Investigating the Effects of Acute Photobiomodulation on Submaximal Rowing Performance and Physiological Responses in Trained Female Rowers.

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Abstract

It is well established that Red Light Therapy (RLT), or Photobiomodulation (PBM), can enhance mitochondrial function, reduce markers of muscle damage, and improve exercise performance and recovery. As a result, RLT has become an increasingly popular non-invasive intervention within sport and exercise settings. Recent research has shown that pre-exercise application of red and near-infrared light may improve time to exhaustion, reduce fatigue, and enhance recovery in activities such as cycling, running, and resistance exercise. However, there is currently no research examining the effects of RLT on rowing performance, particularly during submaximal exercise in trained female rowers.

This thesis is separated into three chapters. Chapter one provides a review of the literature on RLT, beginning with its historical development and underlying physiological mechanisms of action. This review includes a discussion of the interaction between RLT and mitochondrial chromophores, effects on adenosine triphosphate (ATP) production, oxidative stress modulation, and nitric oxide-mediated processes. The chapter further examines the role of RLT in exercise performance and recovery, with particular emphasis on muscle fatigue, endurance capacity, and post-exercise recovery markers.

The literature review also critically evaluates the application of RLT across a range of exercise modalities, including resistance exercise, cycling, and running, while highlighting the variability in outcomes reported across studies. Particular attention is given to inconsistencies in methodological approaches, including differences in wavelength, dosage, timing of application (pre- versus post-exercise), and participant characteristics. Chapter One also identifies key gaps in the current literature, notably the limited research in endurance -based, sport-specific contexts and the underrepresentation of female athletes. These gaps provide the rationale for the present study, with a specific focus on rowing as an endurance sport requiring sustained submaximal performance and efficient recovery. Rowing has continuous physiological demands on both the upper and lower body and relies heavily on sustained submaximal power output and efficient recovery between repeated efforts.

As a result, Chapter Two investigated the acute effects of PBM on submaximal rowing performance and exercise physiology in trained female athletes. Twelve trained female rowers participated in a placebo-controlled, double-blind, randomized crossover design. Each participant completed five laboratory sessions, beginning with a maximal graded exercise test to determine maximal oxygen uptake (VO_{2max}) and establish individualised workload targets for subsequent submaximal trials. The remaining four sessions involved identical rowing protocols performed following one of four treatment conditions: red light (630 and 660 nm), near infrared (810, 830 and 850 nm), combined red and near-infrared light, or placebo condition. Treatment order was randomised, and participants were blinded to the condition. A minimum of 48 hours recovery was maintained between sessions to minimise potential carryover effects. Primary outcome measures included oxygen uptake (VO_2), blood lactate concentration, and blood glucose concentration during progressive submaximal exercise. Secondary measures included respiratory exchange ratio (RER) and ratings of perceived exertion (RPE), providing a comprehensive assessment of both physiological and perceptual responses to PBM.

Statistical analysis revealed participants completed a greater number of submaximal rowing intervals following the red light (7.25 ± 0.75 intervals; $p = 0.046$) and infra-red light (7.25 ± 0.45 intervals; $p = 0.012$) conditions compared with the placebo condition (6.67 ± 0.98 intervals) indicating improved exercise capacity. PBM was also associated with lower blood glucose concentrations during the exercise intensity closest to the lactate threshold in the infra-red condition (p=0.0300; d= 0.58 ±0.51). There were also differences in RER responses between the red light and placebo conditions suggesting alterations in energy utilisation during exercise. However, no significant differences were observed in VO_2, blood lactate concentration, or RPE between conditions. These findings suggest that pre-exercise PBM may enhance submaximal rowing performance through alterations in metabolic responses, including utilisation and glucose regulation, while producing only limited changes in broader physiological responses.

Chapter Three summarises the findings from Chapter Two, identifies the strengths and limitations for the present study, and provides recommendations for future research. Overall, this thesis identified key gaps within the existing literature on PBM (RLT), particularly in relation to sport-specific endurance performance, female athlete populations and submaximal exercise protocols.

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Glossary / List of Abbreviations

ATP – Adenosine Triphosphate

COMB – Combined

HR – Heart Rate

IRED – Infra-red light

LAC – Lactate

LLLT – Low level Laser Therapy

LEDT – Light – Emitting Diode Therapy

L/min – Liters per minute

NO – Nitric Oxide

PLA – Placebo

PBM - Photobiomodulation

RCT – Randomised Controlled Trial

RER – Respiratory exchange ratio

RED – Red light

RPE – Rate of Perceived Exertion

RR – Respiratory Rate

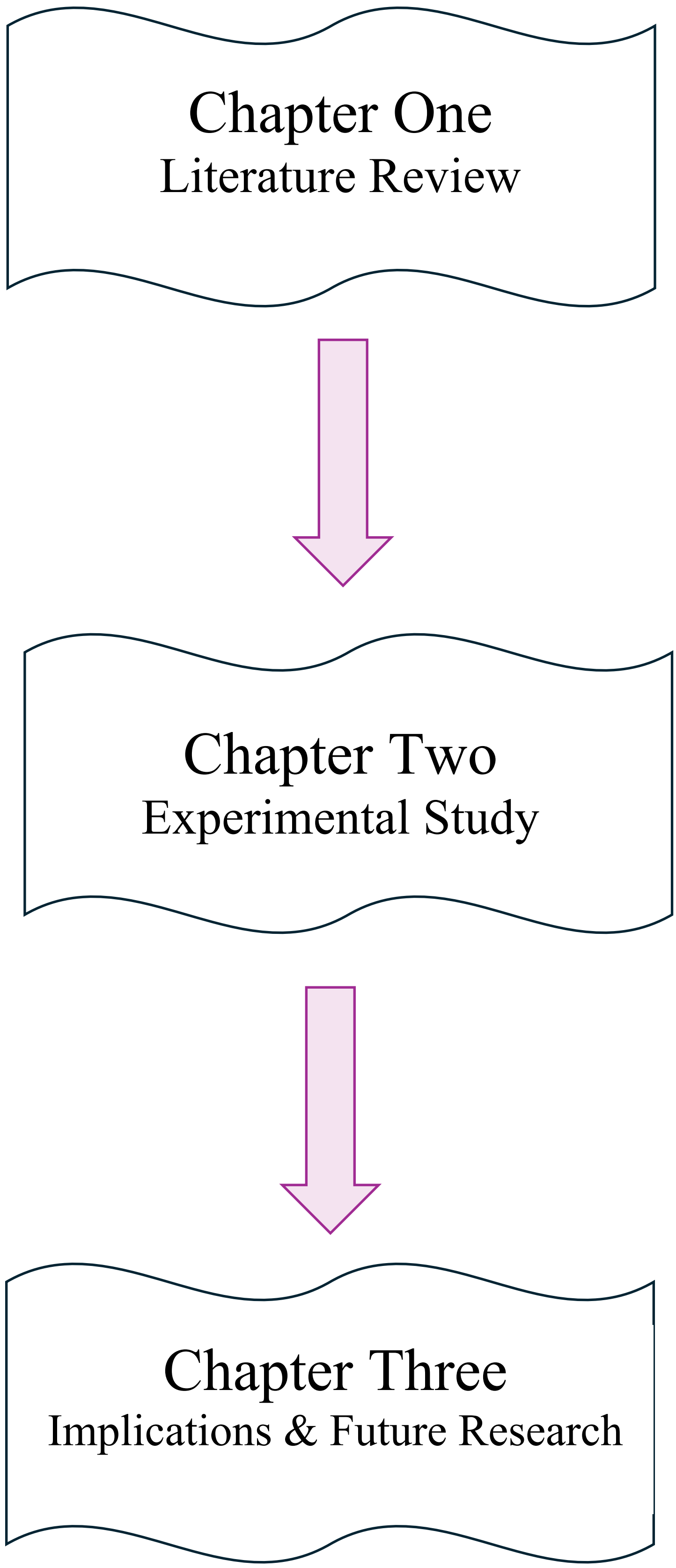
TE – Typical Error

VO_{2Max} – Maximal oxygen uptake

VO_2 – Volume of oxygen consumed per minute

VCO_2 – Volume of carbon dioxide produced per minute

Thesis Outline



Thesis Introduction

Red light therapy (RLT), also referred to as photobiomodulation (PBM), is a non-invasive therapeutic technique that uses red or near-infrared light to stimulate physiological processes at the cellular level. Photobiomodulation involves the application of specific wavelengths of light to enhance tissue repair and reduce inflammation (De Freitas & Hamblin, 2016). Light therapy has been described as a process involving the biological responses of tissues when exposed to light energy from sources such as lasers and light-emitting diodes (LEDs) (Burkow et al., 2014). This interaction enables light energy to penetrate biological tissues, reaching muscles and connective structures where cellular metabolism and tissue repair processes may be enhanced.

In recent years, RLT has gained increasing attention as a potential recovery and performance-enhancing modality in sport and exercise contexts, due to its proposed ability to accelerate tissue repair, reduce muscle soreness, and enhance physical performance. These effects are thought to occur through the absorption of light by mitochondrial chromophores, particularly cytochrome c oxidase, resulting in increased adenosine triphosphate (ATP) production, enhanced cellular metabolism, increased nitric oxide availability, and modulation of inflammatory processes (Hamblin & Demidova-Rice, 2007). Cytochrome c oxidase is the terminal enzyme of the electron transport chain, mediating the electron transfer from cytochrome c to molecular oxygen. It seems that PBM increases the availability of electrons for the reduction of molecular oxygen in the catalytic centre of cytochrome c oxidase, increasing the mitochondrial membrane potential and ATP levels (De Freitas & Hamblin, 2016).

When RLT is applied to biological tissues, red and near-infrared wavelengths penetrate the skin and reach underlying muscle cells, where they interact with mitochondrial cytochrome c oxidase. As noted, the primary mechanisms of PBM centres on cytochrome c oxidase; however, photon absorption also results in the dissociation of inhibitory nitric oxide from cytochrome c oxidase, resulting in vasodilation (De Freitas & Hamblin, 2016). As a result, from the activation of reactive oxygen species and other intracellular signalling pathways, RLT promotes gene expression associated with protein synthesis, cell proliferation, and antioxidant activity, and anti-inflammatory responses (De Freitas & Hamblin, 2016). These cellular adaptations may contribute to enhanced tissue repair and recovery processes, providing a mechanistic basis for the reported improvements in exercise performance and post-exercise recovery observed in athletes (Leal-Junior et al., 2019).

Engagement in sports and physical activity is widely recognised for its health benefits, including improvements in physical fitness and overall wellbeing. However, participation in athletic activities also carries an inherent risk of injury, ranging from minor trauma to more serious or long-term conditions. Sports-related injuries commonly result from acute trauma or repetitive stress and may affect bones, muscles, tendons, ligaments, and other soft tissues (Abou Elmagd, 2016). Burkow et al. (2014) further explains that sports injuries are increasing each year, with an estimated 30 million children and adolescents participating in organised sports annually in the United States. Typical injuries include sprains, strains, abrasions, and swelling. Effective management and recovery strategies are therefore critical for maintaining athlete performance and training continuity. Light-based therapies have previously been used to manage musculoskeletal conditions such as tendinitis, joint disorders, and muscle pain

Light therapies are typically delivered via two primary modalities: Low-Level Laser Therapy (LLLT), which uses focused lasers to treat specific points, and Light Emitting Diode Therapy (LEDT), which uses LED panels to illuminate larger surface areas. Red light is visible to the human eye, whereas near-infrared light is invisible. These wavelengths differ in their penetration depth, with red light (630 – 660 nm) and near-infrared (810 – 850 nm). SOHL Global (n.d.) also states that photons from red light are absorbed more superficially, primarily within the skin layers, whereas near-infrared light penetrates deeper into tissues, including muscles and connective tissue. The difference is important, as deeper penetration may enhance effects on muscle function and recovery.

Although the cellular mechanisms underlying RLT are relatively well-documented, research into its practical applications for sport performance remains limited and in, many areas inconclusive. Majority of studies exploring RLT in sport contexts have focused on general endurance activities, such as treadmill running or cycling. Others have targeted specific populations, or specific sporting cohorts, limiting the generalisability of findings across different sports and athletic demands (Ferraresi et al., 2016). Furthermore, many existing studies prioritise recovery outcomes over performance metrics or fail to assess performance during submaximal effort, which is critical for endurance-based sports like rowing. As such, significant knowledge gaps remain regarding how RLT affects performance and recovery in sport-specific scenarios.

Rowing is a physically demanding endurance sport that requires high levels of aerobic capacity, muscular endurance, and efficient recovery between training sessions. Athletes often complete multiple submaximal efforts in a single session, making efficient recovery and sustained energy production critical to training success (Ingham et al., 2002). Despite its relevance, there is limited research examining the effects of RLT on rowing-specific performance parameters such as power output, heart rate response, and time to fatigue. There a lack of diversity in the types of performance assessments used, with few studies incorporating submaximal testing or ergometer-based, sport specific protocols. It is therefore unclear whether the benefits observed in cycling or running transfer to rowing, given its unique physiological and biomechanical demands. These gaps highlight the need to evaluate both immediate and repeated RLT exposures in real-world endurance sport environments, including rowing.

Phototherapy has demonstrated positive results in various clinical applications related to pain management, wound healing, and inflammation reduction. These therapeutic effects highlight its potential application within athletic populations. In clinical contexts, RLT has been shown to reduce inflammation and alleviate musculoskeletal pain relevant for sports performance. Currently, no studies have investigated the impact of RLT in trained rowers performing a sport-specific protocol. Therefore, this study aims to evaluate the effects of RLT on rowing performance using a repeated -measures experimental design and rowing ergometer protocols. It will assess the short-term responses to RLT across multiple sessions, focusing on submaximal rowing tasks. By addressing the lack of sport-specific and endurance-based research, this study aims to provide novel insight into the application of PBM within rowing performance contexts.

Chapter One

1.0 Literature Review

1.1 Review Aim

This literature review will begin by outlining Photobiomodulation (PBM), including its historical development and the physiological mechanisms underpinning its effects on cellular function, particularly focusing on mitochondrial activity and energy production. This prelude establishes a physiological foundation for its application within sport and exercise performance.

The review will then examine current research investigating the use of red and near-infrared light in exercise settings, focusing on its role in enhancing recovery, reducing muscle fatigue, and improving exercise performance. Particular attention is given to variations in methodological approaches, including differences in wavelength, dosage, and timing of application, and how these factors influence the effectiveness of PBM. Finally, the review evaluates the existing evidence in endurance-based exercise contexts, highlighting the lack of sport-specific research and the underrepresentation of female athletes. These gaps provide the rationale for the present study, which investigates the effects of PBM on submaximal rowing performance and exercise physiology in trained female rowers.

1.2 Background of Photobiomodulation

Following the discovery of lasers in the 1960s, it was demonstrated that laser therapy could improve wound healing and reduce pain, inflammation and swelling (Chung et al., 2012). The first evidence of positive effects of PBM originated accidentally from the work of Dr. Endre Mester at Semmelweis Medical University in Hungary. In an early experiment, Dr. Mester observed that exposure to laser irradiation accelerated hair regrowth and tissue healing in mice (De Freitas & Hamblin, 2016). This early work by Dr. Mester and colleagues highlighted that the non-invasive nature of PBM has shown its potential for pain relief, wound healing and the treatment of conditions such as tendinopathies, nerve injuries and osteoarthritis (De Freitas & Hamblin, 2016).

Phototherapy, encompassing low-level laser therapy (LLLT) and PBM, has evolved substantially since its development in 1967. This form of laser therapy is termed ‘low level’ due to relatively low energy densities used compared to other forms of laser therapy. PBM can be delivered through different modalities, most commonly low-level laser therapy or light-emitting diode therapy (LEDT). While LLLT typically uses targeted, coherent laser light applied to specific muscle groups, LEDT uses broader, non-coherent light sources to treat larger surface areas. While both methods utilise RED and IRED wavelengths, differences in light coherence, penetration depth, and energy delivery may influence physiological outcomes. Specifically, PBM involves the application of RED (visible) and IRED (invisible) wavelengths of light, which exert non-visual biological effects on human tissue. These wavelengths differ in their depth of penetration, with near-infrared light penetrating deeper into biological tissues than red light. This distinction is important when interpreting findings across studies, as variability in delivery method may contribute to inconsistent performance and recovery effects reported in the literature.

Low-level laser therapy (LLLT) employs specific wavelengths, typically within the RED and IRED spectrum, to enhance cellular metabolism and influence tissue microenvironments (Lawrence & Sorra, 2024). These wavelengths penetrate the skin and are absorbed by intracellular chromophores, particularly cytochrome c oxidase within the mitochondrial respiratory chain (Hamblin, 2017). This interaction enhances mitochondrial respiration, resulting in increased ATP production, modulation of reactive oxygen species, and the release of nitric oxide (NO). Collectively, these processes improve cellular energy availability, reduce oxidative stress, and promote tissue repair.

1.3 Mechanisms of Photobiomodulation

1.3.1 Mitochondrial and Cellular Responses to PBM

PBM is proposed to act through the absorption of low-level visible and near-infrared light by cellular chromophores, particularly within the mitochondria. Chromophores are molecules within biological tissues that selectively absorb specific wavelengths of light while allowing others to pass through with minimal interaction. Cytochrome c oxidase is commonly identified as a primary photo-acceptor, although other molecules such as photoactive porphyrins may also contribute. This interaction is thought to initiate a cascade of intracellular responses, including increased ATP production, modulation of reactive oxygen species, and activation of transcription factors that regulate cellular activity (Hamblin & Demidova, 2006).

Beyond its direct mitochondrial effects, PBM influences several secondary physiological pathways that contribute to its overall biological impact. Exposure to red and near-infrared light may increase nitric oxide availability, promoting vasodilation and enhancing blood flow, thereby improving oxygen and nutrient delivery to working tissues. In addition, PBM modulated reactive oxygen species and inflammatory processes, helping to regulate cellular signalling and reduce oxidative stress. Collectively, these responses may contribute to enhanced tissue recovery and improved exercise performance (Hamblin, 2017).

PBM is widely understood to exert its effects through photochemical and photophysical interactions between light photons and biological tissue, rather than through thermal mechanisms (Grandinetti et al., 2015). This distinction is important, as the therapeutic wavelengths used in PBM which typically within the RED and IRED spectrum, can penetrate tissue without generating significant heat. Empirical support for this non-thermal mechanism is provided by studies investigating skin temperature responses during irradiation. Research involving 42 participants of varying skin pigmentation demonstrated no significant increases in skin temperature across a range of clinically relevant doses delivered via a combined red and infrared light sources, including super-pulsed lasers and LEDs (Grandinetti et al., 2015). These findings were consistent across different ages, sexes, and skin tones, suggesting that even with prolonged exposure and higher energy doses, PBM does not induce meaningful thermal changes in tissue. Collectively, this evidence reinforces the view that the physiological effects of PBM are driven primarily by non-thermal processes, likely involving cellular photoreceptors such as cytochrome c oxidase and subsequent modulation of mitochondrial activity, rather than by heat-induced tissue responses (Grandinetti et al., 2015).

Tsai & Hamblin (2017) have stated that the photobiological effects are initiated when light energy is absorbed by specific photo-acceptor molecules, or chromophores, during irradiation. Understanding these light to tissue interactions therefore requires identification of the key molecular targets involved. In the case of IRED light, physiological responses are thought to be mediated primarily by cytochrome c oxidase and water within the cell. Once absorbed, photons are converted into intracellular signals that can trigger a range of biological processes.

In particular, IR-induced changes in water dynamics within membranes, mitochondria, and cells may influenced signalling pathways and regulate the production of reactive oxygen species , ATP, calcium ions, NO, and inositol phosphates. An increase in ATP availability is critical for supporting cellular repair processes and maintaining energy demands during exercise.

Despite these benefits, outcomes remain inconsistent across studies due to variability in wavelength, dosage, timing and participant characteristics. Albuquerque-Pontes et al. (2015) demonstrated that cytochrome c oxidase activity responds differently to specific combinations of wavelength and energy dose, with significant increases observed at 660 nm, 830 nm and 905 nm. Notably, these responses also varied across multiple post-treatment time points, indicating that both dose and timing play a critical role in the physiological effects of PBM. These responses have been claimed as evidence that supports the concept of a biphasic dose-response relationship, whereby suboptimal or excessive doses may fail to elicit beneficial adaptations. Furthermore, the authors suggest that combining the wavelengths may enhance therapeutic effects, adding another layer of complexity to protocol design.

1.3.2 Wavelength Penetration and Tissue Interaction

The extent to which light penetrates the skin varies considerably depending on its wavelength (Figure 1). For instance, red light can reach depths of approximately 6 mm beneath the skin surface, whereas ultraviolet light exhibits very limited penetration, and blue light typically reaches around 1 mm into the tissue (Ash et al., 2017). In contrast, IRED wavelengths penetrate much more deeply, highlighting substantial differences in how various regions of the light spectrum interact with biological tissue (Clement et al., 2005).

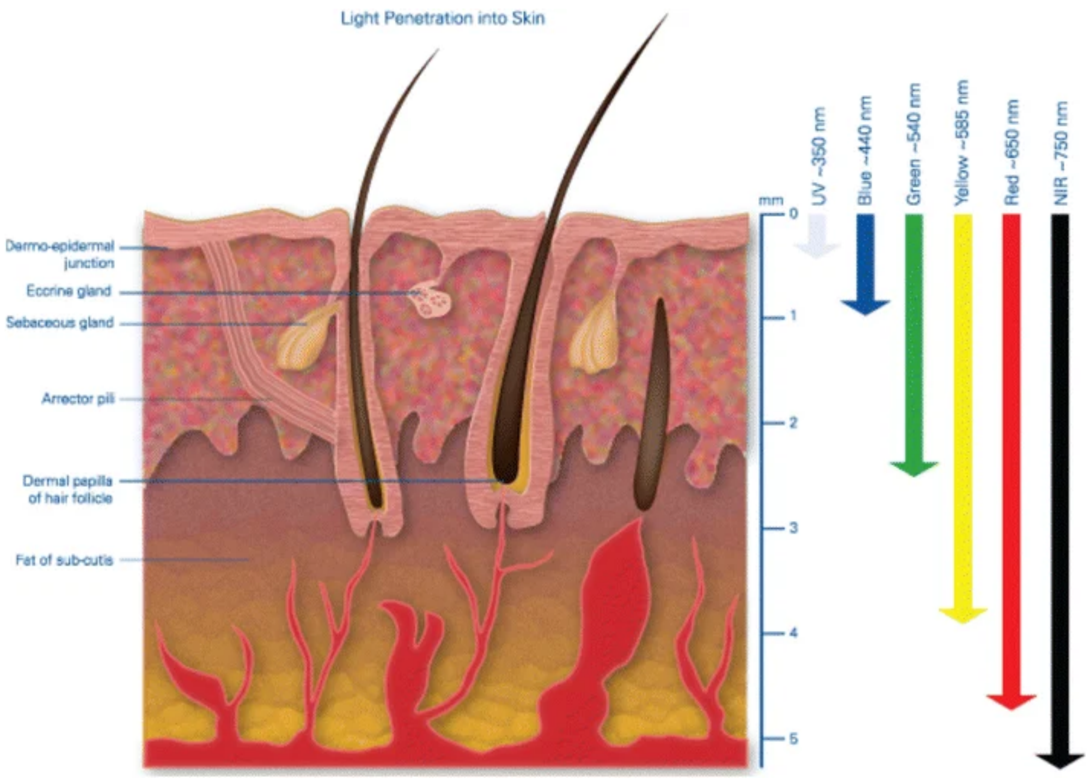


Figure 1: Light penetration into skin illustrating the depth to what wavelengths penetrate human skin (Ash et al., 2017).

1.4 Elements of PBM Effectiveness in Exercise Performance

In addition to mitochondrial effects, PBM has been associated with modulation of inflammatory pathways and regulation of reactive oxygen species, supporting its relevance to recovery processes and training adaptations. Notably, PBM appears to maintain reactive oxygen species at levels that facilitate cellular signalling while limiting excessive oxidative stress, which is important for effective physiological adaptation to exercise. Following photon absorption, PBM can act to promote cellular homeostasis rather than causing oxidative damage (Hamblin, 2017). This controlled increase in oxidative stress can stimulate endogenous antioxidant defence systems, strengthening the body's adaptive capacity (Hamblin, 2017).

In addition to enhancing mitochondrial energy production via the electron transport chain and inflammatory, and antioxidant effects, PBM influences several other processes relevant to recovery and training adaptation. PBM has been shown to upregulate growth factors associated with the development of new blood vessels and tissue repair (Ferraresi et al., 2016). Collectively, these mechanisms may explain the proposed benefits of PBM for enhancing recovery, delaying fatigue, and improving exercise performance. PBM has also been reported to delay fatigue and enhance exercise performance, which may be partly explained by its ability to reduce exercise-induced oxidative stress and upregulate antioxidant defences and ATP production (Tomazoni et al., 2019). Collectively, these processes contribute to improved cellular energy availability, reduced oxidative stress, and enhanced tissue repair.

A key feature of PBM is its biphasic dose-response relationship, whereby lower doses stimulate biological activity while higher doses may inhibit cellular function (Hamblin, 2017). In this context, one of the most consistently reported effects of PBM is a reduction of inflammation, which has been observed across a range of tissues including skeletal muscle, joints and neural structures. For example, LLLT has been reported to be superior to diclofenac and dexamethasone in reducing inflammation following a collagenase injection (Naterstad et al., 2017). This anti-inflammatory response is particularly relevant to conditions involving tissue damage or overuse. An important consideration within PBM research is that both dosage and timing of application significantly influence physiological outcomes. Insufficient energy delivery may produce minimal biological effects, whereas excessive irradiation may suppress cellular activity, reinforcing the importance of optimised dosing strategies (Hamblin, 2017).

In addition to dosage, the timing of PBM application relative to exercise appears critical. Pre-exercise application is proposed to enhance mitochondrial readiness and oxygen utilisation, thereby improving performance, whereas post-exercise application is more closely associated with recovery processes such as inflammation reduction and tissue repair (Ferraresi et al., 2016). Evidence also suggests that PBM effects are not immediate, and peak physiological responses may occur several hours post-application (Ferraresi et al., 2012). This delayed physiological response highlights the importance of optimizing both dosage and timing when designing PBM interventions for athletic performance. Collectively, these findings highlight the difficulty in establishing standardised PBM protocols, particularly when translating from controlled animal models to human athletic performance contexts. As a result, the lack of consistency in PBM application parameters remains a key limitation in the literature and contributes to the variability in reported performance outcomes.

Chung et al. (2012) has explained “when LLLT is applied across a broad range of conditions, it continues to generate debate for two main reasons. Firstly, the precise biochemical mechanisms underpinning its effects are not yet fully understood, meaning its application is often guided by empirical evidence. Secondly, treatment required careful selection of multiple parameters – including: wavelength, power density, pulse characteristics, and timing". It is clear therefore, that if these variables are not optimally chosen, the therapy may be ineffective or even produce adverse results. It is possible therefore, that some negative findings reported in the literature may be due to inappropriate choices of light source, wavelength, or dosage rather than ineffectiveness of the intervention itself.

1.5 Photobiomodulation and Exercise Performance

PBM has progressively been applied within sport and exercise science, transitioning from its original clinical use in wound healing and inflammation management to a potential recovery and performance modality. Early research, including systematic reviews of human trials, suggesting that PBM may influence aspects of muscle performance such as fatigue resistance, torque production, and repetition capacity, while also being associated with reductions in inflammation, oxidative stress, and markers of muscle damage in some contexts (Ferraresi et al., 2016). However, more recent experimental evidence indicates that these effects may not be consistent across all exercise modalities or outcomes.

For example, following exercise-induced muscle damage from high-intensity sprinting, PBM has been shown to reduce soreness in specific muscle groups, such as the calf, but does not appear to significantly improve functional recovery measures including vertical jump or agility performance (D'Amico et al., 2022). These findings suggest that while PBM may reduce soreness in specific muscle groups, it has limited effects on performance recovery following explosive, short-duration exercise appear limited.

Pre-exercise PBM has been investigated as a potential ergogenic aid for enhancing exercise capacity and modulating physiological stress response. For example, in a randomized triple-blind, placebo-controlled crossover trial involving high-level male soccer player, PBM applied prior to progressive running test produced significant improvements in multiple markers of exercise performance and physiology (Tomazoni et al., 2019). Compared to PLA, PBM increased VO_{2max}, extended time to exhaustion, and improved both aerobic and anaerobic threshold responses during high-intensity exercise.

Similarly, Miranda et al. (2016) investigated the effects of pre-exercise PBM therapy, using a combination of super-pulsed lasers and light-emitting diodes, on cardiopulmonary exercise performance in untrained male participants. In a randomised, double-blind, placebo-controlled crossover design, PBM was applied to major lower-limb muscle groups prior to a treadmill-based cardiopulmonary exercise test. The findings showed that participants achieved greater distance covered and longer time to exhaustion following active PBM compared to PLA. In addition, pulmonary ventilation was higher and perceived exertion related to dyspnoea was reduced during the exercise test. Collectively, these results indicate that pre-exercise PBM enhanced exercise tolerance and ventilatory responses during progressive aerobic exercise, suggesting potential benefits for submaximal endurance performance, where sustained energy production relies on efficient mitochondrial function.

In addition to performance outcomes, PBM has been shown to elicited favourable biochemical adaptation, including reductions in muscle damage markers such as creatine kinase and lactate dehydrogenase, alongside decreased inflammatory signalling, which was evidenced by lower interleukin-6 concentrations. Tomazoni et al. (2019) reported that pre-exercise PBM reduced exercise-induced oxidative stress, as demonstrated by lower levels of lipid and protein oxidation markers. In addition, PBM improved exercise performance by increasing VO_{2max}, time to exhaustion, and both aerobic and anaerobic thresholds, while also reducing markers of muscle damage and inflammation. Collectively, these findings suggest that pre-exercise PBM may enhance exercise capacity not only through improvements in aerobic performance, but also attenuating exercise-induced muscle damage, inflammation, and oxidative stress, supporting its potential as a performance-enhancing intervention in sport.

1.6 Photobiomodulation and Endurance/Aerobic Exercise

Reported effects of PBM with the potential to impact exercise performance include increased mitochondrial activity, ATP availability, nitric oxide release, and modulation of inflammatory signaling (Ferraresi et al., 2016). These mechanisms are particularly relevant for endurance exercise, where sustained energy production and fatigue resistance are critical, especially during prolonged submaximal efforts common in rowing and cycling. Several studies demonstrate meaningful improvements in aerobic capacity and exercise tolerance following PBM application. For example, Tomazoni et al. (2019) reported that pre-exercise PBM significantly increased maximal oxygen uptake (VO_{2max}), time to exhaustion, and the exercise intensity at which aerobic and anaerobic thresholds occurred during a progressive running test in high-level athletes. These improvements were accompanied by reductions in markers of oxidative stress and muscle damage.

In a systematic review and meta-analysis of 16 randomised controlled and crossover trials, Nampo et al. (2016) provided further support the potential for PBM to enhance aerobic and muscular endurance outcomes, although the effectiveness appears to depend on the light source used. In this 2016 review that included 297 participants, pre-exercise laser exposure was associated with significant improvements in exercise capacity, including increased repetitions, prolonged time to exhaustion, reduced blood lactate concentrations, and greater peak torque production. These findings suggest a potential role for PBM in enhancing both metabolic efficiency and fatigue resistance during exercise. In contrast, LED-based interventions did not demonstrate statistically significant benefits for power output, lactate response, or time to exhaustion. Importantly, the authors highlighted that the overall quality of evidence was low, with considerable variability in treatment parameters and study designs. This reinforces ongoing concerns within the literature regarding interpretation and translation of findings, particularly within endurance-focused and sport-specific contexts.

In endurance-specific studies, Lanferdini et al. (2018) demonstrated significant improvements in time to exhaustion in competitive cyclists following pre-exercise PBM. Further, Miranda et al. (2016) reported improved ventilatory efficiency and increased exercise tolerance, while Zhao et al. (2012) found improved running performance in female basketball players. Miranda et al. (2016) further reported improvements in aerobic performance following pre-exercise Photobiomodulation, with participants demonstrating increase time to exhaustion (780.2 vs 742.1 s), greater distance covered, and enhanced ventilatory efficiency during a progressive cardiopulmonary exercise test.

Zhao et al. (2012) demonstrated that pre-exercise PBM improved both endurance performance and sleep quality in female basketball players, with participants covering greater distances in a 12-minute run test and reporting improved recovery profiles. This study is particularly relevant given it is one of few studies that included female athletes, a population that remains underrepresented in the broader PBM literature. Overall, these findings support the role of PBM in enhancing oxygen utilization and delaying fatigue onset during endurance exercise.

PBM has also been shown to influence performance and fatigue-related outcomes. Borsa et al. (2013) conducted a systematic review of 10 randomised controlled trials and reported that pre-exercise PBM, including both laser and LED applications, consistently improved skeletal muscle performance by delaying the onset of fatigue, increasing total work and repetitions to fatigue, and enhancing maximal voluntary contraction. In addition, PBM was associated with reduced exercise-induced muscle damage and improved post-exercise recovery, as indicated by both functional measures and biochemical markers. Notably, 24 out of 32 data sets demonstrated significant differences between active and placebo conditions, suggesting a relatively consistent, but variable effect on exercise-related variables. These findings lend further support for the potential role of PBM in enhancing muscular endurance and fatigue resistance.

Short term studies, such as Machado et al. (2017), generally report limited effects on performance and only small improvements in selected recovery markers following a single PBM application. In this study, LED therapy demonstrated a moderate effect on the reduction of delayed onset muscle soreness in one muscle group; however, no significant effects were observed for biochemical markers of recovery (e.g., creatine kinase, lactate), autonomic function, or endurance performance outcomes. These findings reinforce that acute PBM application may produce inconsistent or limited physiological responses depending on the outcome measure, dosage, population, and light parameters. Taken together, this evidence indicates that a single exposure to PBM may be insufficient to lead to substantial or consistent performance and recovery benefits.

PBM has also been shown to influence aerobic performance alongside biochemical markers of fatigue and oxidative stress. In a randomized, double-blind, placebo-controlled crossover trial, LLLT was applied prior to a progressive treadmill test in 22 untrained male participants. De Marchi et al., (2012) reported the intervention significantly improved maximal oxygen uptake (VO_{2max}; $p = 0.01$) and time to exhaustion ($p = 0.04$), indicating enhanced aerobic capacity. In addition to performance outcomes, LLLT reduced markers of oxidative stress, including lipid peroxidation and protein oxidation, as well as muscle damage indicators such as creatine kinase and lactate dehydrogenase. These findings suggest that pre-exercise LLLT may enhance aerobic performance and delay fatigue through modulation of oxidative stress and muscle damage pathways, providing further mechanistic support for its application in endurance exercise contexts. However, despite these positive findings, the use of untrained participants limits the direct applicability of these results to trained athletes.

A meta-analysis by Vanin et al. (2015) further supports the ergogenic effects of PBM on exercise performance, while also providing insight into optimal application parameters. Analysing 13 randomised controlled trials of acceptable methodological quality, the authors reported significant improvements in time to exhaustion (mean increase of 4.12 seconds) and muscular endurance (increase of 5.47 repetitions) following phototherapy, with most studies applying the intervention prior to exercise. In addition, positive effects were observed for markers of muscle damage, including creatine kinase, suggesting a protective effect against exercise-induced tissue stress. Notably, the most consistent benefits were associated with RED or IRED wavelengths and specific dosing ranges, indicating potential wavelength-dependent response.

Given that PBM has been shown to enhance mitochondrial readiness and oxygen utilisation, and modulate oxidative stress, its application may be particularly relevant for submaximal endurance exercise. Improvements in these mechanisms could theoretically reduce the oxygen cost of exercise, delay the onset of fatigue, and enhance exercise economy, all of which are key determinants of endurance performance. In endurance contexts such as rowing, PBM may theoretically improve maintenance of power output, reduce fatigue, and enhance recovery between sessions. However, despite evidence in cycling and running, no studies have examined PBM in rowing specific contexts. Given the high aerobic demand and sustained sub-maximal output required in rowing, this represents a further significant gap in the literature. Further, despite this strong mechanistic rationale, relatively few studies have directly assessed PBM under submaximal conditions relevant to endurance exercise performance, representing a knowledge gap in the literature.

It is also noteworthy that, when comparing findings across the literature, differences emerge between controlled laboratory-based studies and applied sport settings. From the previous research, laboratory-based studies often report more consistent improvements in performance variables such as time to exhaustion and VO_2 kinetics, likely due to tightly controlled protocols and standardised conditions. In contrast, field-based studies conducted in real-world athletic environments tend to report smaller or inconsistent effects, potentially due to greater variability in training status, environmental factors, and the sensitivity of the performance measurement.

This discrepancy suggests that while PBM demonstrates controlled condition effectiveness, it’s the translation to applied sport performance may be more complex, highlighting the need for sport-specific and ecologically valid research designs that assess reliable performance outcomes.

Despite generally positive findings, the literature demonstrates considerable variability in reported outcomes regarding PBM. These inconsistencies may reflect differences in participant characteristics, training status, exercise protocols, and PBM treatment parameters. For example, studies involving untrained individuals may be more likely to demonstrate improvements due to greater scope for physiological adaptation, whereas highly trained athletes may require more specific dosing strategies to elicit measurable effects.

1.7 Summary of Findings in Trained Athletes

A systematic review of literature that has measured outcomes relevant for endurance performance yielded nine studies (Table 1). Of note, out of the nine studies included in Table 1, eight recruited exclusively male participants, with one recruiting a mixed gender cohort (Hemmings et al., 2017). From the 160 individuals represented in Table 1, the participants were predominantly male, with a total sample comprising of 144 males (90%) and 16 females (10%). The underrepresentation of female athletes within PBM research is particularly important given known physiological differences between males and females. Factors such as substrate utilization, fatigue resistance, hormonal fluctuations, and recovery responses may influence how female athletes respond to PBM interventions. Consequently, findings derived primarily from male cohorts cannot be assumed to apply equally to female populations. Addressing this limitation is essential for improving the external validity and practical application of PBM research.

Furthermore, relatively few studies specifically examined endurance-trained athletes, despite PBM mechanisms being highly relevant to aerobic performance and prolonged submaximal exercise. Participants had various competitive backgrounds, including cycling, soccer, rugby, futsal, volleyball, and resistance training. The PBM intervention was consistently applied prior to exercise or competition across all studies, with reported wavelengths ranging from 640 – 950 nm. There was substantial heterogeneity across studies in relation to PBM protocols with some studies utilising combined laser and LED devices while others failed to fully report treatment parameters. Despite generally positive findings, the differences in wavelength combinations, dosage, irradiation sites, timing of application, and delivery methods, make direct comparisons between studies difficult. As a result, the ability to establish standardised evidence-based protocols for athletic performance applications is limited.

Across the studies presented in Table 1, PBM generally demonstrated positive effects on exercise performance, fatigue resistance and recovery-related outcomes in trained athletes. Improvements were most consistently observed in endurance-related variables such as time to exhaustion, repetitions to fatigue, and aerobic performance measures, suggesting that PBM may be particularly beneficial for activities requiring sustained energy production and resistance to fatigue. In contrast, sport-specific performance outcomes, such as total distance covered during match play, showed more variable findings, indicating that physiological improvements may not always directly translate to complex competitive performance outcomes.

A notable pattern across the literature was the consistent reduction in biochemical markers associated with muscle damage, inflammation, and oxidative stress. Several studies reported decreases in creatine kinase, lactate dehydrogenase, blood lactate, and inflammatory markers following PBM application, even in cases where direct performance improvements were limited. Thus, the data suggests that PBM may exert a stronger and more reliable influence on physiological recovery processes than on acute performance enhancement alone.

Table 1. Summary of Studies Investigating Acute Photo biomodulation on Exercise Performance in Trained Athletes**.**

Study	Sport	Participants	Wavelength (nm)	Application Timing	Main Outcomes
(Lanferdini, et al., 2018)	Cycling. Incremental test to exhaustion	20 Males (competitive cyclists)	135 J, 270 J, 405 J and Placebo	Pre - exercise	↑ time to exhaustion
(Pinto et al., 2016)	Field sprint test (Bangsbo sprint test)	12 Males (High-level rugby players)	905 nm (Laser), 875 nm (IR LED), 640 nm (red LED)	Pre - exercise	↑ sprint performance (average time, fatigue index); ↓ blood lactate change; ↓ perceived fatigue
(De Marchi et al., 2019)	Futsal (Match Play)	6 Males (Professional athletes)	905 nm (laser), 875 nm (LED), 640 nm (LED)	Pre – match (40 mins before)	↑ time on pitch; no change in distance covered; improved recovery markers (↓ CK, LDH, lactate, oxidative damage)
(Follmer et al., 2018)	Resistance exercise (elbow flexor isometric contractions)	20 Males (10 BJJ athletes, 10 physically active men)	Not reported	Pre-exercise	↑ time to exhaustion (physically active group), ↑ impulse during fatigue test; PBMT helped delay fatigue across both groups regardless of training status
(Hemmings et al., 2017)	Resistance Exercise (Quadriceps eccentric leg extension to fatigue)	34 Participants (18 Males + 16 Females) Recreationally resistance trained athletes	Not specified in text	Pre exercise. Right after MVIC testing but before the fatigue protocol. LEDT was applied for 30, 60, or 120s per point. Placebo was applied 45 seconds per point	↑ repetitions to fatigue with 60s and 120s LEDT vs PLA; no differences in blood lactate.
(Lanferdini et al., 2023)	Cycling - Time to exhaustion test	16 Males (Trained Cyclists)	670 nm, 850 nm, 880 nm, 950 nm.	Pre exercise (Before each of three successive TTE tests)	↑ time to exhaustion in first two tests, ↑ VO2 kinetics, ↑ muscle

					oxygenation; effects reduced by third test.
(Leal Junior et al., 2009)	Cycling (Wingate test; volleyball and soccer athletes)	20 Males (9 professional volleyball players + 11 adolescent soccer players)	830 nm	Pre exercise	No improvement in performance; ↓ creatine kinase (CK) (volleyball players) and ↓ blood lactate (soccer players) → improved recovery
(Leal Junior et al., 2009)	Resistance exercise (biceps contractions to exhaustion)	10 Males (professional volleyball players)	660 nm and 850 nm	Pre-exercise	↑ repetitions and time to exhaustion; ↓ lactate, CK and CRP → delayed fatigue and improved recovery
(Leal Junior et al., 2019)	Soccer (progressive running test to exhaustion)	22 Males (high level soccer players)	Infrared LLLT (exact wavelength not specified)	Pre-exercise	↑ VO2 max, ↑ time to exhaustion, ↑ aerobic and anaerobic thresholds; ↓ CK, ↓ LDH, ↓ IL-6, ↓ oxidative stress markers (TBARS, protein carbonyls), ↑ antioxidant enzymes (SOD, CAT) → improved performance and recovery
		Total Participants : 160 Males : 144 (90%) Females : 16 (10%)			

Collectively, these findings suggest that PBM demonstrates promising ergogenic and recovery-enhancing potential in trained athletes; however, inconsistencies in methodology, limited sport-specific research, and poor representation of female endurance athletes continue to restrict the practical translation of current evidence. These limitations provide a clear rationale for further investigation within rowing-specific and female athletic populations.

1.8 Translation to Endurance and Rowing Contexts

Rowing presents a unique physiological and biomechanical profile compared to other endurance sports such as running and cycling. It involves a combination of upper and lower body muscle recruitment, high stroke repetition, and sustained submaximal power output interspersed with periods of higher intensity effort. This whole-body demand increases the reliance on coordinated oxygen delivery, muscular endurance, and efficient energy utilisation. As such, the potential benefits of PBM, including enhanced mitochondrial function, improved blood flow and reduced fatigue, may have distinct implications in rowing compared to lower-body dominant endurance sports. However, the absence of rowing-specific PBM research limits the ability to directly translate findings from other modalities, reinforcing the need for targeted investigation in this population.

1.9 Summary and Research Gaps

Overall, PBM demonstrates potential as a performance-enhancing and recovery intervention in trained athletes, with evidence supporting improvements in muscle performance, fatigue resistance, and recovery. These effects are likely underpinned by enhanced mitochondrial function, improved oxygen utilization, and modulation of oxidative stress and inflammation. Some studies relied heavily on subjective outcome measures, while others focus solely on physiological variables, with few integrating both approaches.

Additionally, the literature remains limited by variability in protocols and a lack of standardisation in dosage, wavelength, and the timing of any light therapy intervention. Most studies have focused on short-term outcomes, with limited investigation into long-term training adaptations. Importantly, there is a clear underrepresentation of female participants, with only 10% of participants across reviewed studies being female. Similarly, endurance-trained participants only represented 33.33% in the reviewed studies. As a result, *none* of the participants that met the inclusion criteria were endurance-trained women. This complete lack of research limits the generalisability of findings to endurance-trained female athletes.

This inconsistency limits the ability to draw clear conclusions regarding the efficacy of PBM across different exercise modalities. Participant diversity also remains limited with current research. Most studies have focused on healthy, able-bodied individuals, with minimal representation of female athletes, diverse populations, or individuals, with disabilities. Additionally, accessibility of PBM technology, which often relies on expensive equipment, raises practical considerations regarding its application across different socioeconomic groups. Addressing these gaps is important for ensuring that findings are both generalisable and applicable across a range of populations.

Another limitation within the literature is the selection of performance and physiological outcome measures. Many studies prioritised time-to-exhaustion tests, which are particularly sensitive to changes in endurance capacity, but may lack ecological validity for real-world sport performance, as performance is seldom measured in open -ended efforts. Additionally, limited research has examined submaximal physiological markers such as respiratory exchange ratio (RER), blood glucose, and lactate, which provide important insight into energy utilisation and metabolic efficiency during exercise. These measures, especially at exercise intensities close to the anaerobic physiological threshold, are particularly relevant for endurance athletes, where performance is often determined by the ability to sustain effort rather than reach maximal output. The lack of focus on these variables highlights an important gap in understanding how PBM influences exercise metabolism.

1.10 Conclusion

Overall, the current body of literature suggests that PBM has potential as both a performance-enhancing strategy and recovery modality within sport and exercise contexts. Mechanistically, PBM is supported by well-established physiological mechanisms, including enhanced mitochondrial activity, increased ATP, modulation of reactive oxygen species, and improved nitric oxide - mediated blood flow. These processes can collectively contribute to improved cellular energy availability, delayed fatigue, and enhanced recovery, providing a clear theoretical basis for its application in athletic performance.

Empirical evidence further supports three mechanisms, with systematic reviews and experimental studies demonstrating improvements in time to exhaustion, muscular endurance and markers of muscle damage. However, these findings are not universally consistent, with variability largely attributed to differences in study design, including wavelength, dosage, timing of application, and delivery method (LLLT vs LEDT).

Importantly, significant gaps remain within the literature. There is a clear lack of sport-specific research, particularly in endurance-based modalities such as rowing, where prolonged submaximal effort and aerobic efficiency are key performance determinants. Furthermore, the underrepresentation of female athletes limits the generalisability of current findings, while the limited investigation into submaximal exercise responses fails to reflect the physiological demands of typical endurance training and competition.

From an applied perspective, PBM offers a non-invasive and potentially practical intervention for athletes. The ability of PBM to be administered pre or post exercise, combined with minimal reported side effects, makes it an attractive tool within high-performance environments. However, without clear guidelines around optimal dosage, timing, and application protocols, its performance remains inconsistent. Establishing evidence-based recommendations is therefore essential for translating laboratory findings into real-world athletic practice.

1.11 Research Questions

Collectively, the literature review highlighted four key gaps in the area of PBM:

1. The absence of rowing-specific research,
2. limited investigation of female athletes,
3. a lack of studies examining physiological responses to submaximal exercise, such as lactate response, glucose utilization, and fuel utilisation, at intensities relevant to endurance performance,
4. the wavelength dosage that elicits a meaningful performance improvement

Therefore, addressing these gaps formed the rationale for the present study. The current thesis aims to answer four research questions:

1. Does pre-exercise application of PBM influence blood glucose levels during submaximal rowing exercise in trained female rowers?
2. Does pre-exercise PBM alter blood lactate accumulation during submaximal rowing exercise in trained female rowers?
3. Does pre-exercise PBM affect energy contribution during submaximal rowing exercise, as indicated by RER in trained female rowers?
4. Does red light (630 nm and 660 nm), near-infrared light (810 nm, 830 nm, and 850 nm), or a combination of both red and infra-red light, produce meaningful changes in the physiological responses to exercise intensity just below the anaerobic threshold in endurance trained, female rowers?

Chapter Two

2.0 Abstract

Background: Photobiomodulation (PBM) has been proposed as a non-invasive intervention to enhance exercise performance through improvements in mitochondrial function, energy production, and fatigue resistance. Previous research has reported positive effects of PBM on endurance performance in male cyclists and runners; however, its effects on rowing performance remain unknown. Therefore, the purpose of this study was to investigate the acute effects of PBM on submaximal rowing performance and physiological responses in trained female rowers. **Methods:** Twelve trained female rowers participated in a randomised, double-blind, placebo-controlled crossover study. Following a maximal graded exercise test, participants completed four submaximal rowing trials following exposure to red light (RED), near-infrared light (IRED), combined red and near-infrared light (COMB), or placebo (PLA). Outcome measures included exercise capacity (intervals completed), oxygen uptake (VO_2), blood lactate and glucose concentration, respiratory exchange ratio (RER), and ratings of perceived exertion (RPE). Data were analysed using repeated-measures analysis of variance and effect size calculations. **Results:** RED (7.25 ± 0.75 stages $p = 0.046$) and COMB (7.25 ± 0.45 stages; $p = 0.012$) conditions compared with PLA (6.67 ± 0.98 stages), while IRED demonstrated a similar trend (7.17 ± 0.72 stages; $p = 0.053$). A significant main effect of condition was observed for RER ($p = 0.002$), with lower values observed during the later stages of exercise following RED compared with PLA. Blood glucose concentrations were also lower during the later stages of exercise following RED and IRED, with a significant reduction observed after Interval 6 in the IRED condition compared with PLA (p = 0.030). No significant differences were observed between conditions for VO_2, blood lactate concentration, or RPE. **Conclusion:** Acute PBM exposure improved submaximal rowing exercise capacity in trained female rowers at exercise intensities close to the lactate threshold without altering VO_2, blood lactate concentration, or perceived exertion. These findings suggest that PBM may enhance exercise tolerance through improved metabolic efficiency and fatigue resistance rather than changes in traditional physiological markers. This study provides evidence supporting the potential application of PBM in female rowers performing at exercise intensities relevant to training and competition.

Keywords: Photobiomodulation, red light therapy, rowing, endurance performance, female athletes.

2.1 Introduction

Rowing is a physiologically demanding endurance sport requiring high levels of aerobic fitness, muscular endurance and efficient energy utilisation. Rowing performance has been closely linked to critical power defined as the highest sustainable oxidative metabolic rate (Dwyer et al., 2025). Consequently, interventions that enhance energy production, improve fatigue resistance, or optimise metabolic efficiency may offer potential benefits for rowing performance. One intervention that has gained increasing attention in recent years is PBM, commonly known as red light therapy.

PBM involves the application of RED and IRED light to biological tissues, where photons are absorbed by cytochrome c oxidase within the mitochondrial electron transport chain (De Freitas & Hamblin, 2016). This interaction has been proposed to enhance mitochondrial activity and increase ATP production (Hamblin, 2017). In addition, PBM may increase nitric oxide availability, potentially improving blood flow and oxygen delivery to working muscles (Ferraresi et al., 2016). Lower levels of lactate post-exercise have also been reported in randomised crossover control trial in professional futsal athletes (De Marchi et al., 2019). Collectively, these physiological mechanisms have the potential to contribute to improved fatigue resistance and exercise tolerance during endurance exercise.

Previous research has reported positive effects of PBM on exercise performance. Tomazoni et al. (2019) observed improvements in aerobic performance and exercise capacity following PBM application in trained athletes. Similarly, Lanferdini et al. (2018) reported increased time to exhaustion during endurance exercise following pre-exercise PBM. These findings suggest that PBM may have the potential to enhance performance during prolonged exercise. However, despite these promising results, the mechanisms underlying performance improvements remain incompletely understood, and findings across studies have been inconsistent. For example, a 2022 review reported no effect of PBM on repeated sprint efforts in runners (Dutra et al., 2022).

The inconsistency in results may be partially due to variations in training status, light dose, and test protocols. Of note, relatively few studies have investigated the effects of PBM during submaximal exercise at intensities relevant to endurance performance. As such, several important gaps remain within the current literature. Furthermore, most PBM research has focused on male participants, limiting the generalisability of findings to female athletes. Research examining physiological indicators of energy utilisation, such as blood glucose concentration, blood lactate concentration, and RER, is also limited. Given the unique physiological demands of rowing and the limited evidence available in female endurance athletes, further research is warranted. Therefore, the purpose of this study was to investigate the acute effects of pre-exercise PBM on submaximal rowing performance and physiological responses in trained female rowers. It was hypothesised that PBM would improve exercise capacity and favourably alter physiological responses associated with fatigue and energy utilisation compared with a placebo condition.

2.2 Methods

2.2.1 Participants

Eleven competitive female rowers participated in this study (Age: 23 ± 6.3 y, Weight: 78.5 ± 9.8 kg, VO_2 max: 43.7 ± 5.1 ml/kg/min). All participants were actively engaged in structured rowing training and were members of either Waikato Rowing Club or the University of Waikato Rowing programme. The decision to include female athletes only was made to address the underrepresentation of females in exercise physiology and PBM research, where samples are often male-dominated or mixed samples are reported without gender-specific analysis. Eligibility criteria required participants to have a minimum of three years rowing experience, to be training at least three times per week, and to be between 16 and 32 years of age. Individuals were excluded if they presented with a current musculoskeletal injury, metabolic or cardiovascular conditions, or any medical issue that could impair performance or metabolic response during exercise. Participants were also required to be free from any contraindications to light-based therapy.

Ethical approval was granted by the University of Waikato Human Research Ethics Committee (Appendix A). Prior to commencing testing, participants were provided with an information sheet (Appendix B) and completed a demographic and training questionnaire detailing age, sex, height and weight. Information regarding training history and weekly training volume was also collected to characterise the sample. Written informed consent was obtained from all participants prior to participation (Appendix C).

2.2.2 Research Design

The study employed a placebo-controlled, double-blind, randomised crossover design to investigate the acute effects of PBM on submaximal rowing performance and exercise physiology in trained female athletes. The primary outcomes of interest were oxygen uptake, blood lactate concentration, and blood glucose concentration during progressive submaximal rowing exercise. Secondary measures included RER, and RPE, enabling the assessment of physiological and perceptual responses.

Each participant completed five laboratory sessions. The first session involved completing a pre-test medical questionnaire (Appendix D) followed by a maximal graded exercise test to determine maximal oxygen uptake (VO_{2max}) and establish customized wattage targets for subsequent submaximal trials. The remaining four sessions involved four identical rowing protocols performed immediately following one of four PBM interventions: RED (630 nm and 660 nm), IRED (810 nm, 830 nm, and 850 nm), COMB (red and near-infrared light), or a PLA condition. Treatment order was randomised using a computer-generated randomisation sequence, and both participants and the researchers involved in the data collection were blinded to the intervention condition. A minimum of 48-hours of recovery was observed between sessions to minimise potential carryover effects, which was standardised across all participants.

2.2.3 Experimental Procedures

All testing sessions were conducted at the University of Waikato Sports Laboratory in a temperature-controlled environment (19 ± 1 ºC; relative humidity 45 ± 5%). All respiratory measurements were collected via a Parvo Medics True One 2400 metabolic cart. The metabolic cart was calibrated prior to each testing session using standardised gas calibration and flow verification procedures in accordance with manufacturer guidelines. All trials were performed on the same Concept2 Model D rowing ergometer, with the drag factor standardised to 110 for all participants to ensure consistency across trials.

2.2.4 Maximal Oxygen Uptake Testing

During the initial laboratory visit, participants completed a graded exercise test to determine VO_{2max}. Each participant's most recent 2,000m ergometer performance was used to individualise starting workloads and incremental increases. The protocol began at a workload corresponding to 60% of the participants mean 2,000 m ergometer power output and increased incrementally every two minutes until volitional exhaustion or inability to maintain the prescribed power output for ten consecutive strokes. To calculate the incremental increases for each 2-minute stage, the following method was used:

$$\text{Increment per stage (W)} = (2{,}000\ \text{m W} - 60\%\ \text{W}) \div 7.$$

The protocol was designed to elicit exhaustion within approximately seven stages. Oxygen consumption, carbon dioxide production and ventilation were recorded continuously throughout the test. The highest 30 second rolling average of oxygen uptake was used to determine VO_{2max}, accompanied by secondary indicators such as a plateau in $\dot{V}O_2$ despite increasing workload, RER > 1.10, and a heart rate above 90% of the age-predicted maximum (220 – age).

2.2.5 Photobiomodulation Intervention

Prior to each submaximal trial, participants complete a five-minute PBM session using a commercially available light therapy panel (SOHL Complete, NZ). Participants stood 10 – 15 cm in front of the device and wore a blackout eye mask to maintain blinding. The exposure consisted of 2.5 minutes racing the panel and 2.5 minutes facing away, ensuring anterior and posterior body exposure. A researcher who was not involved in performance measurements programmed the device according to each participant's randomised treatment schedule, and escorted the participant into position ensuring the double-blind protocol was maintained. The placebo condition involved the device being turned on but paused, so no light was emitted but the internal fan was still audible.

2.2.6 Submaximal Rowing Protocol

Immediately following the light exposure, participants were escorted to the rowing ergometer, unblinded, and fitted with a respiratory mask before being seated on the ergometer. Each submaximal trial consisted of graduated four-minute rowing stages at fixed workloads derived from the athletes individual VO_{2max} test until they reached a lactate level of at least 4.0 $mmol\cdot L^{-1}$. One minute passive recovery periods separated each stage. During the passive recovery, capillary blood samples were collected from the earlobe to assess blood lactate concentration (Lactate Pro 2, Arkay Inc., Japan). Participants provided a perceived rating of exertion at the end of each submaximal stage using the Borg 6 – 20 scale (Appendix E), referring to a visible reference chart throughout testing (Borg, 1982). Throughout each submaximal session, oxygen uptake, carbon dioxide output, ventilation and respiratory exchange ratio, were recorded continuously.

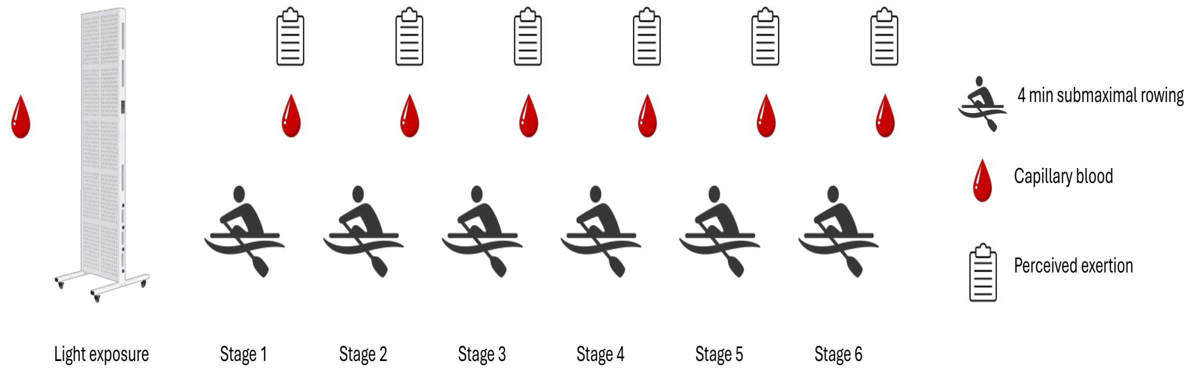


Figure 2: Schematic of the sub-maximal rowing exercise protocol

All biological sampling was carried out according to laboratory safety guidelines. Sampling sites were prepared using sterile alcohol swabs, and all lancets, test strips, and blood contaminated materials were disposed of in designated sharps and waste containers. Environmental conditions, including temperature and humidity, were recorded at the beginning of each session to confirm consistency across testing days. All sessions were administered by the same researcher to enhance procedural reliability and minimise variability introduced by differences in data collection.

2.2.7 Statistical Analysis

A two-way 4 x 6 repeated-measures ANOVA was conducted to assess the effects of 'Condition' (RED, IRED, COMB, PLA) and 'Interval' (1-6) on VO_2, VCO_2, RER, VE, glucose, lactate, and RPE. The interaction between condition and stage was also evaluated. Where appropriate, Bonferroni adjusted *post hoc* comparisons were undertaken. The assumption of normality of residuals was assessed using the Shapiro-Wilk test. Statistical significance was defined as $p \leq 0.05$. To determine the magnitude of effects, effect sizes were interpreted according to Cohen (1988), with thresholds of 0.2, 0.5, and 0.8 representing small, moderate, and large, respectively. Standardised effects ranging from -0.19 to 0.19 were classified as trivial. A difference was termed substantial when the effect did not overlap the thresholds for both positive and negative. Data are presented as mean ± 95% confidence intervals, calculated using the normal approximation method. An effect was considered clear when its confidence interval did not overlap both the small positive and small negative effect thresholds. Lactate threshold was calculated using the Dmax method with a fitted 3rd degree polynomial function (Cheng et al., 1992). The earliest onset of lactate was defined at the lowest value of the ratio lactate/exercise intensity, or the lactate-equivalent (Dickhuth et al., 1999).

2.3 Results

All athletes completed a minimum of six submaximal intervals in each condition. A greater number of intervals were completed following RED ($\bar{x} = 7.25 \pm 0.75$; p= 0.0463; d = -0.62 ± 0.61), IRED ($\bar{x} = 7.17 \pm 0.72$; p = 0.0527; d = -0.5 ± 0.5), COMB ($\bar{x} = 7.25 \pm 0.45$; p = 0.0116,d = -0.71 ± 0.52) when compared to PLA ($\bar{x} = 6.67 \pm 0.98$). The ANOVA revealed a significant main effect of interval for RPE ($p = 1.49 \times 10^{-42}$), VO_2 ($p = 7.74 \times 10^{-38}$), glucose (p = 0.0188), and lactate ($p = 7.12 \times 10^{-82}$). No significant main effects of condition or any interaction effects were detected.

There was a significant effect of both interval ($p = 6.95 \times 10^{-34}$) and condition (p = 0.0020) on RER, with no interaction effect observed. The *post hoc* analysis revealed that RED tended to be lower than PLA after Interval 5 (d = 0.66±0.90; p = 0.1305) and Interval 6 (d = 0.56±0.83; p = 0.1589).

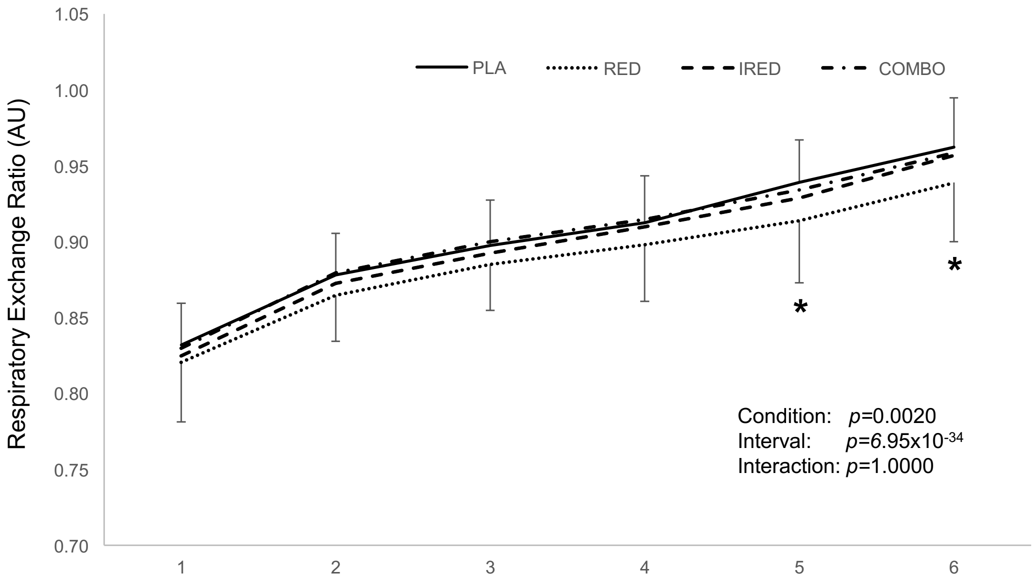


Figure 3. Respiratory Exchange ratio across six submaximal rowing intervals.
PLA: Placebo intervention; RED: red light intervention; IRED: infra-red light intervention; COMBO: combined red and infra-red light intervention; * substantial difference between PLA and RED

There was a significant effect of interval (p = 0.0188) but not condition (p = 0.2062) on blood glucose, with no interaction effect observed. Blood glucose levels were substantially lower in IRED vs PLA after Interval 5 (d = 0.44±0.56; p = 0.1066) and after Interval 6 (d = 0.58±0.51; p = 0.0300). Blood glucose levels were also lower in RED vs PLA after Interval 5 (d = 0.38±0.45; p = 0.0936) and after Interval 6 (d = 0.55±0.68; p = 0.0998). The exercise-induced increase in blood glucose concentration across the six intervals was lower in RED vs PLA (Δ =0.51 ± 0.57 mmol·L -1, d=0.71; p=0.0734).

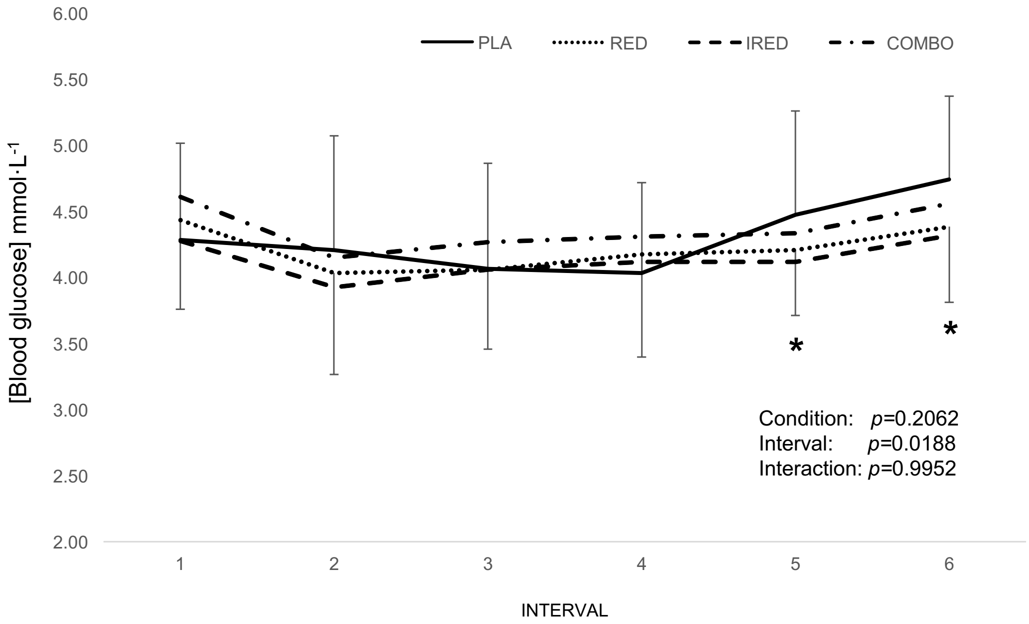


Figure 4. Blood glucose levels across six submaximal rowing intervals.
PLA: Placebo intervention; RED: red light intervention; IRED: infra-red light intervention; COMBO: combined red and infra-red light intervention; * substantial difference between both PLA and IRED and PLA and RED

A one-way ANOVA detected no difference in blood lactate threshold (p=0.986); however, the lactate equivalent was significantly lower in PLA vs COMB condition (139 ± 29 vs 145 ± 24 W; d =0.39 ±0.24; p =0.0134). The respective thresholds for RED ($\bar{x}$ = 164.1 ± 27.6), IRED ($\bar{x}$ = 161.7 ± 22.3), COMB ($\bar{x}$ = 162.8 ± 26.3) and PLA ($\bar{x}$ = 165.5 ± 27.6) were not significantly different.

2.4 Discussion

The aim of this study was to investigate the acute effects of PBM on submaximal rowing performance and related physiological responses in trained female athletes. The primary finding was that PBM improved exercise capacity, as demonstrated by a greater number of intervals being completed in the RED and COMB conditions compared to PLA. In addition to this, PBM was also associated with changes in metabolic responses during exercise, most notably blood glucose levels and trends towards lower RER in the RED condition. These findings occurred without significant changes in oxygen uptake or blood lactate threshold. The absence of changes in VO_2 despite improved exercise capacity may indicate that PBM exerts its ergogenic effects through peripheral muscular adaptations rather than central cardiorespiratory mechanisms. This interpretation is supported by studies reporting improvement sin endurance performance and fatigue resistance without corresponding changes in oxygen consumption. The improvement in performance alongside unchanged physiological variables suggests that PBM may enhance exercise tolerance through processes not captured by traditional metabolic markers such as VO_2 and blood lactate.

The improvement in exercise capacity observed in the present study is consistent with previous research demonstrating performance benefits of PBM in endurance exercise. Lanferdini et al., (2018) has shown that PBM can improve peripheral muscle oxygenation; while Leal-Junior et al., (2019) reported an increase in time to exhaustion and delayed onset of fatigue following pre-exercise PBM. In high level football players, Tomazoni et al., (2019) observed improved aerobic capacity and threshold responses. Vanin et al., (2016) reported that PBM also improved maximal voluntary contraction force in a randomised controlled trial, when applied pre-exercise.

Importantly, the present findings build on previous research by demonstrating performance benefits of PBM in female rowers performing sustained submaximal exercise, an area that has received limited attention in the existing literature. Of note, the improvements were evident at exercise intensities just below the arbitrary onset of blood lactate threshold of 4.0 $mmol \cdot L^{-1}$. The improvement in performance despite no change in VO_2 or blood lactate is consistent with Borsa et al., (2013), who reported improvements in muscular endurance and fatigue resistance following PBM without consistent changes in systemic physiological markers. Together, these data support the idea that PBM may enhance performance by improving energy efficiency and increasing fatigue tolerance.

At a physiological level, PBM is proposed to enhance mitochondrial function, leading to improvements in cellular energy production. Absorption of RED and IRED light by cytochrome c oxidase enhances electron transport chain activity, increasing ATP production and improving cellular energy availability (Hamblin, 2017). This may reduce the relative energetic cost of submaximal exercise, allowing athletes to sustain higher workloads before reaching fatigue. In addition, PBM may enhance nitric oxide availability, improving vasodilation and oxygen delivery to active muscle tissue, which may contribute to improved exercise tolerance. We acknowledge that we did not assess mitochondrial energy production, however, the increased exercise tolerance does again suggest greater overall energy output capacity, either through higher energy efficiency, or a conservation of energy stores at lower exercise intensities.

A key finding of the current study was lower blood glucose levels during PBM conditions, particularly at exercise intensities close to the anaerobic threshold. These data may indicate changes in fuel use, potentially reflecting greater glucose uptake by working muscles or a shift towards more oxidative metabolism (i.e. lesser reliance on glucose mobilization). Ferraresi et al., (2016) support the idea that PBM can influence muscle metabolism and energy utilisation, which may explain these observations.

In addition to the lower blood glucose levels, the trend towards lower RER in the RED condition suggests an increase in the proportion of fat oxidation during submaximal exercise. When combined with the blood glucose data, these findings indicate a potential shift towards improved metabolic efficiency, and the increase in oxidative metabolism would reduce the reliance on finite carbohydrate stores use during prolonged exercise. This increased efficiency could translate into greater energy outputs at exercise intensities relevant to endurance performance, such as rowing, cycling, and running. These metabolic trends are supported by Ferraresi et al., (2016), who reported that PBM can enhance oxidative metabolism and affect fuel use. Similarly, Tomazoni et al., (2019) observed reductions in metabolic stress markers alongside improved performance outcomes following PBM, suggesting that PBM mediated changes in substrate metabolism and improved exercise efficiency can affect muscle damage. However, direct evidence for enhanced fat oxidation during exercise following PBM remains limited, particularly in endurance-trained female athletes. Therefore, the present findings contribute preliminary evidence that PBM may influence metabolic regulation during sustained exercise in female endurance athletes.

For athletes, these findings may have important implications for endurance performance. Greater reliance on fat as a fuel source and reduced carbohydrate use may help preserve glycogen stores, which are important for sustaining endurance performance. In rowing, where athletes perform prolonged submaximal efforts and often train multiple times per day, improved energy efficiency would help maintain performance across repeated training sessions. The implications of such an effect, and the implications for changes in body composition or prevalence of low-energy availability in endurance athletes are unknown.

Despite these trends, no significant differences were observed in blood lactate responses between conditions. These data suggests that PBM did not meaningfully alter lactate accumulation during the submaximal protocol, which contrasts data from Leal-Junior et al., (2009), who reported reductions in blood lactate following PBM in male soccer athletes after a maximal Wingate cycling test. However, lactate in that study was measured during post-exercise recovery, with PBM appearing to accelerate lactate clearance rather than improve exercise performance itself. This discrepancy between findings may therefore be explained by differences in exercise intensity, protocol design, timing of lactate assessment, and participant characteristics. The maximal nature of the Wingate protocol likely produced greater lactate accumulation than the progressive submaximal rowing protocol used in the present study.

Although Nampo et al., (2016) reported reduced lactate accumulation following pre-exercise laser therapy, no such effect was observed in the present study, although we did demonstrate that the lactate equivalent was significantly lower in PLA vs COMB condition. In their systematic review and meta-analysis of 16 randomised controlled and crossover trials, Nampo et al., (2016) reported that laser therapy was associated with improvements in exercise capacity, including increased repetitions, longer time to exhaustion, and reduced blood lactate concentrations. However, these authors also noted that LED-based interventions did not significantly affect lactate, power output, or time to exhaustion, suggesting that PBM outcomes may depend on the type of light source used. This discrepancy between these findings and the present study may further reflect differences in exercise intensity and protocol design, as lactate responses are generally more pronounced during high-intensity or maximal exercise than during the progressive submaximal rowing protocol used in current investigation.

Differences between the present findings and previous literature may also reflect variations in exercise modality, intensity, and protocol design. Many PBM studies have employed controlled laboratory-based assessments, such as time-to-exhaustion tests and isolated muscle protocols, which may be more sensitive to detecting performance-related changes. In contrast, the present study utilised a sport-specific submaximal rowing protocol, which may produce different physiological demands and response patterns. Differences in the dose of the PBM protocol could also explain some of the discrepancies observed with the light exposure duration, irradiance, and wavelengths all contributing to the physiological outcomes observed These methodological differences may contribute to the variability in reported PBM outcomes across studies.

In the present study, the ability to complete more stages indicated improved tolerance to progressive workload accumulation, even without changes in perceived exertion. The disconnect between improved exercise capacity and minimal changes in the perceptual and physiological outcome measures suggests that PBM may influence performance through mechanisms that are not fully reflected by traditional physiological measures. Importantly, this study addresses a key gap in the literature by investigating PBM in trained female rowers. As the majority of previous research has been conducted in male participants and in sports such as cycling and running, generalisability to other exercise modalities and women is limited.

Collectively, the findings of the present study suggest that PBM may improve submaximal rowing performance through mechanisms related to energy utilisation and fatigue resistance rather than through substantial alterations in whole-body physiological responses such as peak lactate and oxygen uptake. While previous research has reported mixed findings regarding metabolic markers such as blood lactate and VO_2, the consistency of improvements in exercise capacity across multiple studies does support the potential ergogenic role of PBM in endurance exercise.

Several limitations should be acknowledged. The PBM protocol was standardised; however, it may not represent the optimal dosage, particularly given the biphasic dose-response relationship described by Hamblin, (2017), where both insufficient and excessive doses may reduce effectiveness. In addition, the distance between participants and the light source was not strictly controlled, and minor differences of a few centimeters may have influenced irradiance and therefore delivered dose (Gonzalez et al., 2024). Variability in PBM delivery methods across the literature, including differences between laser and LED devices, may also contribute to inconsistent findings. Differences in penetration depth and energy delivery characteristics may influence physiological responses and complicate direct comparison between studies.

Overall, the present findings suggest that PBM may enhance submaximal rowing performance primarily through improvements in muscular endurance and fatigue resistance rather than through substantial changes in whole-body oxygen utilisation. Lanferdini et al. (2018) demonstrated significant improvements in time-to-exhaustion performance in competitive cyclists following PBM application, suggesting a potential role in delaying fatigue during prolonged exercise. Similar findings were reported by Vanin et al. (2015), whose systematic review identified consistent improvements in time-to-exhaustion and repetition performance across a range of exercise protocols. In addition to these performance-related outcomes, Leal-Junior et al. (2009) observed reductions in blood lactate concentrations and markers of muscle damage following exercise, indicating that PBM may influence metabolic and recovery processes. However, Nampo et al. (2016) noted that although laser therapy was associated with improvements in exercise capacity and reduced lactate accumulation, the overall quality of the available evidence remained limited.

Our findings highlight the potential of PBM as a pre-exercise strategy to support prolonged submaximal performance, particularly in sports requiring repeated high-volume training, such as rowing. In conclusion, PBM improved submaximal exercise capacity in trained female rowers, as evidenced by an increased number of intervals completed compared to placebo. However, this occurred without significant changes in VO_2 or blood lactate, suggesting that PBM may enhance performance through improved peripheral oxygen efficiency and enhanced contribution of oxidative metabolism at higher intensities leading to fatigue resistance rather than increased aerobic capacity. This hypothesis is supported by the observed reductions in blood glucose and trends towards lower RER indicating a shift in substrate utilisation, with reduced carbohydrate reliance and increased fat oxidation. Further research is required to refine PBM protocols and clarify the mechanisms underlying its effects in endurance performance.

Chapter Three

3.1 Summary & Future Directions

3.1.1 Summary

The aim of the present study was to investigate the acute effects of Red-Light Therapy (RLT), also referred to as Photobiomodulation (PBM), on submaximal rowing performance and associated physiological responses in trained female athletes. Using a randomised, double-blind, placebo-controlled crossover design, participants completed a standardised submaximal rowing protocol following exposure to red light, near-infrared light, combined red and near-infrared light, or placebo conditions. Physiological and perceptual outcome measures included oxygen uptake, blood lactate concentration, blood glucose concentration, respiratory exchange ratio, heart rate, and ratings of perceived exertion at exercise intensives relevant to endurance training and competition.

Overall, the findings suggest that acute PBM exposure may improve submaximal exercise capacity in trained female rowers. Specifically, participants completed a greater number of rowing stages in the red light and combined wavelength conditions when compared to placebo, indicating improved exercise tolerance and fatigue resistance. However, these improvements occurred without significant changes in VO_2, blood lactate concentration, or perceived exertion, suggesting that PBM may influence exercise performance through mechanisms not fully reflected by these traditional physiological markers.

In addition, PBM conditions were associated with lower blood glucose responses and trends towards lower RER values during exercise. These findings may indicate improved efficiency, potentially via altered substrate utilisation, including reduced reliance on carbohydrate metabolism and greater use of oxidative energy pathways during prolonged submaximal exercise. Although the exact physiological mechanisms remain unclear, the findings support previous literature suggesting that PBM may enhance muscular efficiency and exercise tolerance through cellular and metabolic adaptations such as increased peripheral muscle oxygenation and greater energy output from oxidative metabolism.

Importantly, this study contributes novel evidence to the growing body of PBM literature by investigating a female-only, rowing specific population performing sustained submaximal exercise at intensities just below the lactate threshold. Given the limited representation of female athletes and endurance-based sport-specific models within previous PBM research identified in the review of literature, the present findings provide valuable insight into the potential application of PBM within rowing and endurance sport settings. Collectively, the results support the ergogenic potential of PBM while also highlighting the need for further research to clarify optimal treatment parameters and the physiological mechanisms underlying observed performance benefits.

3.1.2 Strengths

A major strength of the present study was the use of a randomised, double-blind, placebo-controlled crossover design. This methodological approach reduced the risk of allocation bias and minimised both participant and researcher expectancy effects, thereby strengthening the internal validity of the study. The crossover design also allowed each participant to act as their own control, reducing the influence of inter-individual variability and improving the sensitivity of performance comparisons between conditions. The use of such a design is particularly important within exercise physiology research, where responses to interventions can vary considerably between individuals.

Another important strength was the inclusion of a female-only athletic population. Much of the existing PBM literature has focused predominantly on male participants or mixed-gender cohorts without sex-specific analysis. By specifically investigating trained female rowers, the present study addressed an identified gap within the literature and provided novel insight into PBM responses in an underrepresented population. Thus, the research enhances both the relevance and contribution of the study to the broader sport and exercise science literature.

The study also demonstrated strong sport-specific relevance with rowing-based submaximal exercise protocol. Previous PBM research has largely focused on cycling, running, resistance exercise, or laboratory-based time-to-exhaustion tests. In contrast, the present study investigated rowing-specific exercise demands within an endurance-focused context, at intensities within relevant exercise domains. Therefore, this work has strong ecological validity and practical application of findings for rowing athletes and coaches.

A further strength was the use of standardised testing procedures across all experimental conditions. All participants completed testing on the same Concept 2 Model D rowing ergometer under consistent environmental and testing conditions, while the same PBM device and treatment procedures were used throughout the study. Participants were also experienced rowers familiar with ergometer testing, reducing potential learning effects and improving consistency across trials.

Finally, the inclusion of both physiological and perceptual outcome measures provided a comprehensive assessment of exercise responses to PBM. The integration of variables such as VO_2, blood lactate, blood glucose, RER, heart rate, and RPE enabled a multidimensional evaluation of metabolic, cardiovascular, and perceptual responses during submaximal exercise. This approach strengthened the overall interpretation of the findings and provided greater insight into the potential mechanisms underpinning PBM-related performance improvements.

3.1.2 Future Recommendations

While the present study contributes valuable insight into the effects of PBM on submaximal rowing performance in trained female athletes, several areas should be considered in future research to further strengthen understanding within this field.

Firstly, future studies should aim to recruit larger sample sizes to improve statistical power and increase the generalisability of findings. The relatively small sample size in the present study may have limited the ability to detect subtle physiological differences between conditions, particularly for variables such as VO_2, blood lactate, and RER. Larger participant cohorts may provide confirmatory results regarding the positive effect on substrate metabolism and allow for greater investigation into individual variability in responsiveness to PBM. Such confirmation would also have important ramifications for both exercise performance and exercise interventions designed to improve body composition.

Secondly, future research involving female athletes should consider monitoring menstrual cycle phase, as fluctuations in oestrogen and progesterone concentrations may influence substrate utilisation, fatigue resistance, and physiological responses to exercise. Accounting for these factors may help reduce variability and provide a clearer understanding of the effects of PBM in female athletes. Hormonal fluctuations throughout the menstrual cycle are known to influence exercise metabolism, substrate utilisation, glycogen availability, and fatigue responses, which may affect endurance performance outcomes (Nicklas et al., 1989). As a result, menstrual phase may have contributed to variability in physiological responses during the present study and could potentially influence responsiveness to PBM interventions. We note that the experimental design would compensate for the effects of menstrual phase on the outcomes reported; however, larger scale trials are still warranted incorporating menstrual cycle tracking to improve testing consistency and provide greater understanding to gender-specific responses to PBM.

Future research should also investigate optimal PBM treatment parameters in greater detail. Variability in wavelength, dosage, irradiance, treatment duration, application timing, and treatment differ between studies. Given the proposed biphasic dose-response relationship associated with PBM, where both insufficient and excessive doses may reduce effectiveness, future studies should aim to establish standardized evidence-based protocols specific to endurance exercise and rowing performance. The PBM protocol was standardised across participants; however, individual differences like body composition, tissue thickness, and positioning relative to the device may have influenced the dose of light received. Therefore, the actual biological stimulus may have varied between participants.

Additionally, tighter control of participant behavior between testing sessions may improve reliability of future findings. Although participants were instructed to maintain consistent dietary intake, training load, and recovery habits, however variables such as stress and sleep can never be fully controlled and strictly standardised. Future investigations may benefit from implementing nutritional standardisation, training monitoring, sleep tracking, or recovery questionnaires to reduce external sources of variability that may influence exercise metabolism and fatigue.

Future studies should also examine the chronic effects of repeated PBM exposure over extended training periods. Chronic interventions may provide greater insight into whether PBM can influence long-term endurance adaptations rather than acute exercise responses alone. It remains possible that repeated PBM exposure over several weeks may produce larger physiological adaptations than those observed following a single treatment. The present study investigated only the acute effects of a single PBM exposure prior to exercise. Limited research has explored whether repeated PBM application over weeks or months may influence long-term endurance adaptations, recovery capacity, training quality, body composition, or performance progression. Future research should also examine elite and internationally competitive rowers, as physiological responses to PBM may differ in highly trained populations where performance margins are considerably smaller.

Finally, future research should continue to investigate PBM within sport-specific endurance settings such as rowing. Additional physiological measures, including muscle oxygenation, glycogen utilisation, mitochondrial markers, and neuromuscular fatigue assessments, may further improve understanding of the mechanisms underlying PBM-related performance changes. Expanding research into female endurance athletes and ecologically valid exercise models will remain important for improving the applicability and translation of PBM research within real-world sporting contexts.

To the authors' knowledge, this thesis presents the first study to investigate the acute effects of PBM on submaximal rowing performance in trained female rowers. The findings provide preliminary evidence that PBM may enhance exercise tolerance and influence metabolic responses during endurance exercise. Given the increasing interest in non-pharmacological performance interventions, these findings contribute important new knowledge to both the PBM and rowing literature while highlighting several avenues for future investigation.

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Appendix

Appendix A – Ethics Application Approval

The University of Waikato
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Gate 1, Knighton Road
Hamilton, New Zealand

Human Research Ethics Committee
Roger Moltzen
Telephone: +64021658119
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THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

12 August 2024

Martyn Beaven
Division of Health
By email: martyn.beaven@waikato.ac.nz

Dear Martyn

HREC(Health)2024#27 : The effect of red and near-infrared light on exercise performance in rowers

Thank you for your responses to the Committee feedback.

We are now pleased to provide formal approval for your project.

Please contact the Committee by email (humanethics@waikato.ac.nz) if you wish to make changes to your project as it unfolds, quoting your application number with your future correspondence. Any minor changes or additions to the approved research activities can be handled outside the monthly application cycle.

We wish you all the best with your research.

Regards,

____

Emeritus Professor Roger Moltzen MNZM
Chairperson
University of Waikato Human Research Ethics Committee

Appendix B – Participant Information Sheet

Participant Information Sheet
University of Waikato –Thesis Research

Research Title: Investigating the Effects of Acute Photobiomodulation on Submaximal Rowing Performance and Physiological Responses in Trained Female Rowers.

Researcher:
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Supervisor:
Dr Martyn Beaven
Division of Health
University of Waikato

Ethics Approval:
This study has received ethical approval from the University of Waikato Human Research Ethics Committee.

Purpose of Study:
This project is being undertaken as part of a master's thesis at the University of Waikato. The purpose of the study is to investigate the effects of Red-Light Therapy (RLT) on rowing performance and recovery in trained female athletes. RLT is a non-invasive modality that is gaining popularity in sport science; however, there is limited research examining its application in endurance-based, sport specific contexts such as rowing. This study aims to help address that gap by assessing both performance and recovery outcomes under controlled laboratory conditions.

What will Participation Involve?
If you agree to take part in this study, you will be required to attend five sessions at the University of Waikato's Human Performance Laboratory. These sessions will include:

- A VO_{2max} test to determine your aerobic capacity and individual training thresholds.
- Submaximal intensity intervals on the Concept 2 rowing ergometer.
- Exposure to Red Light Therapy under specific protocols before exercise.

Each sessions is expected to last between 45 – 60minutes, and sessions will spaced out over two weeks.

You will be fully briefed before each session, and you will have the opportunity to ask questions or withdraw at any time.

Possible Discomfort or Risks:

This study involves physical activity that may lead to some temporary fatigue or muscle soreness, similar to a regular rowing training session.

The VO_{2max} test is physically demanding and will require you to row to volitional exhaustion.

Red Light Therapy is a safe, non-invasive intervention. It uses low-level wavelengths of red and near-infrared light and has been shown to have minimal risk when used appropriately. IF at any point you feel uncomfortable or unwell, you are free to stop the session.

Confidentiality and Data Storage:

All information collected will be kept strictly confidential. Your data will be anonymized using a participant ID, and any identifiable details will be stored separately from performance data in a secure, password-protected system. Only the researcher and supervisor will have access to the data.

The results will be reported in summary form in the final thesis and may be used in academic presentations or publications. No personal or identifiable information will be included in any of these outputs.

Data will be stored securely for at least five years in accordance with University of Waikato research data management policies.

What happens after the study?

Once the data collection phase is complete, your anonymized data will be included in a larger dataset to evaluate overall effects of Red-Light Therapy on rowing performance. This data will inform the findings presented in a master's thesis and may contribute to journal publications or conference presentations. You will not be individually identified in any reports.

Reimbursement or Compensation:

There is no financial compensation for participation, this is completely voluntary.

Questions or Concerns:

If you have any questions about the study, please feel free to contact

Primary Researcher
Amelia Barrell
Email: Barrellamelia1@gmail.com

Supervisor
Dr Martyn Beaven
Division of Health
Email: Marytn.beaven@waikato.ac.nz

If you have any concerns about your rights as a participant, you may contact the University of Waikato Human Research Ethics Committee at (humanethics@waikato.ac.nz)

Appendix C – Informed Consent Form

THE UNIVERSITY OF WAIKATO
Te Whare Wānanga o Waikato

University of Waikato
Adams Centre
Tauranga

University of Waikato Sport Science Laboratory

Informed Consent Form

I (print name) ______________________ consent to participate in physiological assessment on the following terms:

1. I have read the Explanation of Physiological Assessment Procedures attached and have understood what I will be required to do. I have had the opportunity to ask questions and received satisfactory explanations about the assessment/s to be conducted.

2. I understand that I will be undertaking physical exercise at or near the extent of my physical capacity and there is possible risk in the physical exercise at that level, such as episodes of transient light-headedness, fainting, abnormal blood pressure, chest discomfort.

3. I understand that this may occur although the staff in this laboratory will take all proper care in the conduct of the assessment, and I fully assume that risk.

4. I understand that I can withdraw my consent, freely and without prejudice, at any time before, during or after testing.

5. I have told the person conducting the assessment of any illness or physical defect I have that may contribute to the level of that risk.

6. I understand that the information obtained from the test will be treated confidentially with my right to privacy assured. However, the information may be used for statistical or scientific purposes with privacy retained.

7. I release this laboratory and its employees from any liability for any injury or illness that I may experience during the assessment as well as any subsequent injury or illness that is connected to or to any extend influenced by the assessment.

8. I will indemnify this laboratory in respect to any liability it may incur in relation to any other person in connection with the assessment.

9. I hereby agree that I will present myself for testing in a suitable condition and have abided by any requirements for diet and activity prescribed to me by laboratory staff.

______________________________ ______________________
Athlete/Participant Signature Date

______________________ ______________________ ______________
Guardian name (required if < 16y) Athlete/Participant Signature Date

______________________ ______________________ ______________
Witness Name Signature Date

From Australian Institute of Sport, 2013, Physiological tests for elite athletes, 2nd ed. (Champaign, IL: Human Kinetics) and adapted by University of Waikato.

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Appendix D – Pre-Test Medical Questionnaire

THE UNIVERSITY OF WAIKATO
Te Whare Wānanga o Waikato

University of Waikato
Adams Centre
Tauranga

University of Waikato Sport Science Laboratory

Pre-Test Medical Questionnaire

First Name __________________ Surname __________________

Date of Birth __________________ Gender (circle) Male Female

Please answer the following questions by circling the appropriate response, or filling in the blank

1. How would you describe your present level of activity?

Sedentary Moderately Active Active Highly Active

2. How would you describe your present level of fitness?

Unfit Moderately Fit Trained Highly Trained

3. How would you consider your present body weight?

Underweight Ideal Slightly Over Very Overweight

4. Have you had to consult your doctor in the previous six months?

Yes No

If you have answered **Yes**, please give details

____

5. Are you presently taking any form of medication?

Yes No

If you have answered **Yes**, please give details

____

6. Do you have any allergies?

Yes No

If you have answered **Yes**, please give details

____

Please continue filling form over the page

University of Waikato
Adams Centre
Tauranga

University of Waikato Sport Science Laboratory

Pre-Test Medical Questionnaire

7. As far as you are aware, do you suffer from or have you ever suffered from? (circle if yes to any)

Diabetes	Asthma
Epilepsy	Bronchitis
Any form of heart complaint*	Raynaud's Disease
Marfens Syndrome*	Aneurysm/Embolism*
Anaemia	Haemophilia*

8. Is there a history of heart disease in your family?*	Yes	No
9. Do you currently have any form of muscle of joint injury?*	Yes	No
10. Have you had to suspend your training in the last two weeks?	Yes	No
11. Are you suffering from any known serious infections?	Yes	No
12. Have you had jaundice within the previous year?	Yes	No
13. Have you had any form of hepatitis?	Yes	No
14. Are you HIV antibody positive?	Yes	No
15. Have you ever been involved in intravenous drug use?	Yes	No

16. As far as you are aware, is there anything that might prevent you from successfully completing the tests that have been outlined to you?

Yes No

If you have answered **Yes**, please give details

Consent of Athlete/Participant

Athlete/Participant Signature Date

Guardian name (required if < 16y) Athlete/Participant Signature Date

Witness Name Signature Date

From Australian Institute of Sport, 2013, Physiological tests for elite athletes, 2nd ed. (Champaign, IL: Human Kinetics) and adapted by University of Waikato.

Appendix E – Rate of Percieved Exertion

Rating	Perceived Exertion
6	No exertion
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion