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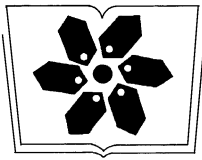
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封面图说:日斜茅荆坝·河北茅荆坝——地处蒙古高原向华北平原过渡地带的暖温带落叶阔叶林,色彩斑斓,正沐浴着晚秋温暖的阳光。

彩图提供:国家林业局陈建伟教授 E-mail: cites.chenjw@163.com

花前渍水预处理对花后渍水逆境下扬麦 9 号 籽粒产量和品质的影响

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摘要:以扬麦 9 号为材料, 研究花前渍水预处理对花后渍水逆境下小麦籽粒产量和品质的影响。结果表明: 与未进行渍水预处理相比, 花前渍水预处理提高了小麦植株对花后渍害的抗性, 生物产量、收获指数和千粒重显著提高, 进而显著提高了籽粒产量; 花前渍水预处理显著提高花后氮素积累量及其对籽粒氮素的贡献率, 降低了花前贮藏氮素运转量及其对籽粒氮素的贡献率, 籽粒球蛋白含量提高, 但显著降低了清蛋白、醇溶蛋白、谷蛋白和全蛋白质含量, 以及干湿面筋含量和沉降值; 花前渍水预处理还提高了籽粒直链淀粉和总淀粉含量和降落值, 降低了支/直链淀粉比, 显著提高了面粉峰值粘度、低谷粘度、崩解值、最终粘度、回冷值和峰值时间, 但对糊化温度无显著影响。

关键词:小麦; 渍水预处理; 产量; 品质

Effects of hardening by pre-anthesis waterlogging on grain yield and quality of post-anthesis waterlogged wheat (*Triticum aestivum* L. cv Yangmai 9)

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Abstract: Waterlogging is becoming one of the major constraints for wheat production and has resulted in severe reductions in both grain yield and quality over the world. Waterlogging events after anthesis usually cause much greater yield loss than those before anthesis. To explore approaches to alleviate the adverse effects of post-anthesis waterlogging on grain yield and quality, a pot experiment with winter wheat (*Triticum aestivum* L. cv Yangmai 9) was conducted. Before anthesis wheat plants were subjected to two water treatments: (1) the Control, where the soil relative water content was maintained at 70–80%, and, (2) a waterlogging pretreatment (maintaining a 1–2 cm water layer above the soil for 2 days). This pretreatment was repeated three times, i. e. at the seven-leaf, the nine-leaf stage and the heading stage. At 7 days after anthesis, plants from both treatments were further divided into two sub-groups and separately subjected to two water treatments lasting for 7 days each. Thus, four treatments were established from 7 DAA onwards: (1) pre-anthesis waterlogging hardening and post-anthesis waterlogging (WW); (2) pre-anthesis waterlogging only (WC); (3) control: non-waterlogging stress during both pre-anthesis and post-anthesis (CC); (4) post-anthesis waterlogging only (CW). The effects of the pre-anthesis waterlogging pretreatment (PWP) on grain yield and quality were then studied. The aim of this study was to test the hypothesis that short-term waterlogging pre-conditioning before anthesis can improve tolerance to post-anthesis waterlogging. It was found that waterlogging at both pre- and post-anthesis reduced grain yield and affected grain quality. However, PWP significantly increased biomass, harvest index, 1000-kernel weight, and consequently improved grain yield of wheat under post-anthesis waterlogging, compared with the non-pretreated plants. PWP also enhanced post-

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anthesis nitrogen accumulation and its contribution to grain nitrogen, while decreased the redistribution of nitrogen accumulated before anthesis as well as the contribution to grain nitrogen. Finally, PWP caused significant increases in contents of globulin, flour dry gluten, wet gluten and sedimentation volume, and resulted in reductions in the contents of albumin, gliadin, glutelin and total protein in the grain. In addition, PWP increased contents of amylase and total starch, and falling number and enhanced peak viscosity, holding trough viscosity, breakdown, final viscosity, setback and peak time. However, PWP did not significantly affect the pasting temperature. We concluded that waterlogging pre-treatment before anthesis could essentially improve the tolerance of wheat plants to severe waterlogging after anthesis, as exemplified by increases in grain yield and the modifications on grain quality traits.

Key Words: wheat; waterlogging pretreatment; yield; quality

渍害是小麦重要的逆境之一,美国^[1]、澳大利亚和日本及东南亚各国^[2]麦类渍害相当严重。长江中下游麦区是我国小麦主产区之一,小麦中后期降雨过多造成的渍害是该区小麦高产稳产的主要限制因子^[3]。灌浆期是小麦籽粒产量和品质形成的关键时期,已有研究表明,花后渍水加速绿叶衰亡,叶片功能期缩短、叶片光合速率下降、干物质积累降低^[3],导致籽粒淀粉和蛋白质产量显著下降^[4],最终严重影响了小麦的产量^[5-6]和品质^[7]。另有研究表明,生育前期适宜的逆境刺激,可提高作物对同一或其他逆境的抗性^[8],如植物经一定干旱^[9-10]、低温^[11]、高温^[12]等锻炼或刺激后,生育后期再经历同样胁迫时,其抗性和适应能力显著增强,产量显著提高^[8]。但生育前期渍水是否也能提高小麦对花后渍水的抵御能力尚未见报道。为此,本研究以扬麦 9 号为试验材料,探讨开花前渍水预处理对花后严重渍水逆境下小麦籽粒产量和主要品质性状的影响,以明确渍水预处理对小麦花后抗渍能力的影响,旨在为长江中下游麦区小麦抗渍调优栽培技术的建立提供理论依据与技术参考。

1 材料与方法

1.1 试验设计

试验于 2008—2009 年在南京农业大学卫岗试验站网室进行。供试材料为扬麦 9 号。试验用土属黄棕壤,含有机质 11.8g/kg、全氮 1.1g/kg、速效氮 30.1mg/kg、速效磷 28.6 mg/kg、速效钾 95.6mg/kg。播前将土过筛后与肥料混匀,称取 7.5kg 装入高 22cm,直径 25cm 的聚乙烯塑料桶,用等量水沉实后播种。每桶施用纯 N 1.2g, P_2O_5 0.36g 和 K_2O 0.9g,相当于大田每公顷施纯 N 360 kg、 P_2O_5 108 kg、 K_2O 270 kg,其中全 N 基追比为 6:4,追肥于拔节期施用。试验于 11 月 15 日播种,每盆留苗 7 株。

开花前设置两个处理:无渍水预处理(相当于田间持水量的 70%—80%)和渍水预处理(保持 1—2cm 水层),预处理时间为 2d,分别在七叶一心、九叶一心和抽穗期对同一批麦苗进行相同的处理。花后 7d 时,将花前每个处理再分成对照(相当于田间持水量的 70%—80%)和渍水胁迫(保持 1—2cm 水层)两个处理,处理时间为 7d。这样,试验最终形成 4 个处理:花前和花后都不渍水(CC)、花前不进行渍水预处理而花后渍水胁迫(CW)、花前渍水预处理但无花后渍水胁迫(WC)、花前渍水预处理且花后渍水胁迫(WW)。试验为随机区组设计,每处理重复 3 次。

1.2 测定项目与方法

开花期选择同天开花、大小均匀的穗子挂牌标记,于开花期和成熟期每处理各取样 3 盆(3 次重复),按旗叶、余叶、茎鞘、穗轴(含颖壳)、籽粒等器官分样。样品 105℃ 杀青 30 min, 80℃ 下烘干至恒重,用于植株氮素转运计算。收获期每处理分别取 3 盆,用于产量构成因素测定。此外,成熟期时每处理收获长势一致的植株 10 盆测产(按 13% 含水量计),籽粒贮存 2 个月后磨粉,用于品质指标的测定。

蛋白质组分采用连续抽取法,蛋白质含量测定采用半微量凯氏定氮法测定^[13],籽粒蛋白质及其组分含量为全氮含量乘 5.7 所得(并折成 14% 的干基)。

氮素运转与分配计算方法为:开花前贮藏氮素运转量(NRA, mg/单茎) = 开花期营养器官氮积累量 - 成熟

期营养器官氮积累量;开花前贮藏氮素运转率(%)=NRA/开花期营养器官氮积累量 $\times 100\%$;花后氮素积累量(NPA,mg/单茎)=成熟期籽粒氮积累量-NRA;对籽粒氮贡献率(%)=NRA(或NPA)/成熟期籽粒全氮量 $\times 100\%$ 。

籽粒淀粉含量按 GB/T15685—1995 旋光仪法测定^[13],直链淀粉用比色法测定^[13]。干、湿面筋含量用上海产 JHGM 面筋烘干仪和 JJJM-54-115-II 面筋洗涤仪测定。降落值用浙江产 JLZ-II 降落值测定仪测定,沉降值用 GB/T15685—1995 标准方法测定。淀粉糊化特性采用澳大利亚 Newport 科学仪器公司生产的快速粘度分析仪(Rapid Viscosity Analyser,RVA)测定。

1.3 数据分析

采用 Windows Excel 和 SPSS (Statistical Package for the Social Science 10.0) 统计软件对试验数据进行方差分析和显著性检验。

2 结果与分析

2.1 花前渍水预处理对花后渍水胁迫下小麦产量及其构成因素的影响

小麦籽粒产量处理间差异显著,以对照最高,WC 处理次之,CW 处理最低,WW 处理籽粒产量较 CW 高 7.3%(表 1);花前渍水降低了单位面积穗数,而花前渍水两处理(WC 和 WW)间和花前未进行预处理(CC 和 CW)间单位面积穗数均无显著差异;每穗粒数以 WW 处理最低,CC 处理次之,CW 和 WC 处理间差异不显著。各渍水处理显著降低了千粒重,其中 WC 和 WW 处理千粒重相近,较对照分别降低 4.9% 和 6.1%,而 CW 处理较对照降低了 29.5%。此外,WW 处理的生物量和收获指数均显著高于 CW 处理。表明与不进行渍水预处理相比,花前渍水预处理可提高花后渍水下小麦籽粒产量。

表 1 不同处理对小麦籽粒产量及其构成因素的影响

Table 1 Effects of different treatments on grain yield and yield components in wheat

处理 Treatment	穗数 Spikes per pot	穗粒数 Kernels per spike	千粒重 1000-kernel weight/g	生物量 Biomass /(g/盆)	籽粒产量 Kernel yield /(g/盆)	收获指数 Harvest index
WW	18.0 bc	38.3 b	38.5 b	30.31 ab	26.5 c	0.34 c
WC	17.5 c	43.0 a	39.0 b	29.12 b	29.4 b	0.40 a
CC	19.5 ab	39.8 ab	41.0 a	31.43 a	31.8 a	0.36 b
CW	20.0 a	42.9 a	28.9 c	27.44 c	24.7 d	0.32 d

同一列不同字母内处理间在 $P < 0.05$ 水平差异显著; WW, 花前渍水预处理+花后渍水胁迫 pre-treatment before anthesis with post-anthesis waterlogging; WC, 花前渍水预处理+无花后渍水胁迫 pre-treatment before anthesis without post-anthesis waterlogging; CC, 无花前渍水预处理+无花后渍水胁迫 non pre-treatment before anthesis without post-anthesis waterlogging; CW, 无前渍水预处理+花后渍水胁迫 non pre-treatment before anthesis with post-anthesis waterlogging

2.2 花前渍水预处理对花后渍水胁迫下小麦籽粒蛋白质及组分含量的影响

与 CC 处理相比,各渍水处理均显著降低小麦籽粒蛋白质含量及产量,其中 WW 降低幅度最大,分别为 32.4% 和 43.2%(表 2)。与花前未渍水处理(CC 和 CW)相比,花前渍水处理(WW 和 WC)显著降低了籽粒醇溶蛋白、谷蛋白含量和总蛋白质含量及产量,但花前渍水处理(WW 和 WC)间和花前未渍水处理(CC 和 CW)间籽粒醇溶蛋白和谷蛋白含量差异不显著。与 CW 处理相比,WW 处理降低了籽粒总蛋白含量及产量和清蛋白含量,而提高了球蛋白含量,两处理间醇溶蛋白和谷蛋白差异显著,但谷/醇比处理间无显著差异。

2.3 花前渍水预处理对花后渍水胁迫下小麦花前积累氮素运转和花后氮素积累的影响

与 CC 处理相比,不同渍水处理均降低小麦花前积累氮素运转量和花后氮素积累量及其对籽粒的贡献率,并最终显著降低籽粒氮积累量(表 3),其中 WW 处理最低,降幅达 26.5%。与 CC 处理相比,CW 显著提高了花前积累氮素对籽粒氮素的贡献率,但花后氮素积累量及其对籽粒氮素贡献率显著降低,籽粒氮积累量也显著降低,表明花后渍水显著影响了花后氮素的积累和运转。与 CW 处理相比,WW 处理显著提高了花后氮素积累量及其对籽粒氮素的贡献率,但更显著地降低了花前积累氮素运转量及其对籽粒氮素的贡献率,导

致籽粒蛋白质积累量降低,这也表明花前积累氮素对籽粒氮积累的贡献大于花后氮素积累。

Table 2 Effects of different treatments on grain protein, protein components and protein yield in wheat							
处理 Treatment	蛋白质含量 Protein content/%	蛋白质产量 Protein yield/(g/盆)	清蛋白 Albumin/%	球蛋白 Globulin/%	醇溶蛋白 Gliadin/%	谷蛋白 Glutenin/%	谷/醇比 Glu/Gli
WW	9.40 c	2.5d	1.82 c	1.14 a	2.28 b	1.60 b	0.90a
WC	10.37 c	3.0b	2.05 bc	0.80 b	2.39 b	2.17 b	0.87a
CC	13.91 a	4.4a	2.28 ab	0.91 ab	3.42 a	3.08 a	0.90a
CW	12.81 b	3.2c	2.39 a	0.80 b	3.19 a	2.96 a	0.93a

Table 3 Effects of different treatments on remobilization of pre-anthesis stored nitrogen and post-anthesis accumulation of nitrogen in wheat						
处理 Treatment	花前积累氮素			籽粒氮积累量 GNA	花后氮素	
	运转量 NRA	运转率 NRR/%	对籽粒氮贡献率 CNR/%		积累量 NPA	对籽粒氮贡献率 CPA/%
WW	31.1 b	85.7 a	79.5 b	39.1 c	8.0 c	20.5 c
WC	30.9 b	85.1 a	75.3 bc	41.1 c	10.1 b	24.7 b
CC	37.5 a	86.9 a	70.5 c	53.2 a	15.7 a	29.5 a
CW	36.3 a	84.1 a	83.4 a	43.6 b	7.2 d	16.6 d

NRR,花前积累氮素运转率(%);Rdistribution rate of pre-anthesis accumulated N (%); CNR,花前积累氮素对籽粒氮贡献率(%); contribution NRA to grain nitrogen (%); GNA,籽粒全氮量(mg/单茎) Grain nitrogen accumulation; NPA,花后氮素积累量(mg/单茎) post-anthesis accumulated nitrogen (mg/stem); NCP,花后氮素积累量对籽粒氮贡献率(%); Contribution of NPA to grain nitrogen (%)

2.4 花前渍水预处理对花后渍水逆境下小麦籽粒淀粉及其组分含量与淀粉产量的影响

与花前未渍水处理(CC和CW)相比,花前渍水处理(WW和WC)显著提高了籽粒直链淀粉和总淀粉含量,其中以WC处理淀粉含量最高,WW次之,但对支链淀粉含量影响不大,并导致支/直比显著降低(表4)。但花前未渍水处理(CC和CW)间和花前渍水处理(WW和WC)间各淀粉组分含量与支/直比差异不显著。与CW处理相比,WW处理显著提高了直链淀粉和总淀粉含量及淀粉产量,但两处理间支链淀粉含量无显著差异,最终降低了支/直比,表明花前渍水预处理主要促进了花后渍水逆境下籽粒直链淀粉的积累。

Table 4 Effects of different treatments on starch contents and yield in wheat grain					
处理 Treatment	总淀粉 Total starch content/%	淀粉产量 Starch yield/(g/盆)	直链淀粉 Amylose Content/%	支链淀粉 Amylopectin content/%	支/直链比 AP/AM
WW	67.67 a	17.9 b	14.92 a	52.75 a	3.54 b
WC	68.10 a	20.0 a	15.05 a	53.05 a	3.53 b
CC	64.34 b	20.5 a	11.90 b	52.44 a	4.42 a
CW	64.14 b	15.8 c	12.14 b	52.01 a	4.29 a

2.5 花前渍水预处理对花后渍水逆境下小麦籽粒面粉品质性状及糊化特性的影响

与CC处理相比,各渍水处理均显著降低小麦面粉干/湿面筋和沉降值,并显著提高了降落值(表5)。花前渍水预处理(WW和WC)间除沉降值差异显著外,其他指标差异不显著。与CW处理相比,WW处理干/湿面筋含量和沉降值显著降低,但显著提高了降落值。

与CC处理相比,花前渍水预处理(WW和WC)显著提高了小麦面粉的峰值粘度、低谷粘度、崩解值和最终粘度,并显著降低了小麦面粉的回冷值和峰值时间,对糊化温度影响不显著;然而,花后渍水处理(CW)显著降低了最终粘度、回冷值和峰值时间(表6)。与CW相比,WW处理显著提高了小麦面粉峰值粘度、低谷粘

度、崩解值、最终粘度、回冷值和峰值时间,但对糊化温度无显著影响,这可能与 WW 处理提高了籽粒直链淀粉含量有关。

表 5 不同处理对小麦面粉品质的影响

Table 5 Effects of different treatments on flour quality traits in wheat

处理 Treatment	湿面筋 Wet gluten /%	干面筋 Dry gluten /%	沉降值 Sedimentation volume /mL	降落值 Falling number /s
WW	23.9 c	9.35 c	61 d	428 a
WC	25.3 c	10.0 c	65 c	431 a
CC	40.0 a	14.5 a	75 a	385 c
CW	34.6 b	12.5 b	72 b	407 b

表 6 不同处理对小麦面粉糊化特性的影响

Table 6 Effects of different treatments on pasting properties of wheat flour

处理 Treatment	峰值粘度 Peak viscosity /cp	低谷粘度 Hold trough /cp	崩解值 Breakdown /cp	最终粘度 Final viscosity /cp	回冷值 Setback /cp	峰值时间 Peak time /min	糊化温度 Pasting Temp /℃
WW	3335 a	1751 a	1583 a	3392 a	1640 b	5.98 c	78 b
WC	3262 b	1721 a	1523 b	3333 b	1630 b	6.02 b	84 ab
CC	2540 c	1440 b	1072 d	3138 c	1703 a	6.09 a	87 a
CW	2595 c	1453 b	1142 c	2893 d	1441 c	5.91 d	84 ab

3 讨论

3.1 花前渍水预处理对花后渍水胁迫下小麦产量的影响

小麦生育中后期渍水导致土壤缺氧,根系活力下降,影响了营养元素吸收^[14-15];同时地上部叶片光合速率下降,物质积累转运降低,最终影响小麦粒重和产量^[3-5, 16-17]。本研究结果显示,无论是花前还是花后渍水都显著降低了小麦籽粒产量,但以 CW 处理减产幅度最大,WW 次之,CW 和 WW 处理间产量差异显著,表明渍水预处理可有效提高花后渍水逆境下小麦籽粒产量,增幅达 7.3%。

从产量构成因素看,WW 处理的穗数与穗粒数虽然低于 CW 处理,但其千粒重显著高于 CW 处理,表明与未进行渍水预处理(CW)相比,花前渍水预处理(WW)对花后渍水下小麦籽粒产量的提高,主要是通过提高小麦千粒重实现的。此外,WW 处理的生物量和收获指数均高于 CW 处理,这也是 WW 处理籽粒产量高于 CW 的重要原因。由此可见,生育前期适宜的渍水预处理,可显著提高花后的抗渍性,可作为是缓减小麦花后渍水逆境伤害的可行途径。但其生理生化机理尚有待于进一步研究。

3.2 花前渍水预处理对花后渍水逆境下小麦籽粒氮素代谢及面粉品质性状的影响

渍水显著影响小麦籽粒蛋白各组分的积累,如渍水处理下小麦籽粒谷蛋白含量及谷蛋白/醇溶蛋白比值和蛋白含量均大幅度下降^[7]。本研究表明,不同渍水处理(WW、CW 和 WC)均不同程度降低了小麦籽粒醇溶蛋白和谷蛋白含量,进而显著降低小麦籽粒蛋白质含量,其中以 WW 处理的降幅最大。本研究同时还发现,与 CW 处理相比,WW 处理虽然显著提高了球蛋白含量,但显著降低了清蛋白、醇溶蛋白和谷蛋白含量,最终降低了谷/醇比。

小麦籽粒积累氮素来源于花前积累氮素的再转运和花后植株直接吸收的氮素^[18],而渍水逆境可显著降低小麦各营养器官花前贮藏氮素再运转量和再运转率,以及花前贮藏氮素总运转量和总运转率,进而降低籽粒氮积累量^[17]。本研究发现,与 CC 处理相比,无论是花前还是花后渍水处理均降低小麦花前积累氮素运转量和花后氮素积累量,并最终显著降低籽粒氮积累量,其中 WW 降幅最大,WC 次之,表明花前渍水对籽粒氮素积累的影响较花后渍水影响大。同时,与 CW 处理相比,WW 处理显著提高了花后氮素对籽粒氮素的贡献率,但更显著地降低了花前积累氮素对籽粒氮素的贡献率,最终引起籽粒蛋白质含量和积累量的降低,说明花

前多次渍水处理将加剧小麦籽粒氮素积累的下降,并且渍水条件下,籽粒氮积累量的降低主要是由花前积累氮素运转量下降引起,这与 Mackown 等^[19]、Heitholt^[20]研究结果相符。因此,应寻求更为适宜的前期渍水预处理方法(如预处理时间、次数和持续时间等),以减缓渍水预处理可能对小麦籽粒品质带来的不利影响。此外,渍水显著降低了籽粒干、湿面筋含量和沉降值,这与范雪梅等^[21]人研究结果基本一致。其中,与 CW 处理相比,WW 处理干/湿面筋含量和沉降值显著降低,这与面筋蛋白即籽粒谷蛋白和醇溶蛋白以及总蛋白含量的变化基本一致。

3.3 花前渍水预处理对花后渍水胁迫小麦籽粒淀粉含量及面粉糊化特性的影响

淀粉约占小麦籽粒重的 65% 以上,对小麦产量和加工品质有重要影响,而小麦籽粒直、支链淀粉含量及比例决定了淀粉的加工品质^[22],其中淀粉糊化特性是反映淀粉品质的重要指标,对面条等食品的食用品质有重要影响^[23]。有报道认为渍水显著降低籽粒淀粉产量和支链淀粉含量,直链淀粉含量提高,从而不同程度地降低籽粒直/支链淀粉比^[7],但对淀粉糊化特性的研究较少。本试验结果显示,花前渍水处理比无花前渍水处理提高了直链淀粉和总淀粉含量,导致支/比显著下降;与 CW 处理相比,WW 处理对支链淀粉含量影响不大,但显著提高了直链淀粉含量,从而显著降低了支/直链淀粉比值。直链淀粉含量和支/直比的变化,导致小麦淀粉糊化特性发生了变化。如本研究中花前渍水预处理(WW)籽粒直链淀粉含量显著高于未预处理(CW),这导致 WW 处理的峰值粘度、低谷粘度、崩解值、最终粘度、回冷值和峰值时间显著 CW 处理。因此,进行花前渍水预处理后,可提高小麦籽粒总淀粉和直链淀粉含量,降低支/直比,导致除糊化温度外的所有糊化性状发生了显著改变,进而会影响小麦的加工品质特性。

4 结论

综上所述,花前渍水预处理显著提高了小麦在花后渍水逆境条件下的生物量与收获指数及千粒重,最终显著提高籽粒产量;花前渍水预处理显著提高了花后氮素积累量及其对籽粒氮素的贡献率,降低了花前贮藏氮素运转量及其对籽粒氮素的贡献率,引起面筋蛋白即醇溶蛋白和谷蛋白及总蛋白含量显著降低,干湿面筋含量和沉降值均下降;花前渍水预处理还提高了籽粒直链淀粉和总淀粉含量及面粉降落值,降低了支/直链淀粉比值,显著提高了面粉峰值粘度、低谷粘度、崩解值、最终粘度、回冷值和峰值时间,但对糊化温度无显著影响。

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