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青海湖裸鲤自主摄食节律与生长特性研究*

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摘要 为探究盐碱环境中鱼类的摄食和生长特性,为耐盐碱鱼类增殖保护和盐碱水养殖提供基础数据,本研究以青海湖裸鲤(*Gymnocypris przewalskii*)为代表,研究其在盐碱水(青海湖湖水)环境中的自主摄食节律,设置自然光照(14L:10D)湖水组和全黑暗(24D)湖水组,以自然光照(14L:10D)淡水组为对照。结果显示,青海湖裸鲤为白昼摄食类型鱼类。在自然光照条件下,淡水环境中,青海湖裸鲤的摄食高峰期为 08:00—11:00,摄食低谷期则为 05:00—08:00;湖水环境中,青海湖裸鲤在 08:00—19:00 呈现较高且持续的摄食现象,其平均每小时摄食量显著高于 05:00—08:00 和 19:00—05:00 时段。而在全暗环境中,青海湖裸鲤摄食的节律性减弱,各时段的平均每小时摄食量较为接近。经 63 d 的自主摄食养殖,在自然光照下,湖水组的青海湖裸鲤在高盐碱环境中的体长增长率为(1.19±0.17)%、体重增长率为(10.66±0.98)%、特定生长率为(0.16±0.02)%/d,均分别显著低于淡水组青海湖裸鲤的体长增长率[(18.66±0.41)%]、体重增长率[(67.32±3.05)%]和特定生长率[(0.82±0.03)%/d],表明生长受到抑制。湖水组和淡水组青海湖裸鲤的体长–体重关系参数(*b*)均小于 3,表明青海湖裸鲤为负异速生长鱼类,其中,湖水组 *b* 值小于淡水组,即湖水组体重增长速率低于淡水组,在一定程度上说明高盐碱环境导致青海湖裸鲤的生长特性发生变化。本研究通过探寻青海湖裸鲤在青海湖水环境以及淡水人工养殖中的摄食节律及生长规律,为青海湖裸鲤人工增殖投喂策略的制定提供理论依据,同时,为盐碱生境中鱼类的摄食习性研究提供基础数据。

关键词 盐碱环境;青海湖裸鲤;自主摄食节律;生长特性

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我国盐碱水资源丰富,约有 4.6×10^7 hm^2 的低洼盐碱水广泛分布于我国内陆及滨海地区,内陆咸水湖泊占据全国湖泊面积的 55%,具有高盐、高碱、高 pH 和水型多样性等特点(胡红浪等, 2021; 刘永新等, 2016; 来琦芳等, 2021)。盐度和碳酸盐碱度作为盐碱水环境中的重要理化因子,与鱼类生长、渗透调节和

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能量代谢的关系紧密(Abou Anni *et al*, 2016; Song *et al*, 2021)。应对高盐与高碱环境，鱼类需通过调节能量供给分别进行渗透调节和酸碱平衡，生长速度普遍受到影响(黄岫等, 2022; 王念民等, 2022)。由于多数水生生物难以在盐碱水中生存生长，大部分盐碱水资源长期处于闲置状态，有效开发盐碱水资源对盐碱生境的修复、拓展渔业发展空间、践行大食物观有着重大意义。

在自然条件下，鱼类的摄食行为存在明显的节律特征。不同鱼类的摄食节律受感官能力差异的影响有所不同，依靠视觉摄食的鱼类通常在白天摄食，而视觉能力较弱、嗅觉发达的鱼类则在夜间活跃并进食(李忠义等, 2018; Kulczykowska *et al*, 2010)，部分硬骨鱼的松果体器官可通过时钟基因节律性表达与褪黑素合成影响摄食节律(Saha *et al*, 2019)。鱼类摄食节律受中枢及外周组织节律性分泌激素(Landgraf *et al*, 2017)和消化酶活性(Solovyev *et al*, 2022)影响，通过调控摄食因子的分泌引起血液中皮质醇和葡萄糖等指标和消化酶活性变化，进而影响摄食行为的发生(高云红等, 2021)。鱼类的摄食节律会影响其代谢强度和对食物的利用率，从而影响生长特性(张鹏飞等, 2020)。因此，人工养殖时遵循鱼类的摄食节律进行投饵可增强鱼体的消化能力(Solovyev *et al*, 2022)和免疫能力(Chen *et al*, 2022)，对鱼类生长具有促进作用。

青海湖裸鲤(*Gymnocypris przewalskii*)，又名湟鱼、无鳞鲤，作为青海湖特有的经济鱼种，在青海湖生态系统平衡中起到关键作用(Xiong *et al*, 2010)。青海湖地处我国西部青藏高原，是我国最大的内陆高原盐碱湖。由于 20 世纪 60 年代过度捕捞以及湖区环境变化，青海湖裸鲤资源量大幅下降，目前，主要通过封湖育鱼和人工增殖放流等措施保护青海湖裸鲤，并维持青海湖生态平衡(周杨浩等, 2022; 王崇瑞, 2011)。作为可在盐碱水环境中生长的特殊经济鱼种，青海湖裸鲤生长速度缓慢，体重为 250~500 g 的青海湖裸鲤通常需要 8~10 年的生长期(王崇瑞, 2011)。已有学者通过消化酶活性的研究提出改善营养组成促进青海湖裸鲤生长(Tian *et al*, 2019)，但对于青海湖裸鲤自主摄食节律的研究少有报道，测定青海湖裸鲤自主摄食节律可确定该鱼种的最佳投喂时间，通过设计与自然模式相匹配的投喂策略来提高饲料转化率并促进生长。由于光照对于养殖鱼存在生理、生长等方面的影响(Karakatsouli *et al*, 2010)，本研究通过自然光照组和全黑暗组对比实验，确定光照周期是否对青海湖裸鲤日摄食规律产生影响，并判断其摄食节律类型。此外，研究测定湖水和淡水环境中青海湖裸鲤的各项生长指标，揭示水环境对青海湖裸鲤生长特性的影响。本研究深入探寻青海湖裸鲤在青海湖水环境及淡水人工养殖中的自主摄食节律及生长规律，为提高青海湖裸鲤人工增殖效率，青海湖渔业资源保护以及盐碱生境中鱼类的摄食习性研究提供数据支撑。

1　材料与方法

1.1　实验用鱼与暂养管理

实验所用青海湖裸鲤由青海湖裸鲤救护中心提供。选取健康且规格相近的青海湖裸鲤暂养于循环缸系统内。暂养用水为曝气 24 h 以上的过滤自来水[开能净水机，型号 AC/KDF-150B(T)-1-150]。暂养期间，水温为(17.46±0.23) ℃，溶解氧为(8.14±0.09) mg/L，总氨氮为(0.56±0.01) mg/L，盐度为 0.40，碳酸盐碱度为 2.04 mmol/L。

实验开始前，青海湖裸鲤需进行自主摄食训练。经驯化学习，裸鲤可通过特定的自动投喂系统(图 1)进行自主摄食(Wang *et al*, 2022)。采用浮性配合饲料(粗蛋白质≥32%、粗脂肪≥5、粗纤维≤8.5)进行投喂。

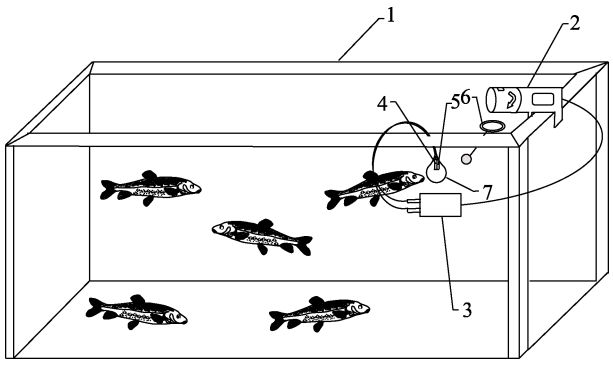

图 1　青海湖裸鲤通过智能投饵装置进行自主摄食的示意图

Fig.1　A schematic diagram of *G. przewalskii* using self feeder

1：鱼缸；2：投饵机；3：光电传感器；4：光电传感器光学发射端；5：光电传感器光学接收端；6：喂食圈；7：保护装置。

1: Aquarium; 2: Feeder; 3: Photoelectric sensor; 4: Optical emitter; 5: Optical receiver; 6: Feeding ring; 7: Protector.

1.2　实验设计

1.2.1　*实验用水配制与盐碱驯化*　实验用湖水根据青海湖裸鲤自然生长所处的青海湖水主要离子比例(Na^+ 23.05%、K^+ 1.34%、Ca^{2+} 0.11%、Mg^{2+} 6.88%、Cl^- 40.39%、CO_3^{2-} 5.07%、HCO_3^- 7.09%、SO_4^{2-} 16.07%)进行配置。根据青海湖湖水历史数据(杨建新等, 2005; Yao *et al*, 2016)将湖水组盐度设为 15.00，碳酸盐碱度

设为 28.00 mmol/L。

实验前进行盐碱驯化，按湖水离子组成将青海湖裸鲤养殖水体盐度提升到 5.00，碳酸盐碱度提升到 8.00 mmol/L，随后每隔 48 h 将盐度提升 2.00、碱度提升 4.00 mmol/L，直至实验湖水盐度达到 15.08±0.02、碳酸盐碱度达到(27.53±0.16) mmol/L。

1.2.2 *青海湖裸鲤自主摄食日节律* 本研究采用自主摄食装置，通过记录裸鲤全天的摄食情况进行摄食节律研究。共设置自然光照淡水组(14L∶10D)、自然光照湖水组(14L∶10D)和全黑暗湖水组(24D)，每组设 3 个重复，每个重复放置 15 尾青海湖裸鲤[体重为(57.96±2.09) g，体长为(16.31±0.17) cm]。自然光照组(14L∶10D)的光照由 LED 灯提供，LED 灯架设在实验缸上方，并定时控制光强变化。根据青海地区的光照周期和光照强度，并参考相关文献(李育森等, 2019; 赵年桦等, 2021; 李艳华等, 2016)将全天分为 5 个时段：自然光照组的 05:00—08:00 和 15:00—19:00 为弱光期(水下光强 500~600 lx)、08:00—11:00 和 11:00—15:00 为强光期(水下光强 900~1 000 lx)、19:00—05:00 为黑暗期(水下光强 0 lx)，各时段表层水下光照强度实测值见表 1。根据 Wang 等(2022)的研究，为保证青海湖裸鲤渗透调节功能，设置全黑暗组(24D)对比研究光照周期对日摄食节律的影响，采用黑色遮光布对缸进行遮光处理，各时段光照强度均为 0 lx。实验容器为 95 cm×60 cm×60 cm 的循环缸，实验期间，不间断充气，水温为(17.24±0.32) ℃、溶解氧为(8.12±0.07) mg/L、湖水组盐度为 15.08±0.02、碳酸盐碱度为(27.53±0.16) mmol/L、pH 为 8.92±0.01，淡水组盐度为 0.40±0.01、碳酸盐碱度为(2.04±0.03) mmol/L、pH 为 7.39±0.03。实验开始后，于每日的 05:00、08:00、11:00、15:00 和 19:00 称量饲料仓所剩饲料的重量，得出各时段青海湖裸鲤的摄食量，实验共持续 5 d，各时段摄食量取 5 d 平均值进行后续分析。

1.2.3 *青海湖裸鲤生长特性研究* 根据摄食节律实验结果设置自然光照周期(14L∶10D)进行青海湖裸鲤生长实验，湖水组实验用水配制同 **1.2.1**。生长实验共持续 63 d，每个实验组共有 3 个重复，每个重复放置 15 尾青海湖裸鲤。实验容器为 95 cm×60 cm×60 cm 的循环缸，采用自动投饵装置进行饲料投喂，并定期向投饵装置添加浮性配合饲料，实验期间的成活率为 100%。养殖 63 d 后，采用 MS-222 (100 mg/L)对每尾青海湖裸鲤分别进行麻醉并测量其体长(精确至 0.1 cm)和体重(精确至 0.1 g)。

表 1 自然光照组各时段光强测定

Tab.1 Measurement of light intensity at each time period in light-dark cycle group

起止时间 Beginning and ending time	时段 Period	光强 Light intensity/lx
05:00—08:00	黎明 Dawn	556.33±12.34
08:00—11:00	上午 Forenoon	919.67±15.33
11:00—15:00	下午 Afternoon	1 045.67±17.07
15:00—19:00	黄昏 Dusk	641.17±11.48
19:00—05:00	夜间 Night	0

1.3 数据分析

统计数据为平均值±标准误(Mean±SE)。计算摄食量[feed intake, FI, g/(kg·h)]、体长增长率(length growth rate, GR_L, %)、体重增长率(weight growth rate, GR_W, %)、特定生长率(specific growth rate, SGR, %/d)、肥满度(condition factor, CF)，并绘制体长体重关系曲线，计算公式如下：

$$FI = TF/(W_n \times t_h/1\ 000)$$
$$GR_L = (L_1 - L_0)/L_0 \times 100$$
$$GR_W = (W_1 - W_0)/W_0 \times 100$$
$$SGR = (\ln W_1 - \ln W_0)/t_d \times 100$$
$$CF = W/L^3 \times 100$$

式中，TF 为摄食总量(g)，W_n 为体重总和(g)，t_h 为摄食时段(h)，L 为体长(cm)，W 为体重(g)，L_0 为初始平均体长(cm)，L_1 为终末平均体长(cm)，W_0 为初始平均体重(g)，W_1 为终末平均体重(g)，t_d 为养殖时间(d)。

采用 SPSS 25.0 统计软件对摄食节律实验各时段摄食量及生长实验各指标进行单因素方差分析(one-way ANOVA)，差异显著则采用 LSD 法进行多重比较，显著性水平为 $P<0.05$。虽然湖水组和淡水组裸鲤为同龄幼鱼，由于自主摄食训练影响，生长实验中湖水组和淡水组裸鲤的初始体重有所差异，采用协方差分析(ANCOVA) (Stanley, 2022; He *et al*, 2018)估算体重的边际平均值对比分析体重增长率及特定生长率的显著性。采用幂指数方程($W=aL^b$)分析裸鲤体长–体重关系，采用 t 检验分析幂指数 b 值与理论匀速生长值 3 是否具有显著差异。全文采用 Origin 2018 软件作图。

2 结果与分析

2.1 不同处理对青海湖裸鲤自主摄食日节律的影响

在自然光照周期下，青海湖裸鲤呈现出白天游动、夜晚潜伏的昼行活动特征。在淡水和湖水环境中，青海湖裸鲤白天摄食量分别占全天的 65.74%和 70.72%，显著高于夜晚($P<0.05$)。淡水环境中，青海湖裸鲤的摄食高峰期位于光照较强的 08:00—11:00，该时段平均每小时摄食量显著高于其他时段($P<0.05$)，

05:00—08:00 的平均每小时摄食量显著低于 11:00—15:00 和 15:00—19:00 的平均每小时摄食量(P<0.05)，显示出明显的白昼摄食节律(图 2A)。在湖水环境中，青海湖裸鲤 08:00—11:00、11:00—15:00 和 15:00—19:00 的平均每小时摄食量无显著差异(P>0.05)，但均显著高于 05:00—08:00 和 19:00—05:00 的平均每小时摄食量(P<0.05) (图 2B)，同样显示出白昼摄食的节律特征。全暗环境中，在全天各时段，湖水组青海湖裸鲤的摄食量无显著差异(P>0.05)，其中 19:00—05:00 的平均每小时摄食量略低，但是未显示出明显的摄食节律(图 2C)。该实验表明，在自然光照周期下，青海湖裸鲤具有明显的摄食节律，在全暗环境中该摄食节律减弱或消失。

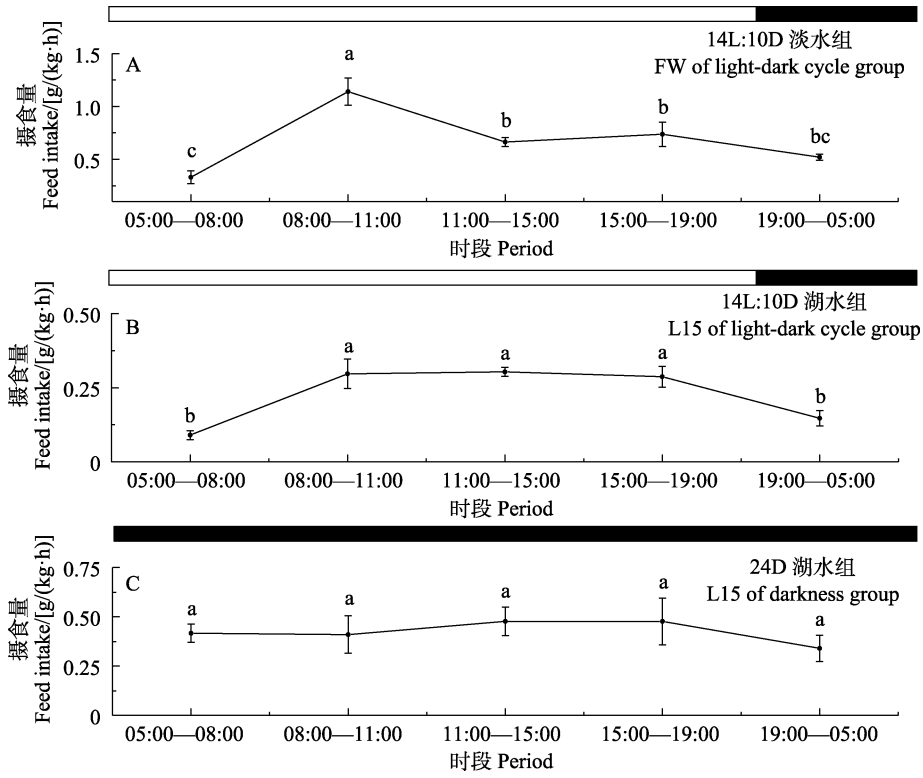

图 2　不同处理对青海湖裸鲤日摄食节律的影响(平均值±标准误, n=3)

Fig.2　Effects of different treatments on feeding rhythm of *G. przewalskii* (Mean±SE, n=3)

FW 为淡水，L15 为盐度为 15 的湖水；不同字母表示差异显著(P<0.05)。

FW is freshwater, L15 is saline-alkaline water with a salinity of 15; Different letters represent significant difference (P<0.05).

2.2　盐碱水环境对青海湖裸鲤生长指标的影响

在不同水环境中，青海湖裸鲤生长指标存在显著差异(表 2)。本研究采用青海湖裸鲤自主索取饵料投饵方式，实验前，青海湖裸鲤通过自主学习主动获取饵料。经过 63 d 的自主摄食实验，各组青海湖裸鲤的成活率均为 100%。在淡水环境中生长的青海湖裸鲤实测体长增长率、体重增长率、特定生长率和肥满度均显著高于湖水环境中青海湖裸鲤各项指标(P<0.05)。由于不同组别的初始体重存在差异，相关指标采用去除初始体重差异的估算边际平均值进行对比分析，淡水环境中青海湖裸鲤的体重增长率和特定生长率估算边际平均值(67.32%和 0.82%/d)同样显著高于湖水环境(10.66%和 0.16%/d) (P<0.05)。

2.3　盐碱水环境对青海湖裸鲤肥满度与体长体重关系的影响

在淡水环境和湖水环境中的青海湖裸鲤体型存在明显差异(图 3)。不同水环境对青海湖裸鲤的肥满度具有显著影响，生活在淡水环境中的青海湖裸鲤肥满度(1.48%)显著高于生活在湖水环境中的青海湖裸鲤(1.19%) (P<0.05)。将青海湖裸鲤的体长与体重拟合成幂函数关系式，可得如下方程：湖水组：W=0.039 98×$L^{2.558}$ (n=90，R^2=0.859 3) (图 4A)；淡水组：W=0.030 07×$L^{2.754}$ (n=90，R^2=0.936 2) (图 4B)。由 t 检验表明，在淡水环境和湖水环境中，青海湖裸鲤的 b 值均显著小于 3，表明青海湖裸鲤为负异速生长鱼类。由于湖水组青海湖裸鲤的 b 值更小，因此，相对于淡水环境，湖水环境中的青海湖裸鲤的体长较体重相对生长速度更快。

表 2 不同水环境中青海湖裸鲤的生长指标

Tab.2 Growth indicators of *G. przewalskii* in different water environments

指标 Indicators	淡水组 Freshwater group	湖水组 Lake water group
实测平均值 Measured mean		
成活率 Surival rate/%	100	100
初始体长 Initial body length/cm	17.03±0.22[a]	15.84±0.37[a]
终末体长 Final body length/cm	20.21±0.32[a]	16.03±0.40[b]
体长增长率 Length growth rate/%	18.66±0.41[a]	1.19±0.17[b]
初始体重 Initial body weight/g	76.84±1.09[a]	46.48±2.67[b]
终末体重 Final body weight/g	122.07±3.09[a]	49.33±2.73[b]
体重增长率 Weight growth rate/%	58.82±2.09[a]	6.16±0.28[b]
特定生长率 Specific growth rate/(%/d)	0.73±0.02[a]	0.10±0.01[b]
肥满度 Condition factor	1.48±0.04[a]	1.19±0.03[b]
估算边际平均值 Estimated marginal mean		
初始体重 Initial body weight/g	61.66±6.91[a]	61.66±6.91[a]
终末体重 Final body weight/g	103.17±1.88[a]	68.23±0.61[b]
体重增长率 Weight growth rate/%	67.32±3.05[a]	10.66±0.98[b]
特定生长率 Specific growth rate/(%/d)	0.82±0.03[a]	0.16±0.02[b]

注：同行数据不同字母表示差异显著(P<0.05)。

Note: Data in the same row with different letters represent significant difference (P<0.05).

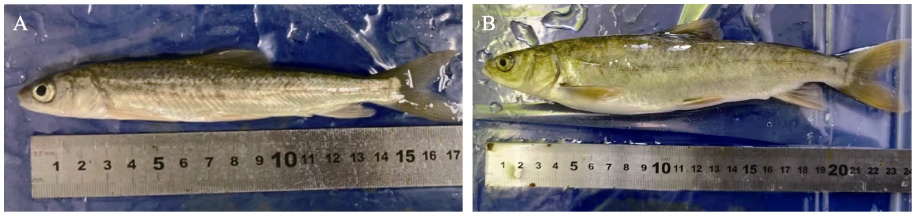

图 3 在湖水(A)和淡水(B)中经 63 d 生长实验的青海湖裸鲤

Fig.3 *G. przewalskii* after 63 d growth in lake water (A) and freshwater (B)

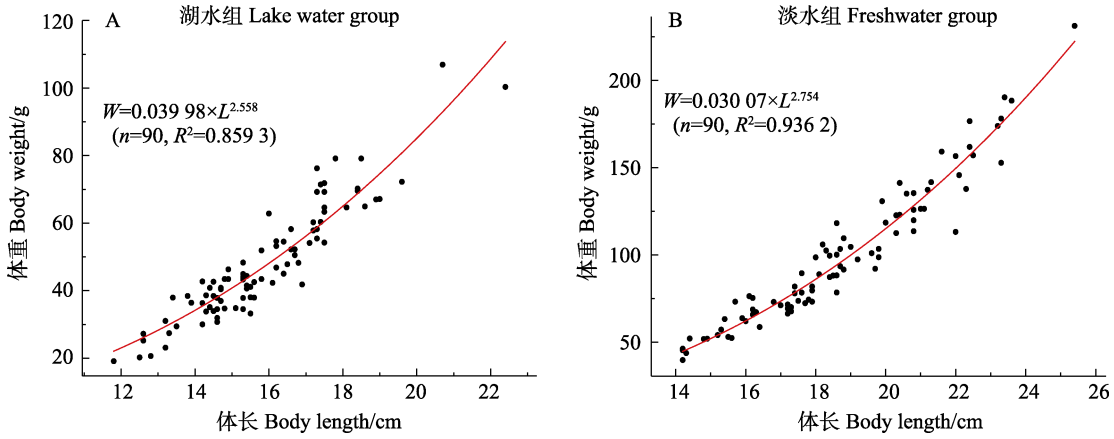

图 4 青海湖裸鲤体长–体重关系曲线

Fig.4 Body length-weight relationship of *G. przewalskii*

3　讨论

3.1　盐碱水环境中青海湖裸鲤的自主摄食节律

在自然光照周期下，青海湖裸鲤表现为白昼摄食类型，摄食节律受明暗交替影响显著。本实验通过自主摄食节律的研究发现，在自然光照周期下，湖水组青海湖裸鲤的摄食主要集中在 08:00—19:00 时段，摄食低谷期为 05:00—08:00 和 19:00—05:00，具有节律性。鱼类的摄食节律通常与明暗交替、摄食周期存在相互影响(Montoya *et al*, 2010)，并分为白昼摄食、夜间摄食、晨昏摄食和无规则摄食类型(Boujard *et al*, 1992)。美洲西鲱(*Alosa sapidissima*)仔、稚鱼摄食高峰期出现在白昼，属于白昼摄食类型，且摄食高峰期长度随仔、稚鱼的生长发育逐渐延长(高小强等, 2015)。胡子鲇(*Clarias fuscus*)的摄食高峰在 07:00—09:00 和 17:00—19:00，属于晨昏摄食类型(Fast *et al*, 1997)。大盖巨脂鲤(*Colossoma macropomum*)的摄食行为和消化生理特征的高峰期位于夜间，属于夜间摄食类型(da Silva Reis *et al*, 2019)。在自然光照周期下，青海湖裸鲤白昼摄食的节律特征显著，而在全黑暗的环境中，青海湖裸鲤不同时段的平均每小时摄食量十分接近，05:00—08:00 与 19:00—05:00 的摄食需求较自然光照同期明显提高，08:00—15:00 的摄食需求较自然光照同期有所下降。鲫(*Carassius auratus*)的生物节律与明暗循环同步(Sáiz *et al*, 2021)，明暗周期与摄食周期的错位会对鲫的生理产生负面影响(Gómez-Boronat *et al*, 2018)。与鲫相似，青海湖裸鲤的觅食行为频率与摄食量随光强的减弱而降低，其摄食节律与光照周期密切相关。鱼类对食物的摄取除了外部光照因素的影响，其激素分泌(Rønnestad *et al*, 2017)和消化酶活性(da Silva Reis *et al*, 2019)均存在内源性节律。为明确光照对青海湖裸鲤昼夜摄食节律的影响，从全黑暗和自然光照周期的各时段摄食量变化趋势来看，光照条件对青海湖裸鲤摄食行为的影响明显，在持续黑暗的条件下，青海湖裸鲤不具备明显的昼夜摄食节律，但仍然表现出白天摄食的倾向。由于光是一个复杂的环境因子，组成部分包含光谱、光强与光照周期，与鱼类的发育和生长关系密切(Wang *et al*, 2019)，光对青海湖裸鲤摄食节律的影响机制还有待进一步研究。

鱼类的消化与饮水行为一般不能同时进行(林浩然, 2011)。Wang 等(2022)研究表明，青海湖裸鲤通过在不同时段划分肠道的不同功能以缓解消化和渗透调节的冲突。由于尚未有渗透调节对摄食节律影响的研究报道，为探寻盐碱水环境对青海湖裸鲤摄食节律的影响，设置淡水对照组进一步观察自然光照周期下青海湖裸鲤的昼夜摄食节律。与盐碱水环境相比，淡水环境中青海湖裸鲤各时段平均每小时摄食量均有所提高，其中，08:00—11:00 为摄食高峰期。由于盐碱水环境中青海湖裸鲤白天摄食量占比高于淡水环境，在 08:00—19:00 呈现出较高且持续的摄食现象，表明青海湖裸鲤在高盐与高碳酸盐碱度的环境中进行的渗透调节会增强其白天摄食的节律特征。

3.2　盐碱水环境对青海湖裸鲤摄食和生长的影响

在盐碱水环境中，青海湖裸鲤摄食量下降、生长性能受到明显抑制。在本研究中，湖水组青海湖裸鲤的摄食率、体长增长率、体重增长率和特定生长率均显著低于淡水组，其原因可能是蛋白质、糖和脂质等物质分解所获能量更多用于渗透调节与酸碱调节。通常水生动物所处生境与摄食、生长有着密切的联系。高渗环境改变水生动物的摄食代谢与能量收支等生理状况，对其运动能力和生长产生影响(吕国华等, 2022; 李江涛等, 2021)。青海湖湖水具有高盐度、高碳酸盐碱度和高 pH 等特点，为典型的盐碱水环境，对鱼类存在盐度和碱度双重胁迫。鱼类在等渗环境中具备最低的渗透调节耗能、最高的摄食量和饵料转化率，当盐度远离等渗点时，鱼类的摄食和生长受到抑制(Luz *et al*, 2008; 逯冠政等, 2022)。淡水鱼鲫在盐度为 0~2 的环境中具有最高的摄食率和游动能力，摄食率、食物预期活动及游动量均随着盐度的上升而下降(Luz *et al*, 2008)。王润萍等(2019)研究发现，广盐性种类海水青鳉(*Oryzias melastigma*)在盐度为 25 时，摄食量最高，显著高于其他盐度组。高碳酸盐碱度容易导致鱼类出现呼吸性碱中毒和氨中毒等生理功能受损现象(Li *et al*, 2020; Yao *et al*, 2016)，影响鱼类的成活率和生长速度。大鳞鲃(*Barbus capito*)在碱度为 10~15.83 mmol/L 时，摄食量、特定生长率和饵料转化率最高，各指标随碱度上升而下降，并在高碱环境中出现抑制生长的现象(党云飞等, 2013)。与尼罗罗非鱼(*Oreochromis niloticus*)通过脂代谢调节供给额外的渗透调节耗能适应高盐环境(宋凌元等, 2020)和瓦氏雅罗鱼(*Leuciscus waleckii*)通过提高血浆中的非必须氨基酸含量作为能量来源适应高碱环境(常玉梅等, 2016)相似，青海湖裸鲤在盐碱双重胁迫下，需要消耗大量的能量进行渗透调节和酸碱调节，存储能量的脂肪和肌肉物质减少，表现为生长缓慢、肥满度下降。

青海湖裸鲤的体长与体重存在具有生物学普适性意义的幂函数关系($W=aL^b$)。在盐碱水和淡水环境

中，青海湖裸鲤的异速生长因子 b 值分别为 2.558 和 2.754，符合大多数鱼类的 b 值范围(2.5~3.5)(Froese, 2006)。由于参数 b<3，青海湖裸鲤群体为负异速生长。本研究发现，盐碱水环境中的青海湖裸鲤的 b 值小于淡水组，说明在相同体长增长速率的前提下，生活在盐碱水环境中的青海湖裸鲤体重增长速率低于生活在淡水环境中，一定程度上说明高盐碱环境导致青海湖裸鲤的生长性能发生变化。

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Self feeding Rhythm and Growth Characteristics of *Gymnocypris przewalskii*

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Abstract The total saline-alkaline land area in China is about 99.13 million hectares distributed across northern China, coastal areas, and areas along the bank of the Huanghe River. About 46 million hectares of saline-alkaline water areas are distributed around these saline-alkaline lands, most of which are thalassic and characterized by a high pH value in excess of 8.8 associated with high-carbonate alkalinity concentrations and various types of ion imbalances. Saline-alkaline waters are stressful environments in which only relatively few organisms are able to survive. Consequently, most of the saline-alkaline water resources have been desolate for a long time. The effective utilization of saline-alkaline water resources will benefit restoration of saline-alkaline habitats and the expansion of aquaculture space. Naked carp (*Gymnocypris przewalskii*) are endemic to the austere saline-alkaline environment of Qinghai Lake. Due to overfishing in the 1960s and environmental changes in the lake area, the resources necessary for naked carp survival in Qinghai Lake declined substantially. At present, the major measures to protect the naked carp and maintain the ecological balance of Qinghai Lake are through

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a fishing ban and artificial stocking and releasing. The feeding behavior of fish under natural conditions has obvious rhythm characteristics, which is an important research topic for healthy aquaculture. To explore the characteristics of self-feeding rhythm and growth performance of fish in a saline-alkaline environment and provide basic data for the protection of native saline-alkaline fish, naked carp were taken as representative in this study. First, the freshwater and lake water group with natural photoperiod (14L:10D) and the lake water group with darkness (24D) were set. The artificial lake water was prepared according to the ionic composition of Qinghai Lake, with the contents of Na^+ 23.05%, K^+ 1.34%, Ca^{2+} 0.11%, Mg^{2+} 6.88%, HCO_3^- 7.09%, CO_3^{2-} 5.07%, Cl^- 40.39%, and SO_4^{2-} 16.07%. The measured salinity of the artificial lake water was 15.08, and the carbonate alkalinity was 27.53 mmol/L. According to the local photoperiod of Qinghai Province, the whole day was divided into five periods as 05:00–08:00, 8:00–11:00, 11:00–15:00, 15:00–19:00, and 19:00–05:00. The feeding rhythm experiment lasted for 5 d, and the average food intake of each period was calculated. The results showed that naked carp had an obvious daily feeding rhythm during their natural photoperiod. In the natural photoperiod, the feeding peak was from 08:00 to 11:00, and the low feeding period was from 05:00 to 08:00 in freshwater. In the lake water, naked carp showed high and continuous feeding from 08:00 to 19:00, and their average hourly feed intake was significantly higher than that from 05:00 to 08:00 and 19:00 to 05:00. Therefore, naked carp were determined to be the daytime feeding fish type. In addition, the high proportion and the continuous feeding in daytime in lake water indicated that the osmotic and acid-base regulation of naked carp in saline-alkaline water may enhance their diurnal feeding rhythm. Whereas in the continuous dark environment, the feeding rhythm of naked carp was weakened, and the average hourly food intake of each period was similar. To explore the growth performance of naked carp under a self-feeding rhythm, the lake water group and the freshwater control group with natural photoperiod were set up. After 63 days of self-feeding, the individual body length and weight of the naked carp were measured after being anesthetized with MS-222. The length growth rate (1.19±0.17)%, weight growth rate (10.66±0.98)%, and specific growth rate (0.16±0.02)%/d of naked carp in the lake water group were significantly lower than those in the freshwater group [length growth rate (18.66±0.41)%, weight growth rate (67.32±3.05)%, and specific growth rate (0.82±0.03)%/d)], indicating that the growth of naked carp was inhibited by high salinity and carbonate alkalinity environment. The parameter *b* of body length-weight relationship curve of the naked carp in both the lake water group and the freshwater group was less than three, which showed that the naked carp was a negative allometric growth fish. The *b* value of the lake water group was lower than that of the freshwater group, and the body length of naked carp increased faster than body weight in the lake water. The growth characteristics of naked carp were affected by the high saline-alkaline environment. The self-feeding rhythm and growth performance of naked carp provided a basic knowledge for creating a feeding strategy for fish cultured in a saline-alkaline environment and recovering endangered native saline-alkaline fish.

Key words　Saline-alkaline environment; *Gymnocypris przewalskii*; Self feeding rhythm; Growth performance