

本砧嫁接对西瓜苗期高温耐性的影响

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摘要:【目的】探究本砧嫁接对西瓜苗期耐高温性能的影响。【方法】以西瓜品种早佳自根苗为对照, 分别测定了对照和以西瓜本砧品种野壮1号为砧木嫁接早佳的嫁接苗, 在42℃高温胁迫处理5 d后接穗的下胚轴长度和粗度、子叶和真叶相对叶绿素含量及叶片颜色、真叶光合荧光参数、丙二醛含量(MDA)等逆境相关物质含量和过氧化物酶活性。【结果】高温及嫁接均可显著提升接穗下胚轴粗度, 嫁接可缓解因高温导致的子叶和真叶颜色失绿, 维持更高的叶绿素含量, 保持更好的光能捕获和转化能力, 维持相对稳定的电子传递链活性, 减轻光系统受损程度, 缓解高温导致的MDA含量升高, 减轻氧化应激而维持膜稳定性。【结论】本砧嫁接通过形态、光合及细胞3个层面协同提高西瓜接穗在苗期的高温耐性, 为西瓜抗逆栽培提供了理论依据。

关键词: 西瓜; 下胚轴; 叶片颜色; 光合荧光; 叶绿素; 氧化应激

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Effect of wild watermelon rootstock grafting on high temperature tolerance of watermelon seedlings

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Abstract: 【Objective】In order to further explore the effect of rootstock grafting on the high temperature tolerance of watermelon seedlings, this study aims to compare and analyze the growth performance of self-rooted watermelon seedlings and watermelon seedlings grafted on wild watermelon rootstock Yezhuang No. 1 under high temperature stress, reveal the mechanism of grafting technology in improving the high temperature tolerance of watermelon seedlings, and provide scientific basis and technical support for stress-resistant cultivation of watermelon. 【Methods】In this study, the self-rooted seedlings of Zaojia watermelon variety was used as a control, and the watermelon rootstock variety Yezhuang No. 1 as the rootstock for grafting. The grafted seedlings and self-rooted seedlings were subjected to high temperature treatment at 42℃ for 5 days. By measuring and recording the length and thickness of the hypocotyl under scion, the relative chlorophyll content and leaf color parameters of cotyledons and true leaves, the photosynthetic fluorescence parameters of true leaves, as well as the content of stress related substances such as malondialdehyde (MDA) and antioxidant enzyme activity such as peroxidase (POD), the effects of grafting on watermelon seedling growth under high temperature stress were comprehensively evaluated. 【Results】Agronomic traits performance: Both high temperature and grafting can significantly increase the thickness of the hypocotyl below the scions, but had little effect on the length of the hypocotyl. Grafted seedlings showed higher relative chlorophyll content (SPAD) between cotyledons and true leaves under high temperature treatment, and the leaf color was more vibrant green,

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indicating that grafting can alleviate chlorophyll degradation and leaf chlorosis caused by high temperature. In addition, the changes in brightness (L^* value), red green value (a^* value), and yellow blue value (b^* value) of the cotyledons and true leaves on grafted seedlings also showed a positive effect of grafting on leaf color. Photosynthetic fluorescence parameters: Under high temperature stress, the actual quantum efficiency ($Y(II)$), photosynthetic electron transfer rate (ETR), and photochemical quenching coefficient (qP) of photosystem II (PS II) in grafted seedlings were significantly higher than those in self-rooted seedlings, while the non photochemical quenching coefficient (NPQ) was lower. These results indicated that grafted seedlings can maintain higher light energy capture and conversion capacity under high temperature conditions, maintain relatively stable electron transport chain activity, and reduce the degree of damage to the photosystem. At the same time, although the PS II maximum photochemical efficiency (F_v/F_m) and potential photochemical efficiency (F_v/F_o) of grafted seedlings decreased, they were still higher or close to the level of self-rooted seedlings, further verifying the heat tolerance advantage of grafted seedlings. Physiological indicators related to adversity: In terms of physiological indicators related to adversity, grafted seedlings showed higher chlorophyll a, chlorophyll b, and total chlorophyll contents under high temperature stress, as well as lower MDA content and POD activity. These results indicated that grafting can enhance the antioxidant capacity of watermelon seedlings, reduce the degree of membrane lipid peroxidation, and maintain the stability and integrity of cell membranes. In addition, although there was no significant difference in soluble sugar content between grafted seedlings and self-rooted seedlings under high temperature treatment, grafted seedlings were able to maintain a relatively stable physiological state under high temperature stress. **【Conclusion】** Grafting enhanced high-temperature adaptability by coordinating morphology and pigment metabolism: Grafted seedlings exhibited more significant morphological adaptive adjustments under high temperatures, such as a significant increase in hypocotyl thickness, which may be related to auxin mediated cell wall remodeling. At the same time, grafted seedlings also exhibited advantages in pigment metabolism, such as higher chlorophyll content and more stable leaf color, which helped maintain light capture capacity and photosynthetic electron transfer efficiency. Stability of Photosynthetic Mechanisms and Heat Resistant Core Mechanisms Revealed by Fluorescence Parameters: Grafted seedlings can maintain more efficient light energy conversion efficiency and relatively stable electron transfer chain activity at high temperatures, thanks to the stability of their photosynthetic mechanism. Specifically, higher qP values and lower NPQ values indicated that grafted seedlings can more effectively utilize light energy for photochemical reactions and reduce energy loss caused by non photochemical quenching. In addition, the PS II damage of grafted seedlings was relatively mild, further demonstrating the heat resistance of their photosynthetic mechanisms. Membrane system protection and oxidative stress balance: Grafting significantly alleviated the phenomenon of membrane lipid peroxidation induced by high temperature, mainly due to the higher antioxidant capacity and stable chlorophyll content of grafted seedlings. Chlorophyll, as a key pigment in photosynthesis, its stability is crucial for maintaining the integrity of membrane systems. At the same time, the lower POD activity of grafted seedlings also indicated that their basic antioxidant capacity was sufficient to eliminate reactive oxygen species (ROS), thereby reducing oxidative stress damage to the membrane system. Physiological integration effect of grafting heat resistance: Compared to cross rootstock grafting, this rootstock grafting may have unique advantages, such as optimized material transport, signal transmission fidelity, and integration of circadian rhythms. These advantages helped graft seedlings maintain a more stable physiological state and higher growth vitality under high temperature stress. This study indicates that rootstock grafting significantly improves the high-tem-

perature tolerance of watermelon seedlings by enhancing hypocotyl stability, maintaining chloroplast pigment homeostasis, optimizing photochemical efficiency and heat dissipation balance, inhibiting membrane lipid peroxidation, and coordinating antioxidant enzyme activity through multiple mechanisms. These findings provide important theoretical basis and technical support for the stress-resistant cultivation of watermelons, and have broad application prospects and promotion value.

Key words: Watermelon; Hypocotyl; Leaf color; Photosynthetic fluorescence; Chlorophyll; Oxidative stress

西瓜作为全球重要的经济作物,2023年全球种植面积超过304万 hm^2 ^[1]。在其栽培过程中常受到高温胁迫的限制,不仅抑制西瓜的生长发育,还会显著降低其产量和品质^[2]。同时连作障碍与土传病害对产业影响严重,导致减产30%~50%,严重时甚至绝收^[3]。传统化学防治引发生态污染,而抗病育种周期长(8~10年)。因此,嫁接技术成为综合防控最有效的绿色手段^[4],近年来被广泛应用于改善作物的抗病性,耐低温、耐旱等耐逆性和抗连作栽培等方面^[5-7]。

西瓜苗期是生理代谢的敏感期,高温会触发一系列连锁反应,包括叶片厚度、栅栏组织厚度、海绵组织厚度和组织紧密度变化,叶绿体膜稳定性受破坏和PS II反应中心失活等光合系统的损伤, F_v/F_m 参数下降,净光合速率、蒸腾速率和气孔导度降低,发生氧化应激、膜脂过氧化、渗透调节失衡及信号通路调控异常,最终抑制幼苗生长、降低存活率,且不同西瓜品种在耐高温方面存在一定差异^[8-9]。嫁接技术能够缓解高温胁迫对西瓜生长的抑制,提高光合效率,并增强抗氧化酶活性,从而促进植物的生物量积累和提升整体耐热性^[10]。此外,不同砧木对嫁接西瓜的光合特性也有显著影响。研究发现,南瓜砧木嫁接的西瓜在高温条件下表现出更高的叶绿素含量、净光合速率(P_n)和叶绿素荧光参数(如 F_v/F_m),表明嫁接可能通过改善光合系统来提高西瓜的高温耐性^[11-12]。在叶片颜色方面,嫁接西瓜表现出与自根苗不同的变化趋势。例如,葫芦砧木嫁接的西瓜在高温胁迫下叶片颜色更加鲜绿,而自根苗则出现褪绿现象^[13-14]。叶绿素含量是衡量植物光合能力的重要指标。研究显示,在嫁接瓜类中叶绿素含量通常高于自根苗,这可能是由于嫁接技术提高了根系的吸收能力和叶片的光合效率^[15-16]。过氧化物酶(POD)作为植物抗氧化系统的重要组成部分,其活性在嫁接西瓜中高于自根苗,这表明嫁接可通过增强抗氧化酶活性来减轻高温引起的氧化损伤^[17-18]。

此外,嫁接还能够降低叶片中丙二醛(MDA)含量,进一步证明了嫁接技术对高温胁迫的缓解作用^[13-14,19]。

嫁接西瓜的主要砧木类型有南瓜、葫芦和野生西瓜。其中,野生西瓜砧木可提高西瓜果实番茄红素等营养物质含量,近年来已成为西瓜嫁接砧木的重要应用类型之一^[20]。野生西瓜砧木嫁接成活率显著高于南瓜砧木,同时果实可溶性糖含量、番茄红素含量显著高于南瓜砧木,且无南瓜砧木常见的异味问题^[21-23]。因此,在生产中成为高品质精品西瓜嫁接栽培的首要选择。本研究以西瓜自根苗为对照,对自根苗和野生西瓜砧木嫁接的西瓜苗进行高温处理,围绕光合荧光参数、叶片颜色、叶绿素含量及过氧化物酶活性等关键指标展开深入探讨,为优化西瓜的高温耐性提供理论依据和技术支持。

1 材料和方法

1.1 试验材料

所用材料为野生西瓜类型砧木品种野壮1号(YZ1),西瓜品种早佳(ZJ)。其中野壮1号种子由宁波市丰登种业科技有限公司提供,早佳种子由新疆昌农种业有限责任公司提供。

1.2 试验方法

试验在宁波市特色园艺作物品质调控与抗性育种重点实验室进行。选择饱满一致的砧木种子进行温汤浸种、催芽。待种子露白后播种于填充有育苗基质的50孔穴盘中,置于人工气候箱内暗培养,温度为26℃,湿度为90%。顶土后,培养条件调整为光周期16 h光照/8 h黑暗,光照度约为25 000 lx,昼夜温度为24℃/16℃,昼夜湿度为80%/85%。接穗种子浸种、催芽,待其露白后播种于填充有育苗基质的方盘中,置于人工气候箱内暗培养,温度为26℃,湿度为90%。顶土后,培养条件调整为光周期12 h光照/12 h黑暗,光照度约8000 lx,昼夜温度26℃/20℃,昼夜湿度80%/85%。以野壮1号为砧木,早

佳为接穗。待砧木真叶展开、接穗生长至子叶直立但未展开时,采用顶插接法嫁接。嫁接后,穴盘浸水至基质水分饱和,穴盘上加盖育苗盖,顶部透气孔密闭,置于培养箱内。前3 d无光照,温度28℃,湿度95%;第4~7天透气孔少量打开,光周期12 h光照/12 h黑暗,光照度8000 lx,昼夜温度26℃/20℃,湿度90%;第8~10天,透气孔全部打开,光周期16 h光照/8 h黑暗,光照度20 000 lx,昼夜温度24℃/16℃,昼夜湿度85%/90%;第11天及之后,去掉育苗盖,光周期16 h光照/8 h黑暗,光照20 000 lx,昼夜温度24℃/16℃,昼夜湿度80%/85%。

嫁接成活后,进行高温处理。试验设置嫁接苗高温(YZ1/ZJ-T)、自根苗高温(ZJ-T)、嫁接苗常温(YZ1/ZJ-CK)和自根苗常温(ZJ-CK)4个处理,均设3次重复,每次重复25株。处理组设置为光周期16 h光照/8 h黑暗,光照度25 000 lx,温度42℃,昼夜湿度80%/85%。对照组设置为光周期16 h光照/8 h黑暗,光照度25 000 lx,昼夜温度24℃/16℃,昼夜湿度80%/85%。

1.3 测定项目与方法

高温处理5 d后测定接穗下胚轴粗度和长度;利用SPAD 502 plus叶绿素仪测定接穗子叶和第一片真叶的相对叶绿素含量(SPAD值);利用LS171色差仪测定接穗子叶和第一片真叶的叶片颜色, L^* (亮度)、 a^* (红-绿)、 b^* (黄-蓝)值。其中 ΔL^* (处理组 L^* -对照组 L^*)为正,表明处理组颜色比对照组浅(偏白), ΔL^* 为负,表明处理组颜色比对照组深(偏黑); Δa^* (处理组 a^* -对照组 a^*)为正,表明处理组颜色比对照组红(偏红), Δa^* 为负,表明处理组颜色比对照组绿(偏绿); Δb^* (处理组 b^* -对照组 b^*)为正,表明处理组颜色比对照组黄(偏黄), Δb^* 为负,表明处理组颜色比对照组蓝(偏蓝)。

利用Junior-PAM调制叶绿素荧光仪测定光合相关参数。植株暗处理20 min后,利用 F_v 模式对接穗第一片真叶测定初始荧光 F_0 ,最大荧光 F_m ,光合电子传递速率ETR($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$),光化学淬灭系数qP,非光化学淬灭系数NPQ,光保护的重要指标PS II调节性能量耗散的量子产额Y(NPQ),光损伤的重要指标PS II非调节性能量耗散的量子产额Y(NO),以及通过公式计算的PS II最大光化学效率即原初光能转化效率 F_v/F_m ,PS II实际光化学效率 $Y(II)=(F_m'-F')/F_m'$,PS II潜在光化学效率 $F_v/F_0=$

$(F_m-F_0)/F_0$ 。

叶绿素a、叶绿素b及总叶绿素含量使用叶绿素含量测定试剂盒(分光法)测定;可溶性糖含量使用可溶性糖含量试剂盒(分光法)测定;丙二醛含量使用丙二醛含量测试试剂盒(分光法)测定;过氧化物酶活性使用过氧化物酶试剂盒(分光法)测定;过氧化氢酶活性使用过氧化氢酶(CAT)试剂盒(分光法)测定。测定方法均按照试剂盒说明书进行。所用试剂盒均来自苏州格锐思生物科技有限公司。

1.4 数据分析

利用WPS office进行方差分析,并通过在线数据分析平台OmicShare tools,利用方差分析LSD多重比较的方法进行组间差异分析。

2 结果与分析

2.1 高温对嫁接和自根西瓜苗期农艺及生理性状的影响

高温及嫁接均可显著提高接穗下胚轴粗度,但在嫁接苗和自根苗中,高温对下胚轴长度影响不显著(表1)。高温对自根苗子叶SPAD值影响不显著,对嫁接苗的影响显著。对于真叶,高温对自根苗及嫁接苗的影响均显著,但嫁接苗高温处理下与自根苗对照无显著差异。

高温对子叶颜色 L^* 影响则不显著,可导致真叶颜色变深(表1)。嫁接降低了高温及常温的子叶和真叶颜色 a^* ,但仅真叶达显著水平。高温导致嫁接苗及自根苗子叶和真叶颜色 a^* 均显著升高。高温导致自根苗子叶和真叶颜色 b^* 降低(19.03 vs 18.14和13.08 vs 11.85),但嫁接苗高温下子叶和真叶颜色 b^* 分别表现为显著上升和降低。另外,高温及嫁接对真叶的影响总体均大于子叶。

2.2 高温对嫁接和自根西瓜苗期光合荧光参数的影响

高温胁迫显著降低了光系统II的实际量子效率 $Y(II)$ 。嫁接苗在高温下 $Y(II)$ 为0.34,居于自根苗高温(0.24)和常温(0.50)之间(表2)。电子传递速率结果显示,嫁接高温处理的ETR(27.36)显著高于自根苗高温处理(19.11),但较各自对照降低约32.4%和52.5%。qP值反映PS II反应中心的开放程度。嫁接苗高温处理的qP(0.64)显著高于自根苗(0.47)。NPQ值显示自根苗高温处理(0.55)显著高于嫁接苗(0.47)。值得注意的是,对照组NPQ值显

表 1 高温下嫁接和自根西瓜苗期农艺及生理性状表现

Table 1 Performance of agronomic and physiological traits in grafted and self rooted watermelon seedlings under high temperature

性状 Trait	YZ1/ZJ-T	YZ1/ZJ-CK	ZJ-T	ZJ-CK
接穗下胚轴长度 Hypocotyl length of scion/cm	2.76±0.08 b	2.74±0.03 b	3.71±0.04 a	3.67±0.07 a
接穗下胚轴粗度 Hypocotyl thick of scion/mm	2.89±0.01 a	2.79±0.02 b	2.37±0.03 c	2.27±0.02 d
子叶 SPAD 值 Cotyledon SPAD value	71.05±0.27 a	68.73±0.79 b	59.95±0.22 c	61.08±0.24 c
真叶 SPAD 值 Leaf SPAD value	52.46±0.48 b	51.01±0.34 c	56.01±0.62 a	53.44±0.29 b
子叶颜色 L^* Cotyledon color L^*	44.66±0.39 b	45.90±0.07 b	47.68±0.15 a	47.34±0.46 a
子叶颜色 a^* Cotyledon color a^*	-6.55±0.15 ab	-7.69±0.07 c	-6.46±0.10 a	-7.15±0.07 bc
子叶颜色 b^* Cotyledon color b^*	18.46±0.31 a	16.91±0.52 b	18.14±0.27 a	19.03±0.16 a
真叶颜色 L^* Leaf color L^*	41.67±0.26 c	45.06±0.71 a	42.62±0.44 bc	42.97±0.25 b
真叶颜色 a^* Leaf color a^*	-5.71±0.18 a	-7.98±0.15 c	-5.18±0.22 a	-6.69±0.06 b
真叶颜色 b^* Leaf color b^*	13.25±0.38 b	15.11±0.22 a	11.85±0.30 c	13.08±0.12 b

注:不同字母代表差异显著($P<0.05$)。下同。

Note: Different letters represent significant differences ($P<0.05$). The same below.

表 2 高温下嫁接和自根西瓜苗期光合荧光参数表现

Table 2 Performance of photosynthetic fluorescence parameters in grafted and self rooted watermelon seedlings under high temperature

性状 Trait	YZ1/ZJ-T	YZ1/ZJ-CK	ZJ-T	ZJ-CK
Y(II)	0.34±0.00 b	0.51±0.02 a	0.24±0.012 c	0.50±0.01 a
ETR	27.36±0.93 b	40.46±0.71 a	19.11±0.93 c	40.21±0.72 a
qP	0.64±0.01 b	0.71±0.01 a	0.47±0.01 c	0.72±0.01 a
NPQ	0.47±0.01 d	0.73±0.01 b	0.55±0.02 c	0.84±0.02 a
Y(NO)	0.43±0.01 b	0.29±0.00 c	0.50±0.01 a	0.27±0.01 c
Y(NPQ)	0.22±0.00 b	0.21±0.01 b	0.26±0.01 a	0.23±0.01 b
F_v/F_m	0.64±0.01 b	0.81±0.01 a	0.66±0.02 b	0.82±0.01 a
F_v/F_o	1.84±0.08 d	4.15±0.06 b	2.20±0.04 c	4.49±0.09 a

著高于高温处理。Y(NO)反映PS II的不可逆损伤程度。自根苗高温处理的Y(NO)最高(0.50),显著高于嫁接苗(0.43),这与 F_v/F_m 和 F_v/F_o 的结果一致。

2.3 高温对嫁接和自根西瓜苗期逆境相关生理指标的影响

常温下嫁接对西瓜叶片叶绿素a含量、叶绿素b含量和总叶绿素含量影响均不显著(表3)。但高温下嫁接苗叶绿素b及总叶绿素含量显著高于自根

苗,且高温导致叶绿素a降低的变幅在嫁接苗中更小,导致叶绿素b和总叶绿素含量在嫁接苗中则为上升。

可溶性糖含量在各组间无显著差异(表3)。高温导致自根苗和嫁接苗MDA含量均升高,但自根苗升高显著,且自根苗高温组MDA含量最高(45.83 nmol·g⁻¹)。高温导致自根苗POD活性升高,且高温组活性最高(546.77 ΔOD₄₇₀·g⁻¹·min⁻¹);导致

表 3 高温下嫁接和自根西瓜苗期逆境相关物质含量

Table 3 Adversity related substances content in grafted and self rooted watermelon seedlings under high temperature

指标 Index	YZ1/ZJ-T	YZ1/ZJ-CK	ZJ-T	ZJ-CK
w(叶绿素a) Chlorophyll a content/(mg·g ⁻¹)	0.97±0.02 ab	1.00±0.02 a	0.83±0.10 b	0.87±0.03 ab
w(叶绿素b) Chlorophyll b content/(mg·g ⁻¹)	0.49±0.02 a	0.41±0.00 b	0.33±0.05 c	0.40±0.01 b
w(总叶绿素) Total chlorophyll content/(mg·g ⁻¹)	1.46±0.03 a	1.41±0.046 ab	1.16±0.15 c	1.28±0.05 abc
w(可溶性糖) Soluble sugar content/(mg·g ⁻¹)	3.66±0.14 a	3.32±0.08 a	3.69±0.22 a	3.38±0.12 a
b(MDA) MDA content/(nmol·g ⁻¹)	28.66±1.27 b	22.88±1.42 bc	45.83±5.58 a	18.73±0.13 c
POD 活性 POD activity/(ΔOD ₄₇₀ ·g ⁻¹ ·min ⁻¹)	393.73±16.16 c	445.32±4.02 b	546.77±8.45 a	449.12±7.44 b
CAT 活性 CAT activity/(mmol·g ⁻¹ ·min ⁻¹)	1.00±0.22 c	11.69±0.25 a	4.34±0.32 b	1.97±0.07 c

嫁接苗 POD 活性降低,且高温组最高(393.73 $\Delta\text{OD}_{470} \cdot \text{g}^{-1} \cdot \text{min}^{-1}$)。对于 CAT 活性,与 POD 活性一样,高温导致自根苗显著升高,嫁接苗显著降低。

3 讨论

3.1 嫁接通过协调形态与色素代谢增强高温适应性

嫁接苗下胚轴粗度在高温下显著增加,且显著高于自根苗高温和常温处理,表现出更显著的形态适应性。这一现象可能与高温通过改变相关基因表达,促进生长素合成,进而促进下胚轴增粗,强化机械支撑,从而提高高温抗性^[24-25]。值得注意的是,高温对下胚轴长度的促进作用在嫁接/自根苗间无显著差异,表明嫁接主要调控径向生长而非纵向延伸。

在色素代谢层面,嫁接苗子叶 SPAD 值显著高于自根苗,且叶色参数 L^* 值降低、 a^* 值增幅较小。与茶树的研究结果类似,表明嫁接可减轻高温引起的叶绿素降解和叶片失绿现象^[26-28]。这源于两个关键机制:(1)叶绿素稳定性增强:嫁接苗高温下总叶绿素含量较自根苗高 25.9%,与 SPAD 值呈正相关^[29]。高叶绿素含量维持了光捕获能力,为光合电子传递提供基础。(2)捕光复合体调控:茶树研究显示,黄化叶片中 CAB 基因家族(如 *CAB1*)表达下调导致叶绿素 *a/b* 结合蛋白减少,引发 L^* 值升高和 a^* 值异常^[27]。嫁接可能通过稳定 CAB 基因表达,避免高温下的色素紊乱。

3.2 光合机构稳定性:荧光参数揭示的耐热核心机制

高温破坏光系统稳定性,但嫁接可提高接穗的叶绿素含量、光合速率,保持电子传递系统稳定,维持了更高效的光能转化效率^[30-31]。嫁接苗 $Y(\text{II})$ 较

自根苗高,且 qP 值显著高于自根苗,与前人研究结果一致。这归因于三重保护机制:(1)电子传递链稳定性:嫁接苗 ETR 降幅显著低于自根苗,表明其光合电子传递系统受高温抑制程度较轻。耐热水稻品种同样在高温下表现出 ETR 稳定性,与 Rubisco 活化酶活性呈正相关^[32]。(2)热耗散精准调控:自根苗 NPQ 值高于嫁接苗,反映其通过增强非光化学淬灭耗散过剩光能,但代价是光能利用效率下降^[33-34]。嫁接苗的较低 NPQ 与更高 qP 结合,实现光保护与光化学效率的平衡。(3)PS II 损伤防控:自根苗 $Y(\text{NO})$ 显著高于嫁接苗,证实其 PS II 核心遭受更严重光损伤^[35]。 F_v/F_m 值在嫁接苗中异常降低,可能与 PS II 天线重组相关:PsbS 蛋白缺失的拟南芥仍能通过增强 ΔpH 诱导能量耗散,但响应速度延迟^[36]。嫁接可能通过调控类囊体膜流动性优化该过程。同时嫁接可引发 P700 等光合相关 RNA 在砧穗间的跨物种移动,但砧穗间的亲缘关系对 RNA 转移具有显著影响^[37-38],这可能是本砧嫁接对高温耐性的影响与异砧嫁接有所不同的原因。

高温下嫁接苗的光合保护策略见图1。

3.3 膜系统保护与氧化应激平衡

高温可导致植株叶绿素降解,膜脂过氧化,MDA 含量增加,POD 活性升高^[39-40],但嫁接可显著缓解高温诱导的膜脂过氧化^[41-42]。与前人研究结果一致,笔者在本研究中发现自根苗 MDA 含量在高温下激增,而嫁接苗中增加并不显著,这种差异可能源于两类协同机制。一是膜脂过氧化抑制:叶绿素降解与 MDA 积累呈显著负相关^[40]。嫁接苗的高叶绿素含量直接减少活性氧(ROS)爆发,降低膜系统损伤风险。二是抗氧化酶动态调节:自根苗 POD 活性在高温下显著升高,反映其处于氧化应激状态;而

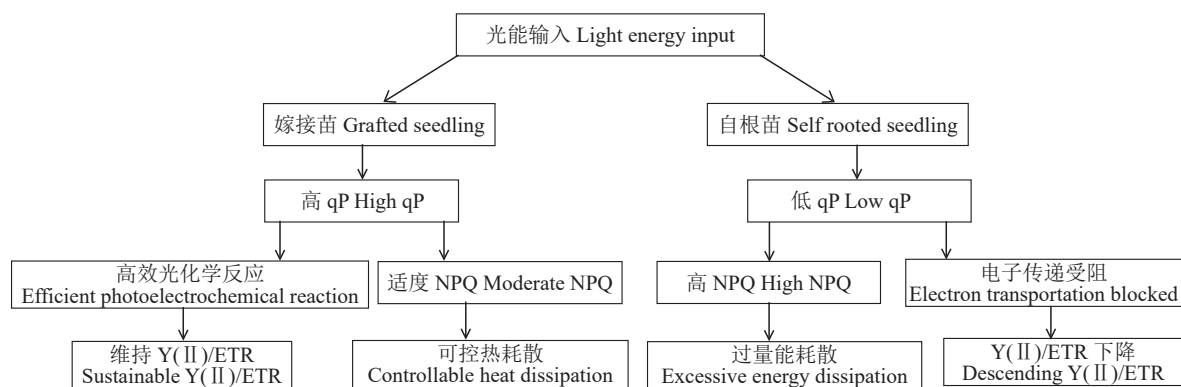


图1 高温下嫁接苗光合保护策略

Fig. 1 Photosynthetic protection strategies of grafted seedlings under high temperature

嫁接苗 POD 活性较低,表明其基础抗氧化能力足以清除 ROS^[42]。

3.4 嫁接耐热性的生理整合效应

本砧嫁接(西瓜/西瓜)相较于异砧(如南瓜砧木)可能具有独特优势:(1)物质运输优化:南瓜砧木虽提高西瓜壮苗指数,但可能导致糖代谢紊乱^[24]。本研究中嫁接苗可溶性糖含量无显著变化,暗示其碳分配更协调。(2)信号传导保真性:同种砧穗间内源激素(如 ABA)和逆境信号分子(如 H₂O₂)的传导效率更高。外源 ABA 可增强 NPQ 和 rETR^[31],本砧嫁接可能通过类似通路协同光保护来提高抗逆性。番茄盐胁迫试验显示,BR 通路在非本砧中的激活程度高于本砧,暗示其对逆境的响应存在遗传距离依赖性^[43],进一步表明本砧嫁接可能在逆境胁迫方面具有优势。(3)昼夜节律整合:拟南芥中 *ELF3* 通过液-液相分离感知温度,调控 *PIF4* 介导的下胚轴生长^[44]。嫁接可能通过维持生物钟基因稳态,避免高温导致的节律紊乱。

3.5 局限性

尽管笔者对本砧嫁接在室内条件下影响西瓜苗期高温耐性的生理机制进行了一定的解析,但处理的温度和时间还不够全面。后续为了更全面地了解本砧嫁接对西瓜高温耐性的影响机制,还需要在不同温度和不同处理时长下,针对更多的表型及生理生化及分子表现进行研究。另外,伸蔓期、开花期等更多发育阶段的高温胁迫影响尚需完善,并进行不同发育阶段影响机制的联合分析。

4 结 论

笔者在本研究中通过对本砧嫁接的西瓜及西瓜自根苗在苗期高温处理后的农艺性状、叶片颜色、SPAD 值、光合荧光参数、叶绿素含量和可溶性糖含量等逆境相关物质的分析,得出以下结论:(1)高温胁迫下,嫁接苗较自根苗的下胚轴粗度显著增加,通过强化机械支撑来增强抗逆性,表现出更显著的形态适应性;(2)嫁接苗子叶 SPAD 值显著高于自根苗,维持更高的叶绿素含量,减轻了高温引起的叶绿素降解和叶片失绿现象;(3)嫁接苗 ETR 降幅显著低于自根苗,Y(NPQ)和 Y(NO)稳定性高于自根苗;(4)嫁接抑制了高温导致的 MDA 含量和 POD 活性的升高,减轻了氧化应激,维持膜稳定性。总体上,本砧嫁接通过三重互作机制以提升西瓜苗期高

温耐性:(1)形态:强化下胚轴稳定性,维持叶绿体色素稳态;(2)光合:优化光化学效率与热耗散平衡,减少不可逆光损伤;(3)细胞:抑制膜脂过氧化并协调抗氧化酶活性,应激响应更高效。可将本砧在提高抗病性及低温耐性的前提下,应用于易受高温胁迫的地区,进行高品质西瓜栽培生产,以提升西瓜产业的稳定性。本研究结果在一定程度上明确了本砧嫁接对西瓜高温耐性的影响机制,为后续野生西瓜耐热基因的挖掘及进一步西瓜本砧育种和本砧嫁接栽培提供了理论参考。

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