水分和养分。温室甜瓜加氧灌溉试验表明,加氧滴灌处理后的甜瓜综合效益始终高于沟灌^[76]。通过地下滴灌系统,加氧灌溉的养分分解成小微粒溶解在水中,更易被作物吸收,而且养分直接输送到根部,有效减少地表径流,可最大程度减少地下水及地表水污染^[77]。

2.3 加氧灌溉的拓展应用

加氧灌溉技术可用于地下或者地表灌溉,最大限度地发挥灌溉水的作用。加氧灌溉技术可采取水肥气相耦合的灌溉方式^[78],实现作物适时适量的精确灌溉^[74, 79]。社会经济快速发展的同时,污水数量日益增多,发展再生水灌溉成为迫切需求。由于再生水中一般均含有氮、磷等营养元素,这样还可以减少肥料的使用,对污水进行处理使其满足农业灌溉的要求;同时通过曝气灌溉向灌溉水中进行掺气,快速提高水中氧气含量,既满足了作物生长的需求,又实现了节水增产的目的^[74]。掺气灌溉与喷灌技术相结合形成掺气水射流^[80],改变了喷头的雨滴粒径分布,提高了1倍间距的正方形组合喷灌均匀性;同时,在掺气喷头工作压力低至100 kPa情况下,喷头仍具有76 mm汞柱高差的掺气负压能力,通过与喷头连接农药或水溶性肥料,可实现喷灌条件下水肥气药的一体化管理。

3 加氧灌溉对土壤通气性的改善作用

3.1 灌溉与土壤通气性的关系

灌溉对土壤通气性的影响首先表现在对大气和土壤中氧气及二氧化碳互换的影响上。灌溉过程中土壤含水量急剧上升而驱替土壤空气,由于微生物和生物等对土壤氧气的消耗,使得土壤氧气浓度降低,根系呼吸作用受到抑制,对作物生长不利^[9]。而且,灌溉不当可能导致破坏土壤团粒结构,增大土壤紧实度,降低土壤通气性。所以灌水导致土壤通气性降低, N_2O 排放增加^[81],严重时会使作物死亡^[82]。灌水过多不仅会增加前期投入,导致土壤长时间缺乏氧气^[83],降低光合作用速率^[84],二氧化碳浓度增加,土壤通气性降低,

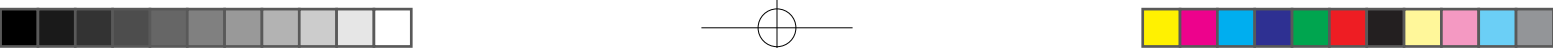


表1 不同加氧灌溉方法的部分研究结果

Table 1 Research results of different oxygation methods						
加氧方法 Aeration technique	作物 Crop	土壤 Soil	产量 Yield	作物反应 Crop response	曝气量 Aeration rate	参考文献 Reference
机械通气 Mechanical ventilation	番茄 Tomato	粉质黏壤土 Silty clay loam	1.0倍和1.5倍根区孔隙通气量 时第一批果实分别+75.1%、 +135.5%	根系生物量增加，果 实产量提高 根系分布，茎粗、单 株叶面积、株高和穗 粒数增加	灌溉后通气量1.0 倍和1.5倍土壤孔 隙体积12%	[62]
	玉米 Corn	砂质黏壤土 Sandy clay loam	2010年较地表滴灌+37.78%，较 地下滴灌+12.27% 2011年较地表滴灌+38.46%，较 地下滴灌+12.5%			[63]
化学加氧 Chemical oxygen adding	西葫芦 Zucchini	重黏土 Heavy clay soil	+25%	根密度增加	5 L hm ⁻² H ₂ O ₂	[20]
	大豆 Soybean	重黏土 Heavy clay soil	+82%	单株荚数和平均荚质 量增加	1 ml L ⁻¹ H ₂ O ₂	
Mazzei空气射流 器加氧 Mazzei air injector	番茄 Tomato	黄黏土 Yellow clayey soil	+29.15%	气孔导度、根冠比和 最大根长增加	15%	[64]
	菠萝 Pineapple	砂壤土 Sandy loam	+4.3%	果实大小、透明物、 含糖量提高	12%	[18]
	辣椒 Pepper	砂壤土 Sandy loam	+39%	数量增加	12%	[65]
	棉花 Cotton	黏土 Clay	+10%	水分利用效率增加	12%	[66]
	菠萝 Pineapple	黏土 Clay	较对照组产量+44%，较不灌溉产 量+26%	果实大小增加	12%	[67]
	番茄 Tomato	中壤土 Medium loam	较不加气+19.49%	茎粗、株高增加	50%	[68]

注：曝气量为空气体积占灌水体积的百分比 Note: Aeration rate is the percentage of the volume of air

作物生长受到抑制^[85]，最终降低产量^[86-87]。

3.2 加氧灌溉对土壤通气性的改善作用

对于植物根系而言，单一目的的灌溉降低了土壤的通气性，有可能造成根系缺氧，严重时会影响作物正常的呼吸作用及生长发育，限制着作物生长潜力的发挥，这一点在黏重和紧实性土壤表现明显。所以在灌水中加入氧气就可以改善土壤通气性不足的局面。加氧灌溉能提高土壤中氧气的浓度，促进土壤二氧化碳的排放，根系活力增强，有利于作物对养分和水分的吸收利用，土壤呼吸作用加

强，土壤通气性改善^[17, 88]，表现为促进作物生长和营养元素吸收利用，产量显著提高^[89-90]。

3.3 土壤通气性改善与土壤性质的响应

土壤物理性质包括土壤质地、土壤结构、土壤孔隙度等，涉及土壤的紧实度、通气性、排水、蓄水能力等等，并且这些性质互相关联。加氧灌溉改善了土壤通气性，不仅满足植物对氧气的需求，而且改变了土壤性质。不良的灌溉会破坏土壤的团粒结构，在土壤表面形成结块，降低了土壤孔隙度，影响植物的生长环境。土壤含水量一定时，土



壤紧实度越大,土壤穿透阻力越大,越不利于作物的生长^[91]。由于根系生长在土壤之间的孔隙中,通过改善土壤通气性,有利于根系的生长发育,达到促进作物生长和提高产量的目的。在水肥供应充足的条件下,良好的土壤通气性有利于作物生长发育^[92-93]。土壤容重对玉米苗期生长有显著影响,而且土壤容重过大会限制玉米根系的生长^[94]。土壤通气性提高时土壤紧实度下降^[95],有利于作物生长发育和产量的提高。土壤化学性质包括土壤中的物质组成、固液两相之间的化学反应、离子及分子在固液相界面上发生的化学反应。土壤通气性的改善对提高土壤中氧气含量有很大帮助,可避免在低氧环境下土壤中还原物质的大量积累,避免因物质还原造成的土壤酸化,降低土壤酸化对植物生长的不利影响。除碳酸盐和二氧化碳以外,土壤中的含碳化合物主要由植物、动物和微生物等生物残体转化而来,氧气浓度的提高可促进土壤生物的活动与繁育,加速有机物的氧化降解^[96],有利于生物残体转化为土壤养分。

土壤中的动物、植物、微生物等总称为土壤生物。微生物分为好气微生物和嫌气微生物两种,土壤通气良好可促进好气微生物的活动和繁殖^[66],分解有机物质,为植物制造出所需的氮素化合物和营养元素,提高水肥利用效率;土壤通气性不良时,有机质的分解速度和养分的有效性将会降低,作物根系无法正常生长^[8],所以良好的通气性对维持土壤微生物的数量和活性至关重要。土壤动物在生命历程中对土壤理化性质产生显著的影响,是物质小循环的活跃参与者。土壤脱氢酶与相对气体扩散系数成正相关,过氧化氢酶与氧化还原电位成正相关^[97]。

3.4 土壤通气性改善与作物的响应

土壤通气性的改善,有利于促进土壤与大气中的气体交换、提高根系呼吸,改善植物生长^[72]。根际通气性良好时,土壤氧气的充足供应能促进植物呼吸作用和产生能量,根系会向地上部分提供植物生长所需的能量和物质,从而促进植物茎和叶的生长,促进光合作用,有利于叶绿素的合成和积累营养物质^[67]。低氧胁迫情况下作物新陈代谢发生紊乱,植物无氧呼吸会产生乙醇等有害物质,损害作物根系,能量供应不足,叶片气孔关闭,植物蒸腾作用降低,地上部光合作用减少^[6]。良好的通

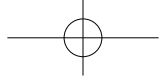
气性能使得作物根系功能处于最佳状态,有利于根区微生物的活动,最终使作物生长发育得到改善。提高土壤通气性,最终能够促进作物产量和品质的提升^[17]。

3.5 加氧灌溉研究中存在的问题

由于加氧灌溉需要添加一些基础设施,铺设各种管道和建造加压设备,同时也需要消耗电力和需要人工来管理,还需要增加设备的维护和更换的费用,这样增加了生产投入,尽管加氧灌溉的方法可以提高产量和品质,获取更大的经济效益,但是相比之下增加的投入应该小于因为增产增收带来的经济收入,并且所有的新增投入应该在一段时期内收回成本。所以,加氧灌溉多适合于蔬菜、水果、花卉等经济作物,对于一些附加值较低的作物而言不太经济。随着滴灌技术的改进和滴灌系统投资成本的下降,加氧灌溉同样可应用于粮食作物。实际生产中,文丘里空气射流器加氧灌溉管道百米以外的沿程水气均匀性呈下降的趋势,导致田间作物产量不均匀^[70, 98]。化学加氧技术比较简便,可以快速缓解根区缺氧状况^[21];但是过氧化氢为强氧化剂,施用不当可能伤害作物,改变土壤生物的构成。连续曝气的条件下,水稻的根表面积和氧化强度提高,叶片叶绿素含量减少,干物质质量下降;曝气过量也会破坏土壤微生物群落,长远来看,对作物生长不利^[99]。

4 展 望

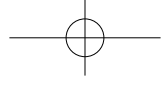
随着加氧技术的日趋成熟,加氧灌溉的推广应用将为水资源短缺和粮食安全保障提供解决方案。未来的研究可以从以下几个方面开展:(1)构建反映作物水肥高效利用、优质高产的综合性土壤通气性指标,强化加氧灌溉对土壤通气性的改善效应和定量评价方面的研究。(2)加强土壤水分、氧气和溶质耦合运移规律研究,优化调控土壤碳氮循环转化,提高土壤养分利用效率、降低温室气体的环境足迹。(3)研发用于地表、畦灌和沟灌等灌溉方式的新型加氧灌溉技术,制定适宜的水肥气一体化灌溉技术参数、灌溉周期、灌溉用量和适宜的土壤氧气浓度。(4)深化研究水气耦合灌溉下农田环境水分和养分的环境效应。(5)加氧灌溉对土壤生物群落和土壤理化性质长效的作用机制。



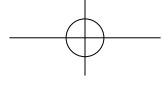
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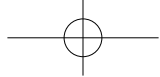
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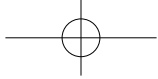
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Advancement in Research on Soil Aeration and Oxygation

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Abstract Water, nutrients, gas and heat are the four main factors in soil to ensure soil fertility. Traditional irrigation management often ignores the importance of soil aeration. Hypoxia stress is often attributed to soil compaction, high ground water table or unreasonable irrigation. Under hypoxia stress, plants declined in aerobic respiration with part plant root dying, and leaves atrophying, thus leading to a low water and nutrient use efficiency. As an integrated index of soil permeability and status of soil oxygen, soil aeration represents one of the overall properties of soil fertility, which reflects the relationships between soil biological oxygen consumption, carbon dioxide production and gas exchange between soil and atmosphere. Insufficient soil aeration would surely disturb the balance between the four factors of soil fertility, making the soil deteriorating in soil physical and chemical properties, which in turn negatively affect crop growth and yield. Irrigation displaces air in soil pores with water, causing temporal hypoxia, which may be localized



and last a long time, particularly in heavy clay soils, where a wetting front is maintained due to frequent pulsing irrigation events. A system, termed oxygation or aerated irrigation, has been developed, mixing pure oxygen, air bubbles or hydrogen peroxide solution into the irrigation water that flows and carries oxygen to the plant root zone. Researches have demonstrated that oxygation or adding oxygen into irrigation water may improve crop yield and quality. In order to explore mechanism of the improvement by oxygation, this review begins with the effects of hypoxia stress on soil biology, crop physiology and crop production, and influencing factors, quantitative indicators and evaluation criteria, and measuring and calculating methods of soil aeration. Then it summarizes characteristics, application methods, and biological effects of different oxygation technologies, and furthermore, problems existing in the researches. Besides, it discusses effects of oxygation or aerated irrigation on soil aeration. In the end, it brings forth prospects of the researches on oxygation or aerated irrigation in anticipation of providing some reference for future researches.

Key words Hypoxia stress; Oxygation or aerated irrigation; Dissolved oxygen; Soil aeration; Evaluation indicator

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