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土壤肥力对双季优质食味水稻籽粒品质的影响

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摘要:【目的】土壤肥力是决定水稻产量的重要因子之一,但其对稻米品质的影响则鲜有报道。旨在阐明土壤肥力对双季优质食味水稻籽粒品质的影响,为协同提升双季稻产量和稻米品质提供科学依据。【方法】分别以湘早籼45和泰优871作为早稻和晚稻品种,选择土壤母质相同的低肥力(F_L)、中肥力(F_M)和高肥力(F_H)红壤性双季稻田开展田间试验,以明确土壤肥力对双季优质食味水稻籽粒品质的影响。【结果】早稻和晚稻季平均而言,与 F_L 相比, F_M 和 F_H 处理的精米率分别提高1.0和3.2个百分点,整精米率分别提高1.4和1.6个百分点。与 F_L 相比, F_M 和 F_H 使稻米垩白粒率分别降低1.3和3.5个百分点,使垩白度减少1.2和1.5个百分点。与 F_L 相比, F_M 和 F_H 使稻米直链淀粉含量分别降低3.7%和7.0%,使胶稠度分别提高20.0%和37.5%。在以 rapid viscosity analyzer (RVA)谱特征值表示的米粉粘度特性中,崩解值以及最终黏度随土壤肥力升高均呈递减趋势,消减值则随土壤肥力升高而增加。【结论】提高土壤肥力对双季优质稻的加工品质、外观品质、蒸煮品质和营养品质有改善作用,而一定程度上代表食味品质的RVA谱特征值却有变劣趋势。

关键词:土壤肥力;红壤;双季稻;稻米品质

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Effect of soil fertility on grain quality of good-taste double-season rice cultivars

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Abstract: [Objective] Soil fertility is a pivotal factor influencing rice yield, while its impact on rice quality remains unclear. This experiment aims to explore the effects of soil fertility on the grain quality of good-taste double-cropped rice, thereby simultaneously improving the grain yield and quality of double-cropped rice. [Method] In this study, a field experiment was conducted in low-fertility (F_L), medium-fertility (F_M), and high-fertility (F_H) rice fields with the same red soil parent material, using Xiangzaoxian 45 and Taiyou 871 as early

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and late rice varieties, respectively, in order to clarify the effect of soil fertility on the grain quality of double-season high-quality edible rice. **[Result]** The results showed that compared with FL, the milled rice rate of FM and FH treatments increased by 1.0 and 3.2 percentage points, respectively, and the head rice rate increased by 1.4 and 1.6 percentage points, respectively, in the early and late rice seasons. Compared to F_L , F_M and F_H decreased the chalky grain rate by 1.3% and 3.5%, with the chalkiness degree reduced by 1.2% and 1.5%, respectively. Compared to F_L , the content of amylose decreased by 3.7% and 7.0% in F_M and F_H , while the gel consistency increased by 20.0% and 37.5%, respectively. In the viscosity characteristics of rice flour determined by the rapid viscosity analyzer (RVA), both the breakdown value and the final viscosity showed a decreasing trend with the increase of soil fertility, while the setback value increased with the increasing soil fertility. **[Conclusion]** The processing quality, appearance quality, cooking quality and nutritional quality of double cropping high quality rice were improved by increasing soil fertility, while the RVA profile characteristic value, which represented the eating quality to a certain extent, had a tendency to deteriorate.

Keywords: soil fertility; red soil; double season rice; rice quality

【研究意义】水稻是我国最重要的口粮作物,对保障国家粮食安全至关重要^[1-2]。随着人们生活水平的持续提升,优质食味稻米的供需矛盾愈加突出^[3]。稻米品质不仅受遗传基因的影响,还受到栽培技术和气候条件等多种因素的共同作用^[4-6]。土壤肥力不仅影响水稻产量,对稻米品质也有重要作用^[7]。探明土壤肥力对优质食味水稻稻米品质的影响对协同提升水稻产量和品质具有重要意义。**【前人研究进展】**土壤肥力可能通过土壤有机质和养分供给调控稻米品质^[8]。高肥力土壤具有丰富的有机质和养分含量,同时具备良好的土壤结构,有利于促进水稻米质的提升^[9]。此外,高肥力土壤有机质不仅促进了根系的生长,也有利于提高根系活力和根系吸收面积,从而促进水稻对营养元素的吸收^[10]。土壤肥力的提升提高了微生物活性,有利于促进微量元素的矿化和吸收^[11],而土壤中微量元素的含量与稻米质量显著相关^[12]。微量元素能够降低稻米的垩白度及垩白粒率,提高其整精米率和蛋白质含量^[13]。有研究^[14]表明,土壤肥力的提升有利于协同水稻对氮磷钾的吸收以改善稻米的加工品质,显著提高稻米的糙米率、精米率和整精米率。然而,也有研究^[15]表明,土壤肥力的提升导致土壤中速效氮含量过高,水稻植株吸收过多的氮素,从而造成稻米蛋白质含量增加、直链淀粉含量升高、食味品质下降。

【本研究切入点】稻米品质的形成受遗传因素和环境条件的双重影响。目前有关土壤肥力对稻米品质的研究尚未形成一致的结论。而且,前人的研究多采用盆栽方法探明土壤肥力对稻米品质的影响,田间试验较少,尤其是对双季优质食味水稻的研究还未见报道。**【拟解决的关键问题】**本研究在土壤母质相同、土壤肥力不同的红壤性稻田上开展田间试验,旨在阐明土壤肥力对双季优质食味水稻稻米品质的影响,为双季稻产量与品质的协同提升提供科学依据。

1 材料与方法

1.1 试验地概况

试验于2021年在江西省南昌市进贤县张公镇的江西省红壤研究所内(116°20'24" N, 28°15'30" E)开展。该地区属于典型的亚热带季风气候区。该区域的主体种植制度为早稻-晚稻-冬闲,包括4月至7月的早稻季、7月至11月的晚稻季,以及11月至翌年4月的冬闲季。本研究以土壤有机质含量作为土壤肥力的核心表征指标,并据此选取3块不同土壤肥力梯度的田块开展试验^[16]。3块不同土壤肥力的稻田具有相同的土壤质地、气候条件和作物种植历史。本研究的前期结果表明,土壤有机质越高,水稻产量越高。与低土壤有机质田块相比,中、高肥力土壤有机质田块水稻产量分别提高5.4%、19.9%。因此,以土壤有机质为筛选指标能代表土壤的肥力状况^[17]。供试田块土壤均为第四纪红黏土发育而来的水稻土。耕层土壤(0~15cm)的基本理化性质如表1所示,早晚稻降水量以及日均气温如图1所示。

表 1 不同肥力田块的土壤基本理化性质
Tab.1 Topsoil properties(0–15 cm)at the experimental sites with different soil fertility

土壤肥力 Soil fertility	pH	容重/ (g·kg ⁻¹) Bulk density	有机质/ (g·kg ⁻¹) Organic matter	总氮/ (g·kg ⁻¹) Total N	碱解氮/ (mg·kg ⁻¹) Alkaline N	速效钾/ (mg·kg ⁻¹) Available K	速效磷/ (mg·kg ⁻¹) Olsen P
低肥力 Low fertility	5.2	1.3	20.3	1.2	105.0	60.0	10.1
中肥力 Medium fertiltiy	5.3	1.2	28.5	1.7	137.8	50.2	13.8
高肥力 High fertility	5.3	1.1	37.7	2.2	172.7	34.0	33.2

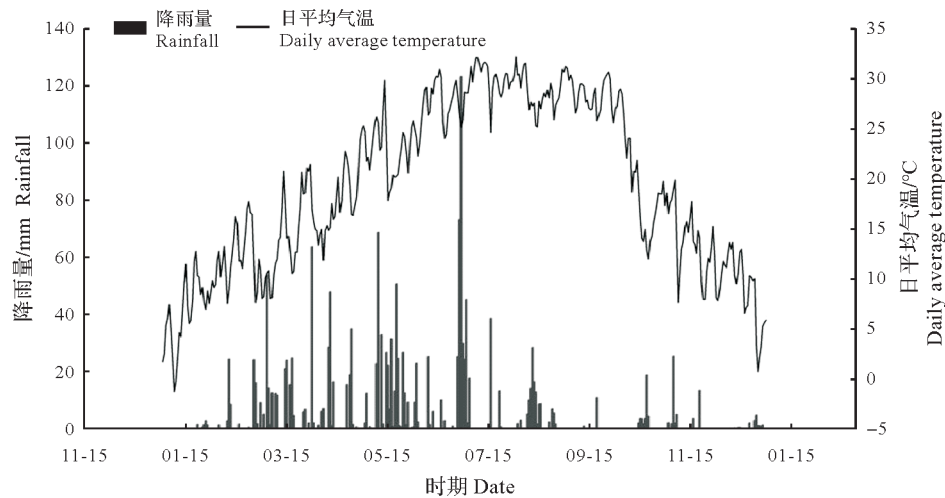


图 1 试验点降雨量和日均气温

Fig.1 Rainfall and daily average temperature at the experimental site

1.2 试验设计及田间管理

试验采用完全随机设计。3块试验田的土壤肥力分别为低(F_L)、中(F_M)、高(F_H)(表 1),每个田块划分为 3 个小区,各小区面积统一设定为 50 m²。本试验选用湘早籼 45 和泰优 871 分别作为早稻和晚稻品种,均采用大田水育秧,人工移栽。早稻于 3 月 24 日播种,7 月 15 日收获,移栽密度为 25 cm×14 cm,每穴栽植 3 苗;晚稻于 6 月 25 日播种,10 月 14 日收获,移栽密度为 25 cm×16 cm,每穴栽植 2 苗。不同土壤肥力处理的化肥施用保持一致。氮、磷、钾肥料分别选用尿素、钙镁磷肥及氯化钾。磷肥(以 P₂O₅ 计)和钾肥(以 K₂O 计)的施用量均为 75 kg/hm²,氮肥(以纯 N 计)的施用量为 150 kg/hm²。氮肥按照 5:2:3 的比例分基肥、分蘖肥与穗肥 3 次施用,磷肥全部作基肥,钾肥按 *m*(基肥):*m*(穗肥)=5:5 施用。基肥、分蘖肥、穗肥分别在移栽前 1 d、移栽后 7 d、倒二叶期施用^[16]。早、晚稻的整个生育期内,田间水层维持在 2~3 cm。田间病虫害及杂草的管理措施与当地的高产栽培标准相一致。

1.3 稻米米质测定

1.3.1 稻米加工品质

收获后将稻谷样品置于阴凉通风处风干,室温下存放 3 个月至理化性质稳定。依据国家最新标准(GB/T 1354—2018)对稻米品质进行测定。取 200 g 稻谷过糙米机研磨,获得糙米并称量,称取单位精确至 0.01。之后,将糙米过精米机研磨,获得精米并称量,称量单位精确至 0.01。最后,将精米进行筛分,保留整精米后进行称量。依据质量数据,计算糙米率、精米率和整精米率^[18]。

1.3.2 稻米外观品质

将整精米均匀铺设于扫描仪(ScanMaker i800 Plus)的扫描区域,运用万深种子大米外观检测软件对垩白粒率、垩白度和长宽比进行分析与测定^[18]。

1.3.3 稻米 RVA 谱特征值

将精米研磨成米粉后,使用孔径为 0.25 mm 的网筛进行过筛。随后,称取 3 g 米粉样品,并与 25 g 水混合均匀。采用 Super 3 型快速黏度测试仪(RVA)对样品进行淀粉黏度特性测试,利用 TCW(Windows 热循环)软件对淀粉的黏度数据进行分析^[19]。

1.3.4 稻米蒸煮食味品质

将整精米进行机械粉碎后,利用 0.25mm 的筛网进行筛分后获得米粉样品待测。直链淀粉含量和胶稠度分别依据国家标准(GB/T 1354—2018)中的碘蓝比色法和米胶延伸法进行测定。米粉的蛋白质含量使用 Kjeltac 8400 型凯氏定氮仪测定氮含量,再根据氮含量乘以 5.95 换算出稻米的蛋白质含量^[20]。

1.4 数据分析

利用 SPSS 27.0 软件(SPSS Inc., USA)进行统计分析,采用最小显著法 LSD 法(Least Significant Difference)进行多重比较,于 $P<0.05$ 水平进行显著性检验。由于早稻和晚稻在同一田块上进行,稻米的加工品质、外观品质、RVA 谱特征值和蒸煮食味品质均采用土壤肥力(F)和季别(S)两因素方差分析。

2 结果与分析

2.1 土壤肥力对双季稻稻米加工品质的影响

由表 2 可知,随着土壤肥力的升高,糙米率、精米率、整精米率均呈显著上升趋势。与 F_L 处理相比, F_M 、 F_H 处理的糙米率增加了 0.2、0.8 个百分点,精米率分别增加了 1.0、3.2 个百分点,整精米率分别增加了 1.4、1.6 个百分点。晚稻的糙米率和精米率由小到大均为 F_L 、 F_M 和 F_H 。土壤肥力和作物季节对糙米率和精米率有显著交互效应(图 2)。早稻 F_H 处理的糙米率显著高于 F_M 处理,而 F_M 和 F_L 处理之间无显著差异, F_H 处理的早稻精米率显著高于 F_M 处理,而 F_M 和 F_L 处理之间无显著差异;晚稻糙米率和精米率由大到小依次为 F_H 、 F_M 和 F_L 。

表 2 土壤肥力(F)和季节(S)对双季稻稻米加工品质的影响

Tab.2 The impact of soil fertility(F)and season(S)on the milling quality of double-cropped rice

变异来源 Variation sources	糙米率/% Brown rice	精米率/% Milled rice	整精米率/% Head rice
土壤肥力(F) Soil fertility			
F_L	80.7c	64.6c	56.3b
F_M	80.9b	65.6b	57.7a
F_H	81.5a	67.8a	57.9a
季节(S) Season			
早稻(Early)	79.7b	62.1b	51.9b
晚稻(Late)	82.4a	69.9a	62.6a
F-values			
F	**	**	**
S	**	**	**
F×S	*	*	NS

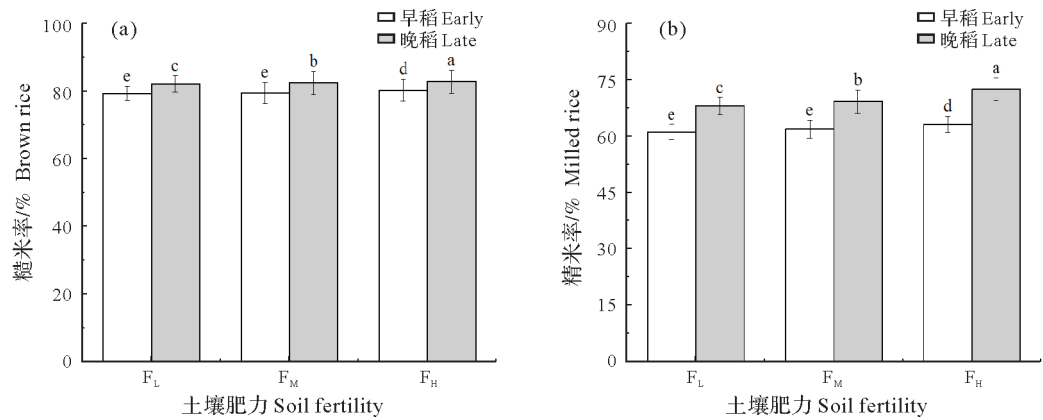
F_L 、 F_M 、 F_H 分别表示低、中和高肥力土壤。同列不同小写字母表示土壤肥力和季节的主要效应差异显著。*($0.01<P\leq 0.05$)和 **($0.001<P\leq 0.01$)表示主效应和交互效应显著。NS 为无显著差异($P>0.05$)。

F_L 、 F_M 、 F_H denote low, medium, and high soil fertility, respectively. Different lowercase letters in the same column indicate that the main effects of the soil fertility and season are significantly different. Significant main and interactive effects are indicated by * ($0.01<P\leq 0.05$) and ** ($0.001<P\leq 0.01$). NS indicates non-significance ($P>0.05$).

2.2 土壤肥力对双季稻稻米外观品质的影响

由表 3 可知,提升土壤肥力显著降低了垩白粒率和垩白度。长宽比随土壤肥力升高呈先上升后不变趋势。与 F_L 处理相比, F_M 、 F_H 处理的垩白粒率分别下降了 1.3、3.5 个百分点,垩白度分别下降了 1.2、1.5 个百分点。与 F_L 处理相比, F_H 处理的长宽比增加了 0.1 个百分点, F_H 处理和 F_M 处理之间没有显著差异。土

壤肥力与作物季节在垩白粒率和垩白度方面表现出显著的交互作用(图3)。早稻的垩白粒率由大到小依次为 F_L 、 F_M 和 F_H , F_H 和 F_M 处理的早稻垩白度显著低于 F_L 处理,而 F_H 和 F_M 处理之间无显著差异; F_H 处理晚稻的垩白粒率和垩白度显著低于 F_L 和 F_M 处理,而 F_L 和 F_M 之间无显著差异。



土壤肥力和季节对糙米率(a)和精米率(b)有显著互作作用。F_L、F_M和F_H分别表示低、中和高肥力土壤。不同小写字母表示处理间差异显著(P<0.05)。误差棒则表示标准差(n=3)。

Soil fertility and seasons significantly interacted to affect the brown rice rate (a) and milled rice rate (b). F_L, F_M, F_H represent low, medium, and high soil fertility, respectively. Different lowercase letters indicate significant differences among treatments (P<0.05). The error bar indicates the standard deviation (n=3).

图2 土壤肥力对稻米糙米率(a)和精米率(b)的影响

Fig.2 Effects of soil fertility on the brown rice rate(a) and milled rice rate(b)

表3 土壤肥力(F)和季节(S)对双季稻稻米外观品质的影响

Tab.3 The impact of soil fertility(F) and season(S) on the appearance quality of double-cropped rice			
变异来源	垩白粒率/%	垩白度/%	长宽比
Variation sources	Chalky grain rate	Chalkiness	Length-width ratio
土壤肥力(F) Soil fertility			
F _L	16.2a	6.1a	3.4b
F _M	14.9b	4.9b	3.5a
F _H	12.7c	4.6c	3.5a
季节(S) Season			
早稻(Early)	22.7a	8.6a	3.1b
晚稻(Late)	6.5b	1.8b	3.9a
F-values			
F	**	**	**
S	**	**	**
F×S	*	**	NS

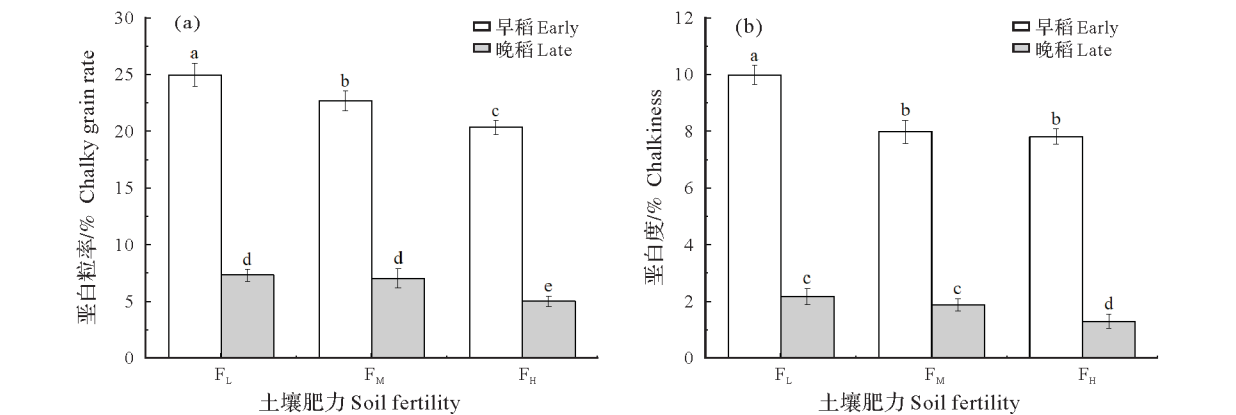
F_L、F_M、F_H分别表示低、中和高肥力土壤。同列不同小写字母表示土壤肥力和季节的主要效应差异显著。*(0.01<P≤0.05)和**(0.001<P≤0.01)表示主效应和交互效应显著。NS为无显著差异(P>0.05)。

F_L, F_M, F_H denote low, medium, and high soil fertility, respectively. Different lowercase letters in the same column indicate that the main effects of the soil fertility and season are significantly different. Significant main and interactive effects are indicated by * (0.01<P≤0.05) and ** (0.001<P≤0.01). NS indicates non-significance (P>0.05).

2.3 土壤肥力对双季稻稻米蒸煮食味品质的影响

由表4可知,随着土壤肥力的升高,稻米的蛋白质含量和胶稠度呈显著上升趋势,直链淀粉呈显著下降趋势。与F_L处理相比,F_M、F_H处理的蛋白质含量增加了3.8%、13.6%,直链淀粉含量分别降低了3.7%、7.0%,胶稠度分别增加了20.0%、37.5%。土壤肥力和作物季节对蛋白质和直链淀粉有显著互作效应

(图4)。早稻的蛋白质含量由低到高依次为F_L、F_M和F_H,F_H和F_M处理早稻的直链淀粉含量显著低于F_L处理,而F_H和F_M之间无显著差异;晚稻的蛋白质含量由低到高依次为F_L、F_M和F_H,直链淀粉含量由高到低依次为F_L、F_M和F_H。



土壤肥力和季节对垩白粒率(a)和垩白度(b)有显著互作作用。F_L、F_M和F_H分别表示低、中和高肥力土壤。不同小写字母表示处理间差异显著($P<0.05$)。误差棒则表示标准差($n=3$)。

Soil fertility and seasons significantly interacted to affect the chalky grain rate(a)and chalkiness(b).F_L,F_M,F_H represent low, medium, and high soil fertility, respectively.Different lowercase letters indicate significant differences among treatments ($P<0.05$). The error bar indicates the standard deviation($n=3$).

图3 土壤肥力对稻米垩白粒率(a)和垩白度(b)的影响

Fig.3 Effects of soil fertility on the chalky(a)and chalkiness(b)of rice grains

表4 土壤肥力(F)和季节(S)对双季稻稻米蒸煮食味品质的影响

Tab.5 The Impact of soil fertility(F)and season(S)on the cooking and nutritional quality of double-cropped rice

变异来源	蛋白质含量/(g·kg ⁻¹)	直链淀粉含量/(g·kg ⁻¹)	胶稠度/mm
Variation sources	Protein	Amylose	Gel consistency
土壤肥力(F) Soil fertility			
F _L	73.5c	185.1a	41.6c
F _M	76.3b	178.2b	49.9b
F _H	83.5a	172.2c	57.2a
季节(S) Season			
早稻(Early)	73.2b	194.4a	44.6b
晚稻(Late)	82.2a	162.6b	54.6a
F-values			
F	**	**	**
S	**	**	**
F×S	**	**	NS

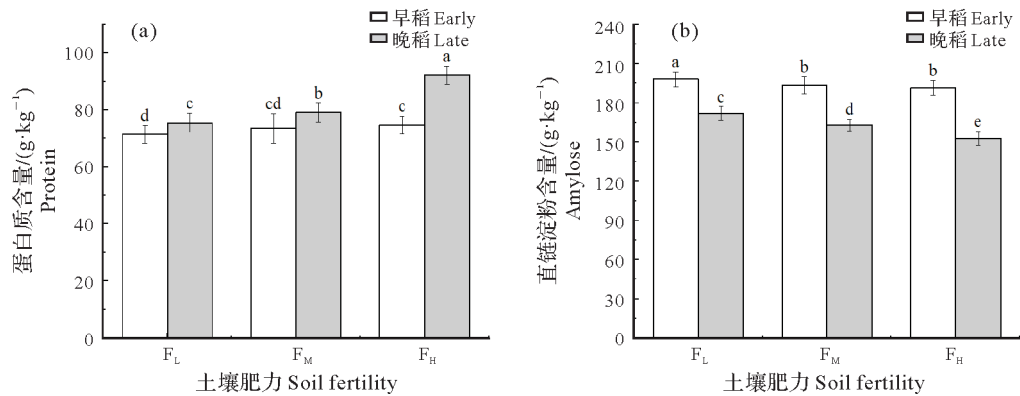
F_L、F_M、F_H分别表示低、中和高肥力土壤。同列不同小写字母表示土壤肥力和季节的主要效应差异显著。*(0.01<P≤0.05)和**(0.001<P≤0.01)表示主效应和交互效应显著。NS为无显著差异(P>0.05)。

F_L,F_M,F_H denote low, medium, and high soil fertility, respectively.Different lowercase letters in the same column indicate that the main effects of the soil fertility and season are significantly different.Significant main and interactive effects are indicated by * (0.01<P≤0.05)and ** (0.001<P≤0.01).NS indicates non-significance(P>0.05).

2.4 土壤肥力对双季稻稻米 RVA 谱特征值的影响

由表5可知,随着土壤肥力的升高,稻米的峰值黏度和崩解值均呈现下降态势,而消减值则呈显著上升趋势。与F_L处理相比,F_M、F_H处理的峰值黏度降低了12.0%、14.5%,热浆黏度分别降低了3.9%、7.1%,

崩解值分别降低了6.4%、9.8%,最终黏度分别降低了3.0%、6.5%,消减值增加了57.9%、97.6%,糊化温度增加了2.5%、5.1%。土壤肥力和作物季节对热浆黏度、崩解值、消减值和糊化温度有显著互作效应(图5)。随着肥力的提升,早晚稻的热浆黏度和崩解值由大到小依次为 F_L 、 F_M 和 F_H ,早晚稻的消减值和糊化温度由低到高依次均为 F_L 、 F_M 和 F_H 。在早稻季,与 F_L 处理相比, F_M 、 F_H 处理的热浆黏度分别降低了4.9%、8.9%,崩解值分别降低了6.1%、8.7%,消减值分别增加了14.4%、20.2%,糊化温度分别增加了1.7%、3.3%。在晚稻季,与 F_L 处理相比, F_M 、 F_H 处理的热浆黏度分别降低了2.5%、4.8%,崩解值分别降低了7.1%、12.3%,消减值分别增加了73.3%、135%,糊化温度分别增加了3.1%、6.6%。



土壤肥力和季节对蛋白质含量(a)和直链淀粉(b)有显著互作作用。 F_L 、 F_M 和 F_H 分别表示低、中和高肥力土壤。不同小写字母表示处理间差异显著($P<0.05$)。误差棒则表示标准差($n=3$)。

Soil fertility and seasons significantly interacted to affect the protein (a) and amylose (b). F_L , F_M , F_H represent low, medium, and high soil fertility, respectively. Different lowercase letters indicate significant differences among treatments ($P<0.05$). The error bar indicates the standard deviation ($n=3$).

图4 土壤肥力对稻米蛋白质(a)和直链淀粉(b)的影响

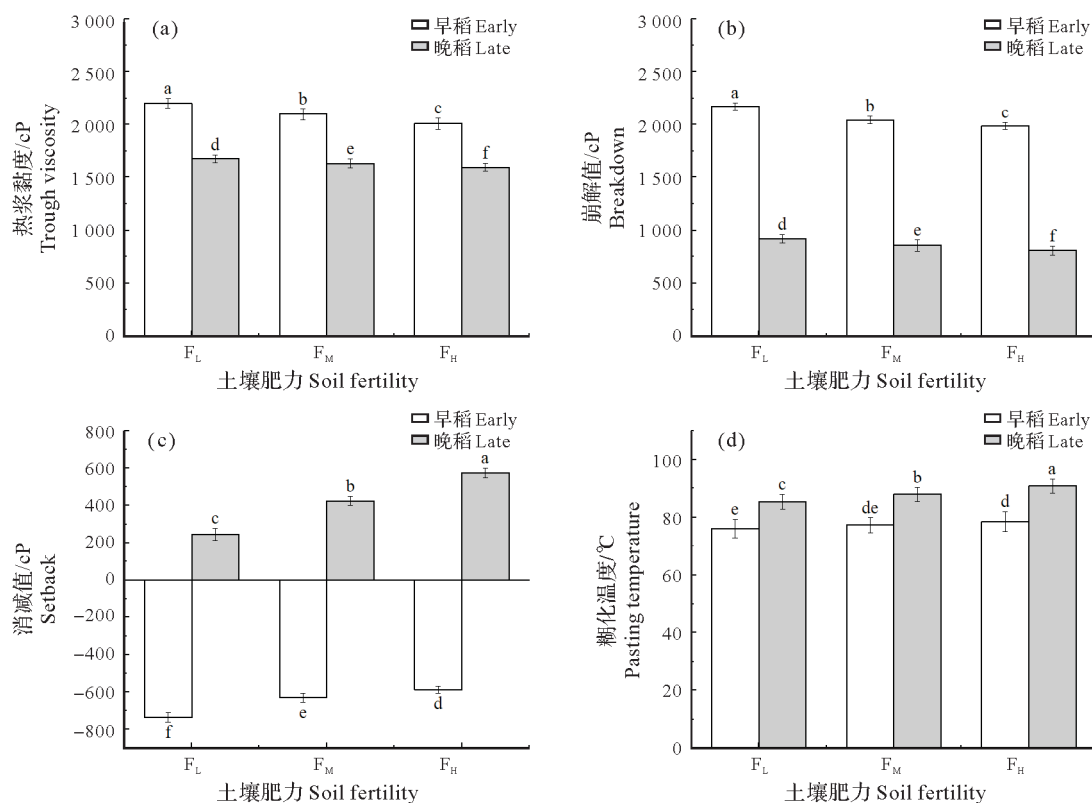
Fig.4 Effects of soil fertility on the content of protein(a)and amylose(b)in rice grains

表5 土壤肥力(F)和季节(S)对双季稻稻米RVA谱特征值的影响

Tab.5 The Impact of soil fertility(F)and season(S)on RVA parameters of double-cropped rice							
变异来源 Variation sources	峰值黏度/cP Peak viscosity	热浆黏度/cP Trough viscosity	崩解值/cP Breakdown	最终黏度/cP Final viscosity	消减值/cP Setback	回复值/cP Consistency	糊化温度/℃ Pasting temperature
土壤肥力(F) Soil fertility							
F_L	3 848.2a	1 940.6a	1 547.1a	3 226.5a	-246.0c	1 285.9c	80.6c
F_M	3 384.8ab	1 865.7b	1 448.5b	3 130.7b	-103.5b	1 366.7b	82.6b
F_H	3 289.3b	1 802.2b	1 395.7c	3 015.5c	-5.8a	1 459.3a	84.7a
季节(S) Season							
早稻(Early)	4 163.0a	2 102.9a	2 067.2a	3 511.0a	-651.4b	1 480.7a	77.3b
晚稻(Late)	2 609.2b	1 636.0b	860.3b	2 737.4b	414.6a	1 260.6b	88.0a
F-values							
F	**	**	**	**	**	**	**
S	**	**	**	**	**	**	**
F×S	NS	**	*	NS	**	NS	*

F_L 、 F_M 、 F_H 分别表示低、中和高肥力土壤。同列不同小写字母表示土壤肥力和季节的主要效应差异显著。*($0.01<P\leq 0.05$)和**($0.001<P\leq 0.01$)表示主效应和交互效应显著。NS为无显著差异($P>0.05$)。

F_L , F_M , F_H denote low, medium, and high soil fertility, respectively. Different lowercase letters in the same column indicate that the main effects of the soil fertility and season are significantly different. Significant main and interactive effects are indicated by * ($0.01<P\leq 0.05$) and ** ($0.001<P\leq 0.01$). NS indicates non-significance ($P>0.05$).



土壤肥力和季节对热浆黏度(a)、崩解值(b)、消减值(c)、糊化温度(d)有显著互作作用。F_L、F_M和F_H分别表示低、中和高肥力土壤。不同小写字母表示处理间差异显著($P<0.05$)。误差棒则表示标准差($n=3$)。

Soil fertility and seasons significantly interacted to affect the trough viscosity (a), breakdown value (b), setback value (c), and pasting temperature (d). F_L, F_M, F_H represent low, medium, and high soil fertility, respectively. Different lowercase letters indicate significant differences among treatments ($P<0.05$). The error bar indicates the standard deviation ($n=3$).

图5 土壤肥力对稻米热浆黏度(a)、崩解值(b)、消减值(c)和糊化温度(d)的影响

Fig.5 Effects of soil fertility on the viscosity of rice trough (a), breakdown value (b), setback value (c), and pasting temperature (d)

3 讨论

本研究表明,土壤肥力升高显著提高了稻米的糙米率、精米率和整精米率。这可能是高肥力土壤的土壤有机质含量增加,而高有机质促进了土壤氮矿化作用^[20],为水稻供给了更多的氮素。氮素供给增加提高了蛋白质含量,增加了稻米的硬度,从而增强了稻米在碾磨过程中的抗磨损力^[21],保持了稻米颗粒的完整度。另外,高土壤肥力可以提供作物生长所需的养分,如氮、磷、钾等。充足的养分提高了个体优势和群体质量^[22-23],使灌浆结实期内籽粒内物合理分配,致密性增强,促进了稻米的充实度和颗粒饱满度^[24],进而提高精米率和整精米率。

本研究发现,土壤肥力升高显著降低了稻米的垩白粒率和垩白度。有研究表明,土壤肥力提高改善了土壤的物理性质^[25],使土壤持水量增加、团聚体更稳定^[26],从而促进水稻根系发育。强大的根系促进了水稻对水分和养分的吸收,增强了植株的蒸腾和呼吸作用,进而降低冠层温度,减轻高温胁迫,从而减少垩白粒率和垩白度。此外,Liu等^[27]和Tang等^[28]研究表明,高肥力土壤为水稻生长提供了丰富的有效氮,缓解了土壤微生物与作物之间的氮竞争,促进了水稻的氮素吸收,有利于降低垩白粒率和垩白度。

在本研究中,土壤肥力升高显著降低了稻米的直链淀粉含量,提高了胶稠度。这可能是由于土壤肥力升高提高了氮素吸收^[29-31]。另外,如上所述,高土壤肥力上水稻群体的冠层温度更低,有利于降低直链淀粉的含量^[32]。随土壤肥力的提升,RVA谱特征值中的峰值黏度、崩解值下降,消减值和糊化温度逐渐增加。这说明土壤肥力对稻米淀粉黏滞性存在一定的负效应,即土壤肥力升高在一定程度上抑制了稻米黏滞性的形成。这可能是由于土壤肥力升高使水稻中的蛋白质含量增加,淀粉颗粒间的蛋白质不利

于淀粉粒的糊化和膨胀,使米饭黏度低,硬度大,则降低米饭口感,导致食味变差^[33]。

本研究表明,早稻季和晚稻季的米质对土壤肥力提升的响应有所不同。对于糙米率和精米率,随着土壤肥力的升高,晚稻的增幅总体高于早稻。这可能是由于早晚稻生育期长短不同造成的^[34]。晚稻的生长期较长,需要更多的养分支持其生长和发育,因此对土壤养分的需求可能更高。高肥力土壤能够更好地满足晚稻的养分需求,有利于晚稻后期的光合作用和籽粒充实^[35]。而对于垩白粒率和垩白度,随着土壤肥力的升高,早稻的降幅总体高于晚稻。这可能是由于早晚稻生长后期的气象条件不同造成的,早稻季灌浆期的温度高于晚稻季,导致垩白粒率和垩白度大幅提高^[36]。而高肥力土壤的有机质含量高、土壤结构发育良好,有利于提高土壤的保水性能,从而降低高温对水稻的胁迫作用^[25-26]。对于蛋白质含量,随着肥力提升,晚稻的增幅高于早稻。这可能是由于晚稻更好的氮素需求促进了植株对氮素的吸收,而高肥力土壤促进植株的氮代谢,进而增加籽粒中蛋白质的含量^[37-38]。对于直链淀粉含量,随着肥力提升,晚稻的降幅大于早稻。这可能与籽粒的蛋白质含量有关,有研究^[38]表明水稻籽粒直链淀粉与蛋白质含量呈负相关关系。另外,早稻季和晚稻季籽粒品质对土壤肥力的不同响应还可能跟早晚稻的品种不同有关。不同品种的特性和遗传背景差异可能导致其对水分、温度和养分等环境条件的响应有所差异^[39-40]。

本研究的前期结果^[17]发现,提高土壤肥力并配施适宜的化学氮肥不仅能提高水稻产量,还有利于提升氮肥利用效率。而本研究表明,提高土壤肥力有利于改善稻米品质,但食味品质有变劣的趋势,主要是因为提高了籽粒的蛋白质含量。因此,在根据土壤肥力配施适宜氮肥的同时,可以通过调整氮肥运筹,比如降低后期氮肥的比例,来降低籽粒的蛋白质含量,从而协同提升双季优质稻的产量和品质。同时,因地施氮有利于减少化学氮肥投入,降低氮素损失,改善生态环境。

4 结 论

在不同土壤肥力上开展的田间试验研究表明,提高土壤肥力能够增加稻米的整精米率、蛋白质含量及胶稠度,降低垩白粒率和直链淀粉含量,但RVA谱特征值有变劣趋势。高肥力条件下RVA谱特征值变劣可能与氮素吸收增加导致籽粒蛋白质含量升高有关。因此,提升土壤肥力总体上有助于改善双季优质稻的加工品质、外观特性、蒸煮性能和营养价值,但对食味品质则有不利影响。因此,应根据土壤肥力调整化肥氮的用量和运筹方式,以协同不同品质间的矛盾,实现产量和米质协同提升。此外,不同品种的营养需求不同,对环境条件的响应也有所差异,品种与土壤肥力对稻米品质的互作效应及其机理还有待进一步研究。

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