Jurnal SPORTIF: Jurnal Penelitian Pembelajaran
Vol. 11 No. 3, December 2025, pp. 529 - 546
https://doi.org/10.29407/js_unpgri.v11i3.27392

Experimental analysis of high-intensity interval training (HIIT) effects on vo_2max and recovery efficiency in football players

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Received: 27 October 2025; Revised: 12 November 2025; Accepted: 13 December 2025; Available online: 31 December 2025.

Abstract

HIIT is a fast and effective way to enhance aerobic performance and recovery capacity, particularly in sports such as professional football. This study investigates the impact of structured HIIT training on the aerobic capacity and recovery of professional footballers. This investigation examined the impact of a six-week structured HIIT program on aerobic capacity and post-exercise recovery in professional footballers. 24 male professional players aged 18-22 were randomly assigned to two groups: the HIIT group (n = 12) performed a 4x4-minute interval protocol at 90-95% HRmax with 3-minute active recovery at 60-70% HRmax, while the control group (n = 12) continued football training. Aerobic capacity (VO_2Max) was determined using the Yo-Yo Intermittent Recovery Test Level 1 (YYIR1), whereas HRR and RPE measured recovery. The HIIT group showed a substantial increase in VO_2Max ($p < 0.01$; $d = 1.3$) from 49.3 ± 4.1 to 54.8 ± 3.7 mL/kg/min, while the control group showed no significant change (48.9 ± 4.4 to 49.8 ± 4.2; $p = 0.21$). The HIIT group showed a 17% increase in post-exercise HRR ($p < 0.05$), indicating faster recovery and greater parasympathetic reactivation. These results suggest that HIIT enhances aerobic endurance and the body's ability to recover quickly after intense activity, helping football players maintain energy, reduce fatigue, and perform effectively in training and matches. This study shows that planned HIIT programs can assist coaches optimize training time and match performance for professional football players.

Keywords: High-intensity interval training, VO_2Max, heart rate recovery, professional football, aerobic performance.

How to Cite: Pratama, L., Saleh, M., Yanto, A. H., Kurniawan, W. P., & Permadi, A. (2025). Experimental analysis of high-intensity interval training (HIIT) effects on vo $_2$ max and recovery efficiency in football players. Jurnal SPORTIF : Jurnal Penelitian Pembelajaran, 11(3), 529–546. https://doi.org/10.29407/js_unpgri.v11i3.27392

Authors contribution: a – Preparing concepts; b – Formulating methods; c – Conducting research; d – Processing results; e – Interpretation and conclusions; f - Editing the final version.

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ISSN : 2477-3379 (Online)
ISSN : 2548-7833 (Print)

INTRODUCTION

Soccer requires significant aerobic endurance and swift recovery between successive high-intensity efforts over 90 minutes of competition, making VO_2Max and post-exercise recovery two fundamental objectives in performance training. VO_2Max reflects maximal aerobic capacity, while recovery indicators such as heart rate recovery (HRR), rating of perceived exertion (RPE), and blood lactate concentration provide insight into autonomic and metabolic regulation following exertion (Miao et al., 2024; Wulandari, 2022).

In recent years, High-Intensity Interval Training (HIIT) has emerged as one of the most effective and time-efficient conditioning strategies to meet these combined demands. HIIT has been consistently shown to improve VO_2Max and autonomic recovery regulation, making it particularly suitable for the intermittent, high-intensity nature of soccer performance (Buchheit & Laursen, 2013; Sitompul et al., 2025; Wittels et al., 2023). By inducing cardiovascular and metabolic adaptations, HIIT enables players to tolerate repeated high-intensity efforts while improving recovery between bouts, without extending total training duration, an important consideration in congested training schedules (Rahmania Putri et al., 2023; Umam et al., 2024).

The characteristic “run–stop–accelerate” movement pattern of soccer requires players to continuously alternate between aerobic and anaerobic energy systems during match play. This pattern closely mirrors the physiological principles of HIIT, which alternates brief periods of high-intensity exertion with structured recovery intervals. Consequently, the work–rest rhythm inherent in soccer competition aligns directly with HIIT-based conditioning models. Empirical evidence indicates that 4×4-minute high-intensity intervals enhance VO_2Max more effectively than continuous running or lactate-threshold training, while also improving stroke volume and soccer-specific work capacity (Daanen et al., 2012; Sugiono et al., 2023). Adjustments in interval duration, intensity, and recovery periods elicit superior cardiorespiratory and neuromuscular responses that better replicate match demands. Moreover, varying interval structures allow for positional specificity, whereby forwards benefit from shorter, sprint-oriented bursts, midfielders from longer, aerobic-dominant intervals, and defenders from shuttle-based patterns that simulate lateral and backward movements.

When HIIT protocols are systematically designed—through appropriate work-to-rest ratios, training modalities, and periodization—they reliably stimulate mitochondrial biogenesis, increase cardiac output, and enhance metabolic tolerance, collectively contributing to improved VO_2Max and greater tolerance for repeated high-intensity actions (Hadjarati & Massa, 2023; Mappaompo, 2023). Recovery markers such as HRR, RPE, and lactate clearance further allow practitioners to assess parasympathetic reactivation and overall physiological readiness. Evidence demonstrates that 4–6 weeks of HIIT can improve heart rate variability indices (e.g., RMSSD) and HRR, indicating positive autonomic nervous system adaptations associated with faster recovery and reduced fatigue risk (Crowley et al., 2022; Ma et al., 2023). Active recovery strategies have also been shown to accelerate lactate clearance more effectively than passive rest among soccer players, reinforcing the role of HIIT in supporting both performance and recovery processes (Katoch et al., 2025; Nurkadri et al., 2021).

The Indonesian context further amplifies the relevance of HIIT-based conditioning. The majority of Indonesian football players, particularly at youth, regional, and developmental levels, are aged between 13 and 21 years and often train under constrained conditions, including non-standard playing fields, limited access to GPS tracking systems, rudimentary heart-rate monitoring, inconsistent physiotherapy support, and irregular conditioning periodization (Akbar, Karim, Zakaria, et al., 2024). Under such circumstances, fundamental physiological indicators such as HRR and RPE become essential tools for daily training assessment. Domestic studies consistently report that HIIT and interval-based training improve VO_2Max and produce favorable HRR profiles in adolescent and young

ISSN : 2477-3379 (Online)
ISSN : 2548-7833 (Print)

adult football players, even when implemented through simple field-based protocols (Bahtra et al., 2023). Regional evidence from Southeast Asia further suggests that HIIT conducted in hot and humid climates enhances cardiovascular adaptation due to heat-induced metabolic stress, providing additional physiological advantages for Indonesian athletes (Akbar, Karim, & Zakaria, 2024).

Despite these encouraging findings, several gaps remain within national research. Most Indonesian studies emphasize improvements in VO_2Max while rarely incorporating recovery-related variables such as HRR, HRV, or post-exercise lactate, despite their importance for monitoring fatigue and preventing overtraining in juvenile and semi-professional players. Methodological inconsistencies, ranging from variations in work-to-rest ratios to differences in intervention duration and training modality, also obscure the determination of the most effective HIIT dosage for Indonesian football settings. Environmental stressors related to heat and humidity further complicate recovery responses, underscoring the need for investigations that concurrently evaluate aerobic capacity and recovery adaptation.

Intermittent performance assessments such as the Yo-Yo Intermittent Recovery (YYIR) test are widely employed in soccer due to their sensitivity to changes in repeated high-intensity performance and their ability to replicate match demands (Bok & Foster, 2021; Kunz et al., 2019). The YYIR test enables simultaneous estimation of VO_2Max and assessment of HRR within a single testing session, directly supporting the dual physiological indicators examined in this study. Indonesian research has demonstrated the applicability of YYIR in juvenile and amateur athletes, showing strong associations with aerobic capacity and match-running parameters (Chandra et al., 2025). Nevertheless, the interpretation of YYIR outcomes requires caution, as performance may be influenced by factors such as pacing familiarity, fitness level, gender, and environmental conditions. Accordingly, integrating YYIR with recovery biomarkers such as HRR, RPE, and lactate measures offers a more

 https://doi.org/10.29407/js_unpgri.v11i3.27392
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comprehensive representation of aerobic and recovery dynamics, particularly under HIIT-based conditioning (Fang et al., 2021).

Based on these considerations, the present study investigates the effects of a structured HIIT program on VO_2Max and post-exercise recovery in soccer athletes using a controlled pre–post experimental design. By concurrently examining changes in aerobic capacity and recovery indicators, including HRR and, where applicable, RPE and lactate within Indonesian football contexts, this study addresses existing methodological gaps. It contributes both theoretical insight and practical, resource-efficient conditioning guidance for clubs and academies operating under real-world constraints.

METHOD

This study employed an experimental pre-test–post-test control group design to examine the effects of High-Intensity Interval Training (HIIT) on VO_2Max and post-exercise recovery in soccer athletes. A total of 24 male participants (aged 18–22 years) from a professional soccer academy were recruited. All participants were medically cleared, had a minimum of two years of structured training experience, and provided written informed consent prior to participation. Ethical approval was obtained from the Muhammadiyah University Sorong Research Ethics Committee (No. UMSORONG/C-3/2025/118).

Participants were randomly assigned to either the HIIT group or the control group using a simple randomization procedure, in which each athlete selected a coded number to ensure equal probability of group allocation. This approach minimized selection bias and supported baseline equivalence between groups. The control group continued to follow the academy's standard training routine, while the HIIT group undertook a structured six-week intervention.

The HIIT program consisted of three non-consecutive training sessions per week. Each session included a 10-minute warm-up, followed by four 4-minute high-intensity intervals performed at 90–95% of maximal heart rate (HRmax), interspersed with 3-minute active recovery periods at

60–70% HRmax, and concluded with a 10-minute cool-down. Training loads were monitored using Polar H10 heart rate sensors, which demonstrate high reliability for beat-to-beat heart rate monitoring in athletic populations (ICC = 0.96–0.99; r > .98). All drills were designed to simulate soccer-specific sprinting and recovery demands.

To control potential confounding variables, participants were instructed to refrain from additional external training, maintain consistent dietary intake, and adhere to regular hydration and sleep routines throughout the intervention. Compliance was monitored through weekly activity logs, sleep checklists, and verbal confirmation prior to each session, with any deviations documented in a training diary.

Aerobic capacity and physiological recovery were defined as the primary outcome variables. VO_2Max was assessed using the Yo-Yo Intermittent Recovery Test Level 1 (YYIR1), a field-based test with high test–retest reliability (ICC > .90) and strong construct validity for soccer-related endurance assessment (Bok & Foster, 2021). Post-exercise recovery was evaluated using the one-minute Heart Rate Recovery (HRR_1min), defined as the difference between the peak heart rate at test completion and the heart rate measured 60 seconds post-exercise. HRR was recorded using the Polar H10 device, which has an error rate of less than 1 bpm in short-term recovery measurements. Perceived exertion was assessed immediately after testing using the Borg 6–20 Rating of Perceived Exertion (RPE) scale, a validated measure of internal training load.

All pre- and post-intervention assessments were conducted under controlled environmental conditions, with the ambient temperature maintained between 28 °C and 30°C and the relative humidity between 70% and 80%. Testing sessions were scheduled between 4:00 p.m. and 6:00 p.m. to minimise circadian variability in physiological responses. Participants were encouraged to follow similar dietary and sleep patterns and to abstain from stimulants prior to testing.

Statistical analyses were performed using SPSS version 26. Descriptive statistics were calculated for all variables, followed by assumption testing using the Shapiro–Wilk and Levene tests. Paired t-tests were applied to examine within-group pre–post changes, while independent t-tests were used to compare post-intervention differences between groups. Two-way ANOVA was not employed, as the study focused on isolated pre–post changes rather than interaction effects across multiple time points. Effect sizes were calculated using Cohen's d. An a priori power analysis (power = 0.80, $\alpha = 0.05$) indicated that a sample size of 12 participants per group was sufficient to detect medium-to-large physiological effects associated with HIIT interventions. Statistical significance was set at $\alpha = 0.05$.

RESULT

Shapiro–Wilk normality tests and Levene's homogeneity tests indicated that all baseline variables (VO_2Max, HRR, RPE) met statistical assumptions ($p > 0.05$). Compliance with these assumptions confirms that both groups began the study with equivalent physiological conditions, ensuring the validity of post-intervention comparisons. The data analysis commenced with descriptive statistics to delineate the participants' basic characteristics prior to the intervention. The preliminary data were crucial to confirm that the physiological and anthropometric conditions of both groups were equivalent prior to the administration of medication. The analytical results indicate that both the HIIT group and the control group exhibit reasonably uniform features for age, height, weight, body mass index (BMI), and physiological parameters, including initial VO_2Max, HRR, and RPE. The mean age of participants in the HIIT group was 20.1 ± 1.3 years, while in the control group it was 19.9 ± 1.4 years. The mean height of participants was 170.6 ± 4.9 cm for the HIIT group and 171.1 ± 5.1 cm for the control group. Weight and BMI exhibited no statistically significant variations ($p > 0.05$). The initial values of VO_2 Max, HRR, and RPE in both groups were not statistically different, indicating that all participants started the trial with comparable fitness levels.

ISSN : 2477-3379 (Online)
ISSN : 2548-7833 (Print)

Table 1. Initial Characteristics of Participants (Mean ± SD)

Variable	HIIT Group (n=12)	Control Group (n=12)	p-value
Age (years)	20.1 ± 1.3	19.9 ± 1.4	0.68
Height (cm)	170.6 ± 4.9	171.1 ± 5.1	0.72
Body Weight (kg)	65.8 ± 5.4	66.2 ± 5.1	0.81
BMI (kg/m²)	22.6 ± 1.4	22.7 ± 1.5	0.88
VO_2Max (mL/kg/min)	49.3 ± 4.1	48.9 ± 4.4	0.74
HRR (beats/minute)	22.8 ± 5.1	21.9 ± 4.8	0.65
RPE	15.2 ± 1.1	15.0 ± 1.2	0.59

Table 1 presents the baseline characteristics of the participants and shows no significant differences between the HIIT and control groups across all demographic and physiological variables ($p > 0.05$). This finding confirms that both groups were comparable prior to the intervention, thereby fulfilling the prerequisite for a valid evaluation of training effects. All 24 participants completed the entire six-week intervention period, and no missing data were observed for any outcome variable. Consequently, the analysis was conducted using the full sample (n = 24) under a per-protocol approach, ensuring that the reported outcomes accurately represent physiological changes among participants who fully adhered to the intervention. Statistical assumption testing further supported data suitability, as the Shapiro–Wilk normality test and Levene's homogeneity test indicated that all variables met the required assumptions ($p > 0.05$), allowing valid between-group comparisons.

Regarding training effects, the results summarized in Table 2 demonstrate that the HIIT group experienced a substantial improvement in aerobic capacity, with VO_2Max increasing from 49.3 ± 4.1 to 54.8 ± 3.7 mL/kg/min, corresponding to a Δ = +5.5 mL/kg/min and a large effect size (d = 1.3; $p < 0.01$). In contrast, the control group showed only a minimal increase in VO_2Max (Δ = +0.9 mL/kg/min), which was not statistically significant ($p = 0.21$). Rather than reiterating the numerical values already presented in Table 2, the key implication of these findings is that the structured HIIT protocol elicited an improvement of more than 10% in aerobic capacity. Such a magnitude of change is practically meaningful, as it is associated with enhanced high-intensity running capacity, improved tolerance to repeated efforts, and greater match endurance in soccer athletes.

Table 2. Comparison of Pretest–Posttest VO_2Max (mL/kg/min)

Group	Pre-test (Mean ± SD)	Post-test (Mean ± SD)	p-value	Effect Size (d)
HIIT (n=12)	49.3 ± 4.1	54.8 ± 3.7	< 0.01	1.3
Control (n=12)	48.9 ± 4.4	49.8 ± 4.2	0.21	0

As shown in Table 2, the HIIT group demonstrated greater improvements in both aerobic capacity and post-exercise recovery compared with the control group, reflecting stronger physiological readiness for repeated high-intensity actions. Specifically, Table 2 indicates a clear enhancement in VO_2Max following the intervention, with the HIIT group exhibiting a significant increase from 49.3 ± 4.1 to 54.8 ± 3.7 mL/kg/min ($p < 0.01$; $d = 1.3$), whereas the control group showed no meaningful improvement ($p = 0.21$; $d = 0.2$). The absolute change in VO_2Max further emphasizes this contrast, as the HIIT group achieved a +5.5 mL/kg/min increase compared with only +0.9 mL/kg/min in the control group.

All 24 participants completed the six-week intervention without dropout, and no missing VO_2 Max data were recorded at either the pre-test or post-test stages. Accordingly, the analysis was conducted using the entire sample (n = 24) under a per-protocol framework, ensuring that the reported outcomes accurately reflect physiological adaptations among athletes who fully adhered to the training program. Collectively, these findings suggest that a six-week HIIT intervention is more effective in enhancing aerobic capacity than traditional soccer training. From a practical standpoint, the concurrent improvements in aerobic capacity and recovery capacity support the integration of HIIT into weekly training microcycles to improve repeated-sprint performance, sustain work rate, and facilitate faster recovery between efforts, capabilities that are fundamental to the intermittent demands of soccer, particularly in teams with limited training time.

Jurnal SPORTIF: Jurnal Penelitian Pembelajaran, 11 (3) 2025 | 529-546
ISSN : 2477-3379 (Online)
ISSN : 2548-7833 (Print)

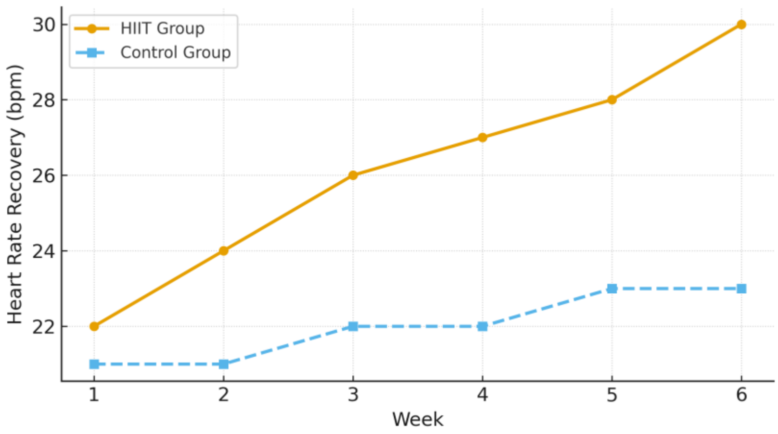

Figure 1. Heart Rate Recovery (HRR) Trends in the HIIT and Control Groups

Figure 1 illustrates a clear improvement in heart rate recovery (HRR) following the intervention, with the HIIT group demonstrating a 17% increase in HRR trends ($p < 0.05$), indicating enhanced parasympathetic reactivation and improved post-exercise autonomic balance. This trend is reflected quantitatively by an increase in HRR values from 22.8 ± 5.1 bpm to 26.7 ± 4.8 bpm, with a broader pattern showing progression from approximately 22 bpm to nearly 30 bpm across the intervention period. In contrast, the control group exhibited only minor changes, remaining relatively stable from 21.9 ± 4.8 bpm to 22.4 ± 4.6 bpm, demonstrating that traditional training did not elicit comparable recovery-related adaptations. Collectively, these patterns confirm the superior influence of high-intensity interval training on autonomic regulation and cardiovascular recovery efficiency after high-intensity exertion.

In parallel with recovery-related improvements, the structured HIIT program also produced substantial gains in aerobic capacity. The HIIT group exhibited a significant increase in average VO_2Max from 49.3 ± 4.1 to 54.8 ± 3.7 mL/kg/min ($p < 0.01$; $d = 1.3$), whereas the control group showed only a negligible change from 48.9 ± 4.4 to 49.8 ± 4.2 mL/kg/min ($p = 0.21$). When interpreted together, the concurrent enhancement of VO_2 Max and HRR indicates that HIIT induces meaningful physiological adaptations, encompassing increased aerobic capacity, improved balance of the autonomic nervous system, and faster recovery following intense activity. The magnitude of these improvements reflects enhanced autonomic control, reduced post-exercise fatigue, and greater readiness for subsequent training sessions, thereby demonstrating that a structured HIIT intervention is more effective than standard training in improving both aerobic performance and recovery efficiency.

DISCUSSION

This study demonstrates that a six-week HIIT program produced substantial improvements in both VO_2Max and post-exercise heart rate recovery (HRR) compared with conventional training. The approximately 11% increase in VO_2Max aligns with international and regional studies reporting improvements of 8–12% following comparable 4×4-minute HIIT protocols, indicating that the magnitude of adaptation observed is both expected and physiologically meaningful. Likewise, the 17% enhancement in HRR exceeds the 10–15% improvements commonly reported in previous HIIT research, suggesting a stronger autonomic response and faster parasympathetic reactivation among the participants. Together, these adaptations contribute to reduced fatigue accumulation, improved tolerance to repeated high-intensity efforts, and more consistent performance across congested competitive schedules, outcomes that are particularly relevant for soccer players operating under high match density.

Consistent with global evidence (Bici & Kasa, 2025; Fang et al., 2021), the present findings confirm that HIIT elicits rapid aerobic and autonomic adaptations in team-sport athletes. Importantly, these results also align with improvements reported in Indonesian youth and sub-elite players (Arianto & Setyawan, 2019; Bahtra et al., 2023), thereby reinforcing the external validity of the intervention across different performance levels. This relevance is amplified in the Indonesian football ecosystem, where academies such as Askot Surabaya Elite Youth, PPLP Papua Barat, and several Liga 3 East Java teams frequently operate with limited sports science infrastructure and inconsistent conditioning periodization. Under such constraints, HIIT represents a highly feasible

ISSN : 2477-3379 (Online)
ISSN : 2548-7833 (Print)

conditioning strategy, as it requires minimal equipment while producing meaningful physiological adaptations (Reinhardt et al., 2020).

A key novelty of this study lies in its concurrent evaluation of VO_2Max and HRR within a single, structured HIIT protocol, an approach rarely documented in Indonesian football research, which has traditionally emphasised aerobic capacity alone. The integration of aerobic and autonomic indicators under hot–humid field conditions enhances the ecological validity of the findings. It provides dual physiological insight that better reflects real-world training environments faced by local clubs and academies.

From a physiological perspective, the observed improvements align with well-established theories of HIIT-induced central and peripheral adaptations. High-intensity intervals stimulate mitochondrial biogenesis through PGC-1α activation and enhance stroke volume via repeated hemodynamic stress, collectively explaining the observed increases in VO_2Max (Hardinata et al., 2023; Hostrup et al., 2022). Enhanced oxidative enzyme activity and improved buffering capacity further support sustained high-intensity performance characteristic of soccer. These empirical gains therefore closely match theoretical predictions of HIIT-driven adaptations, reinforcing the scientific validity of the intervention.

The pronounced improvement in HRR indicates enhanced modulation of the autonomic nervous system, characterised by greater vagal reactivation and reduced sympathetic dominance. Such adaptations are commonly observed after 4–6 weeks of HIIT and are associated with improved heart rate variability indices, particularly RMSSD (Casanova-Lizón et al., 2022; Shushan et al., 2023). HRR also serves as a practical readiness indicator, enabling coaches to adjust next-day training intensity and recovery strategies based on athletes' physiological responses (Laursen & Buchheit, 2019). Indonesian studies demonstrating improved lactate clearance through active recovery further support the simultaneous enhancement of metabolic and autonomic recovery pathways, especially under tropical climate stress where rapid autonomic stabilization is essential to prevent excessive fatigue.

The 4×4-minute HIIT protocol employed in this study mirrors formats widely recognized as effective in both elite and sub-elite soccer contexts (Hov et al., 2023). Local academies frequently apply comparable field-based variations, including shuttle-run HIIT, small-sided interval games (3v3 or 4v4), and repeated half-field runs. For instance, 15 m shuttle HIIT is commonly used in Liga 3 East Java teams, offering high-intensity stimulus without extensive pitch requirements. Such drills closely replicate match demands and allow consistent implementation within weekly microcycles, even in resource-limited settings.

Future training cycles may benefit from incorporating longitudinal biomarkers such as heart rate variability (RMSSD, LF/HF ratio) and blood lactate trends to improve the interpretation of autonomic modulation and metabolic load over time. Even basic field-based lactate testing or smartphone-based HRV monitoring can enhance load management, facilitate early detection of overreaching, and inform individualised training adjustments. These approaches would support more precise athlete development pathways across Indonesian football systems.

At the policy level, the present findings align with Indonesia's DBON framework, which emphasizes scientifically grounded conditioning strategies for national athlete development. Standardizing HIIT-based periodization across youth academies, Liga 3 training centers, and regional PPLP programs may promote more uniform aerobic development and recovery efficiency, while facilitating systematic monitoring across priority sports groups.

Theoretically, this study contributes to sport physiology by integrating aerobic (VO_2Max) and autonomic (HRR) adaptations within a single HIIT intervention conducted in tropical training environments. Unlike prior research that often examined these variables independently, the combined evaluation presented here offers a more holistic understanding of adaptation mechanisms in intermittent sports. Practically, the study provides clear guidance for coaches working in resource-constrained contexts by outlining feasible HIIT formats, recovery monitoring strategies, and workload management tools that can be implemented without advanced technology.

Several limitations should be acknowledged. The homogeneous sample of male athletes aged 18–22 years restricts generalizability, and the six-week duration captures only short-term adaptations without addressing long-term retention across a full competitive season. Additionally, the absence of longitudinal lactate and HRV measurements limits the interpretation of sustained autonomic and metabolic adaptation. While the Yo-Yo Intermittent Recovery test is suitable for soccer-specific assessment, future studies employing direct breath-by-breath VO_2 Max measurements would further enhance physiological precision.

Future research should extend intervention duration, compare different HIIT configurations within unified periodization models (e.g., 15″/15″, 30″/30″, sprint-interval training), and integrate strength or power training to examine transfer effects to match performance. Expanding samples to include female athletes and varied competitive levels will further enhance applicability. Despite these limitations, the present study provides a distinctive, contextually grounded contribution by bridging global HIIT evidence with Indonesian football realities, thereby strengthening the scientific basis for practical conditioning and recovery strategies in local clubs and academies.

CONCLUSION

A study found that a 4x4-minute HIIT program improves the physiological performance of football players, with an approximate 11% increase in VO_2Max and a 17% increase in HRR after six weeks of training. These adaptations include improved oxygen utilisation, enhanced cardiac function, and autonomic reactivation, demonstrating that HIIT is a realistic and efficient soccer conditioning strategy. Many Indonesian football teams train with inadequate facilities and need field-based conditioning methods that may be used on standard pitches without additional equipment. Thus, youth academies, regional clubs, and semi-professional teams can use HIIT to improve aerobic capacity and recovery efficiency under real-world training conditions.

This study is unique in evaluating aerobic capacity (VO_2Max) and post-exercise recovery (HRR) in a single HIIT session, a departure from traditional Indonesian football research that mostly focuses on aerobic capacity. This study utilises both metrics to gain a deeper understanding of how HIIT enhances performance readiness and recovery dynamics in applied training. The findings expand the sport-science literature by demonstrating aerobic and autonomic adaptations that are still scarce in the national context.

Future research should expand on these findings by analyzing more extended intervention periods, comparing HIIT configurations (e.g., 15/15, 30/30, sprint-interval protocols), and including diverse athlete populations like females, youth academies, and elite professionals. Longitudinal physiological markers, such as heart rate variability indices, lactate kinetics, neuromuscular stress, and sleep-recovery biomarkers, would enhance evidence-based HIIT periodisation and comprehension of long-term adaptation mechanisms. These advances will improve conditioning tactics and standardize, context-appropriate HIIT in Indonesian football.

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