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ORIGINAL PAPER

A field-based analysis of artificial football pitches with different vegetal infills

Jorge Garcia-Unanue[1] · **Jose Luis Felipe**[1,2] · **Katie Mills**[3,4] · **Mickael Benetti**[3] · **Alvaro Medina-Sanchez**[1] · **Johsan Billingham**[3] · **Leonor Gallardo**[1] · **Antonio Alonso-Callejo**[5]

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Abstract

This study compared the effects of artificial football surfaces incorporating different vegetal infills on players' physical performance. It also examined how these systems differed from natural grass and from traditional third-generation artificial turf using recycled rubber from end-of-life tyres. A quasi-experimental field design was conducted with 30 amateur male football players who completed a standardised battery of sprint, agility, and fatigue tests across seven surface types: five artificial turfs with vegetal infills (processed olive pits, pinecone granules, corn cob, cork cob, and wood chips), one with rubber infill, and one natural grass pitch. Performance metrics included sprint velocity, acceleration, force, repeated sprint ability, fatigue countermovement jump, and change of direction time. All artificial turf systems complied with the FIFA Quality Programme for Football Turf and were verified using FIFA-standardised mechanical test procedures for surface–player interaction. Mechanical properties were assessed at five locations per field using standardised test methods, including shock absorption, deformation, energy return, and rotational resistance. Sprint performance was broadly comparable across all surfaces, with players achieving similar maximal sprint velocities regardless of infill type or reference surface (natural grass or ELT). Wood chip infill was linked to lower force production and slower sprint times. No single vegetal infill outperformed others across all variables, highlighting the need for individual evaluation. These findings indicate that some vegetal infills may provide performance characteristics comparable to existing systems, although their suitability for wider implementation will depend on further long-term, environmental, and context-specific evaluations.

Keywords Sports surfaces · Vegetal infills · Athlete kinetics · Neuromuscular fatigue · Soccer

Abbreviations

5-0-5 time	Total time to complete the 5-0-5 agility test
ACCmax	Maximum acceleration in 40-m sprint test
AG	Artificial ground
CMJ	Countermovement jump
COD	Change of direction
Corn	Corn residue
Cork	Cork granules
ELT	End-of-life tires
EOR	Energy of restitution
ER	Energy return
FG	Firm ground
F_0	Theoretical maximum force
HG	Hard ground
NG	Natural grass
OP	Olive pits
PA	Peak absorption
PC	Pine cone

✉ Jose Luis Felipe
Joseluis.felipe@uclm.es

[1] IGOID Research Group, Physical Activity and Sport Sciences Department, Universidad de Castilla- La Mancha, Avda. Carlos III, s/n, Building 23, 45071 Toledo, Spain

[2] Performance Analysis Department, Unión Deportiva Las Palmas, Las Palmas de Gran Canaria, Spain

[3] Football Innovation Subdivision, Fédération Internationale de Football Association (FIFA), Zurich, Switzerland

[4] Sports Engineering Research Group, Sheffield Hallam University, Sheffield, UK

[5] Department of Sports Sciences. Faculty of Medicine, Health and Sports, Universidad Europea de Madrid, Madrid, Spain

PD	Peak deformation
RSA	Repeated sprint ability
$\mathrm{RSA}_{\mathrm{Acc-diff}}$	Difference in maximum acceleration between first and last sprint
$\mathrm{RSA}_{\mathrm{Best-t}}$	Best sprint time in RSA test
$\mathrm{RSA}_{\mathrm{CMJ-diff}}$	Difference in countermovement jump height before and after RSA test
$\mathrm{RSA}_{\mathrm{Dec-diff}}$	Difference in maximum deceleration between first and last sprint
$\mathrm{RSA}_{\mathrm{Time-diff}}$	Percentage difference between first and last sprint times
$\mathrm{RSA}_{\mathrm{V-Loss}}$	Velocity loss across sprints
$\mathrm{RSA}_{\mathrm{Vmax-diff}}$	Difference in maximum velocity between first and last sprint
RR/PT	Rotational resistance / Peak torque
SA	Shock absorption
SG	Soft ground
VD	Vertical deformation
Vmax	Maximum velocity in 40-m sprint test
V_0	Theoretical maximum velocity
WC	Wood chips

1 Introduction

The mechanical and structural characteristics of the playing surface—such as pile height, fibre density, elastic layer composition, and infill type—play a crucial role in determining football players' physical performance and perceived exertion [1, 2]. These components influence key mechanical properties including shock absorption, vertical deformation, energy restitution, and rotational resistance, which govern how forces are transmitted during sprinting, cutting, and jumping actions [3, 4]. Variations in these characteristics can affect performance indicators such as acceleration, speed, and fatigue, as well as players' subjective experience during training and competition [3, 4]. Understanding these effects is essential for optimising performance and minimising injury risk, particularly in the context of the increasing use of artificial turf systems in both professional and amateur football [5].

Artificial turf football fields have become playing surfaces of major international relevance. Their development stabilized with the arrival of third generation (3G) fields, which introduced standardised structural components—such as longer pile height, elastic shock pads, and performance infills—that improved player-surface interaction, enhanced safety, and met FIFA quality standards, reducing variability and promoting global adoption [6, 7]. In this sense, previous studies have shown that the mechanical properties of artificial turf systems are largely determined by the type of performance infill [8–10] and influence players' physical responses and subjective perceptions [2, 3, 11]. Previous studies comparing different infill materials within artificial turf systems designed to meet the FIFA Quality Programme requirements have shown that several alternative infills can also fall within the permitted performance range when installed in systems engineered to comply with these standards [2, 6]. Among these alternatives, vegetal infills refer to plant-based or agro-industrial granular materials—such as cork, olive pits, pinecone granules, or wood chips—used as performance infills in place of traditional rubber. This suggests that, despite differences in composition, some vegetal infills may achieve mechanical properties comparable to conventional rubber-based infills when designed to meet these standards. While these findings suggest that alternative infill solutions may offer comparable mechanical performance to conventional materials, such as End-of-Life Tires (ELT), the scientific literature still lacks systematic comparisons analysing key performance indicators with players across fields with vegetal infills and other traditional football surfaces. Although FIFA-compliant systems fall within a defined range of mechanical properties, the specific type and quantity of performance infill can influence player–surface interaction. Therefore, even if two systems use infills from the same category (e.g., ELT-based or vegetal materials), they should not be assumed to perform identically. Differences in infill composition, particle size, depth, and installation practices can influence mechanical behaviour and, consequently, athletic performance.

This need for further research has become more urgent following recent regulatory developments in the European Union. In 2023, the European Commission adopted a restriction under the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation that bans the sale of products containing intentionally added microplastics, including the granular infill material used in artificial turf pitches [12]. This has had an impact on artificial sports turf, as the main performance infill used in 3G surfaces is composed of microplastics, especially ELT [13]. The regulation, promoted by the European Chemicals Agency (ECHA), grants a transition period until 2031 for the replacement of these materials, which are currently the largest single source of intentionally released microplastics in the environment [14].

This regulatory shift is expected to accelerate the development and implementation of new, alternative vegetal infills derived from agro-industrial or natural materials [15]. However, for these new materials to be viable, they must not only comply with environmental regulations but also meet the demands of sports performance and player safety. Infill alternatives must demonstrate adequate mechanical behaviour, provide positive player perceptions—such as comfort, stability, and confidence in traction—and minimise injury risk. These surface-related factors are important because they influence athletes' willingness to adopt new surfaces, affect movement efficiency, and can reduce the likelihood of non-contact injuries associated with poor grip or excessive hardness. Laboratory studies suggest that the type of infill can affect the player-surface interaction differently depending on its elastic capacity, especially its resistance to rotation [16, 17]. Within the safety recommendations for the surface, harder surfaces can lead to better performance in short duration and high intensity actions [2]. However, studies with athletes in controlled exposures show that the elastic behaviour of the surface and the balance between its properties affect the accumulated fatigue and physiological demands during long-term efforts [18].

Therefore, the type of infill in artificial turf can affect performance in different ways, and when considered together with other surface components—such as pile height and shock pad—it can influence key aspects of playing behaviour. It is essential to evaluate these new systems through a multidisciplinary lens that includes sport performance, sport engineering, physiological response and fatigue. In this sense, the aim of this study was to compare how fields with different vegetal infills affect players' kinetic performance and to assess the differences between these fields and the most common football surfaces: natural grass and traditional artificial turf with ELT as performance infill.

2 Methods

2.1 Study design

A cross-sectional, quasi-experimental field study with repeated-measures within-subject design was conducted involving amateur male football players from Spain. Participants completed a standardised performance testing protocol across different artificial turf systems with vegetal infills and natural grass. The study protocol was registered in the ClinicalTrials.gov database (NCT06939218) and approved by the Research Ethics Committee of University of Castilla-La Mancha (Spain), in accordance with the ethical principles of the Declaration of Helsinki (CEIS-2024-29441).

2.2 Participants

The sample consisted of 30 male football players (19.55 ± 1.74 years; 69.90 ± 7.58 kg; 174.45 ± 6.80 cm), all with a minimum of five years' experience playing and training on artificial turf and currently competing in the Tercera Federacion (Spanish 5th division) or national under-21 category, which represents the highest regional level and is predominantly played on artificial turf. The sample size was determined through a priori power analysis using GPower software (version 3.1), assuming an alpha level of 0.05, statistical power of 0.80, and an expected medium effect size (f = 0.25) for repeated-measures ANOVA. The analysis indicated that a minimum of 28 participants was required; therefore, 30 players were recruited to account for potential dropouts. Recruitment was carried out in collaboration with the Faculty of Sport Sciences at the University of Castilla-La Mancha (Spain). Players were recruited from different clubs, which, while necessary to ensure an adequate sample size, also enhanced the ecological validity of the study by capturing a broader range of training environments and playing styles within the same competitive level. Players with active or chronic injuries were excluded. All participants provided written informed consent and agreed to comply with the study protocol.

Following recruitment, participants were randomly assigned into two subgroups of 15 players each. Testing was conducted in groups on half-pitch areas, utilizing the designated surface assigned for each session.

2.3 Procedure

The testing protocol was carried out during the first quarter of 2025 (from the 10th of February to the 25th of April) to ensure that participants were in a consistent physical condition, having undergone several months of regular training prior to the assessments. Prior to data collection, one familiarisation session was held on a football pitch not included in the study, to ensure players were familiar with the testing protocols. Sessions were then held consecutively on Tuesdays between 12:00 and 14:00 under stable weather conditions (clear skies, a wind speed between 0.0 and 0.1 m/s, and ambient temperature of approximately 20° ± 5 °C). All sessions were supervised by 5 experienced researchers, with extensive experience in football-specific performance testing procedures, to ensure strict adherence to the protocol. Participants were instructed to avoid strenuous exercise and competitive matches during the 24 h preceding each testing session to minimize residual fatigue.

Each participant was evaluated on seven different surface systems: one traditional artificial turf with rubber infill made from ELT, one natural grass pitch (NG), and five artificial turf systems with vegetal infills, including olive pits granules (OP), pinecone granules (PC), corn residue granules (Corn) cork granules (Cork) and wood chips granules (WC) (Fig. 1). The NG pitch was maintained according to FIFA Quality Programme standards and complied with the FIFA Natural Turf Guidelines for football practice. The surface consisted of a typical cool-season species blend and was maintained at a mowing height of 25–30 mm. All artificial turf systems were commercially available configurations

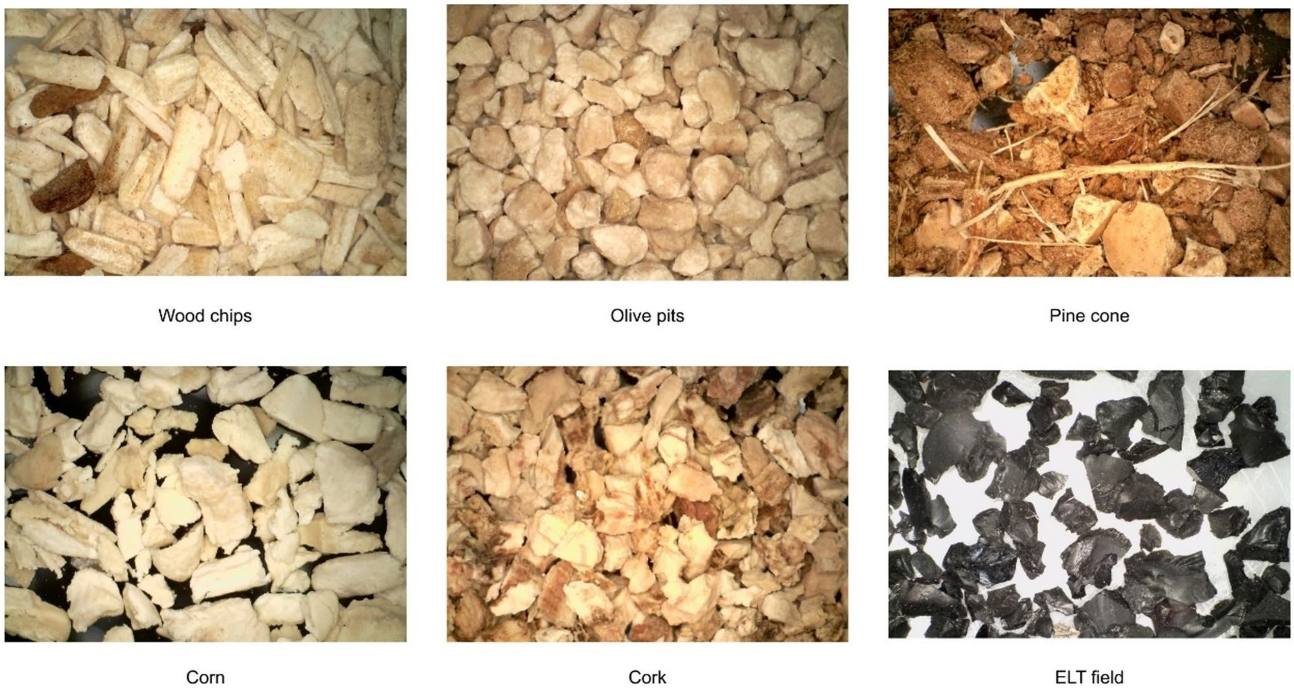

Wood chips
Olive pits
Pine cone
Corn
Cork
ELT field

Fig. 1 Visual comparison of six alternative infill materials for sports surfaces: **a** Wood chips, **b** Olive pits, **c** Pine cone, **d** Corn, **e** Cork, and **f** ELT field. Images are shown at a comparable scale; granule sizes range approximately from 0.3 to 3.0 mm depending on the material.

Table 1 Characteristics of the systems

System	Pile height (mm)	Pile weight (g/m^2)	Tufts m^2 (nº/m^2)	Sand rate (kg/m^2)	Sand size (mm)	Sand bulk density (g/cm^3)	Perf. infill rate (kg/m^2)	Perf. infill size (mm)	Perf. infill bulk density (g/cm^3)	e-layer
WC	45	1176	13,860	27	0.40–1.00	1.6	4	0.80–2.50	0.255	Yes
OP	40	1544	7560	20	0.32–1.00	1.5	8	1.00-2.50	0.724	Yes
PC	45	1160	9200	15	0.32–1.30	1.5	7	0.32–3.15	0.300	Yes
Corn	45	1521	12,876	25	0.05–0.63	1.5	5	0.80–1.60	0.560	Yes
Cork	45	1160	9200	18	0.32–1.00	1.5	2.5	0.80-2.00	0.120	Yes
ELT	60	1414	8858	30	0.25–1.00	1.5	11	0.63–2.50	0.456	Yes
NG	23	NA	NA	NA	NA	NA	NA	NA	NA	NA

All parameters have a ± 10% variation range. WC: Wood Chips; OP: Olive Pits; PC: Pine Cone; ELT: End-of-Life Tires; NG: Natural Grass; e-layer: Elastic Layer. Infill size and bulk density values were provided by the manufacturers and verified through spot laboratory measurements to confirm consistency with supplier specifications

installed according to manufacturer specifications and verified to meet FIFA Quality Programme requirements; incorporated a shockpad (e-layer) and a synthetic carpet with pile heights ranging from 45 to 60 mm, which is the standard range for FIFA Quality Programme-compliant systems (Table 1). This variation reflects commercially available configurations rather than any experimental inconsistency. Importantly, all surfaces met FIFA requirements for player–surface interaction, and mechanical properties were verified through FIFA-standardised mechanical test procedures (shock absorption, vertical deformation, energy return, and rotational resistance) prior to performance assessments. Therefore, the observed differences can be attributed primarily to the infill type, as other structural components remained within the same functional specification. Due to their supply chain, vegetal infills are highly dependent on seasonality and location, so the raw material supplier can change and is not usually controlled. Furthermore, since these are existing fields, it is not possible to provide this information with certainty. From a technical point of view, infills are considered equal if its apparent density, particle size and typology (e.g., cork, olive pits, etc.) are the same. The specific values are showed in Table 1. These mechanical characteristics are known to influence elements of player–surface interaction such as stability, force transmission, and perceived grip; however, direct links to performance outcomes or injury risk should be interpreted cautiously, as such relationships are multifactorial.

Each playing surface was required to meet the FIFA Quality requirements across all surface-player interaction properties (FIFA 2024a; 2024b). To ensure compliance and to characterize the mechanical behaviour of each surface, the following properties were assessed prior to each testing session and mechanical properties were verified through FIFA-standardised test procedures by accredited technicians for surface–player interaction at five locations within the work area: shock absorption (SA; FIFA Test Method 2015-04a), peak absorption (PA; FIFA Test Method 2024-03), vertical deformation (VD; FIFA Test Method 2015-05a), peak deformation (PD; FIFA Test Method 2024-04), energy of restitution (EOR; FIFA Test Method 2015-13), energy return (ER; FIFA Test Method 2024-05), and rotational resistance/peak torque (RR/PT; FIFA Test Methods 2015-06a and 2024-06). The specific characteristics of each surface are presented in Table 1. These tests form part of the FIFA Quality Programme for Football Turf, which establishes international standards for artificial surfaces to ensure player safety and consistent performance. SA and VD assess the surface's ability to attenuate impact forces and provide adequate compliance, reducing injury risk during high-intensity actions. EOR evaluates how efficiently the surface restitutes energy during foot strike, influencing running economy and fatigue. RR measures the grip and traction characteristics of the surface, which are critical for stability during cutting and turning manoeuvres. Together, these parameters provide a comprehensive profile of player–surface interaction and confirm that all tested fields met the required thresholds for elite football use. Table 2.

The physical testing protocol was designed to minimise uncontrolled variability by avoiding match-play scenarios and instead employing standardised, football-specific drills widely used in training contexts. This approach ensured repeatability and sensitivity to performance differences attributable to the playing surface. Instead, incorporating a series of reproducible and widely used simulated tasks that have demonstrated high test–retest reliability and are sensitive to detecting performance variations arising from surface characteristics [1, 2, 4, 19–22]. The protocol began with a standardised warm-up based on the FIFA 11 + programme [23], followed by two 40-m maximal sprint trials. After a 5-min active recovery period, participants performed 2 countermovement jump (CMJ) trials (CMJ_{pre}) prior to the repeated sprint ability (RSA) test. The RSA protocol consisted of six 20-m sprints incorporating a 180° change of direction, with 20 s of passive recovery between efforts. Immediately following the RSA test, participants completed 2 additional CMJ trials (CMJ_{post}) to assess neuromuscular fatigue. In total, 4 CMJ trials were recorded per participant. The CMJ involves a rapid downward movement followed by an explosive vertical jump, allowing assessment of

Table 2 Player-surface interaction test results of the seven playing surface systems evaluated, measured according to FIFA test methods

Field	SA (%)		PA (%)		VD (mm)		PD (mm)		EOR (%)		ER (J)		RR/PT (Nm)	
	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
WC	62.4	1.7	66.1	1.4	9.3	0.2	12.5	0.6	38.1	1.9	3.1	0.1	35.9	0.8
OP	57.4	2.1	60.8	0.6	7.7	0.2	10.9	1.0	42.0	1.0	3.1	0.1	32.5	1.9
PC	58.9	0.8	62.8	0.4	8.5	0.3	11.7	0.4	36.3	0.7	3.3	0.1	38.1	1.8
Corn	62.0	0.4	64.6	0.7	8.2	0.1	12.1	0.2	36.4	1.2	3.0	0.1	44.8	1.3
Cork	62.7	1.2	65.7	0.9	8.6	0.5	12.0	0.6	37.0	1.4	3.0	0.1	31.5	2.4
ELT	64.9	1.0	66.4	1.3	9.9	0.1	13.7	1.1	42.6	0.2	4.7	0.1	33.9	0.6
NG	61.6	2.6	66.7	3.0	6.6	0.9	9.4	1.7	22.1	3.5	1.2	0.2	34.5	2.7
FQ reqs.	55–70		60–75		4–11		≤16		For info		For info		25–50	

SA: Shock absorption; PA: Peak absorption; VD: Vertical deformation; PD: Peak deformation; EOR: Energy of restitution; ER: Energy return; RR/PT: Rotational resistance/Peak Torque; FQ requs: FIFA Quality field test requirements according to FIFA Quality Programme for Football Turf Manual 2015 (v3.5) for SA, VD, EOR and RR and Manual 2024 for PA, PD, ER and PT (the manuals change the test methods and some measure units); $\bar{x}$ Mean; SD Standard Deviation.

lower-limb power and neuromuscular function. Following another 5-min active recovery, participants completed the 5-0-5 change of direction (COD) test, performing two trials with each leg. The 5-0-5 test involved a 10-m approach sprint, a timing gate trigger, a 5-m sprint in one direction, a 180° turn, and a 5-m return sprint through the gate [24] (Fig. 2).

Participants wore their habitual football boots, as used during official match play, to preserve ecological validity. Footwear characteristics were documented for all participants. The distribution of stud configurations across the 30-player squad indicated that Firm Ground (FG) models, designed for natural firm surfaces, represented the majority with 16 players (53.3%). Artificial Ground (AG) boots, optimized for synthetic turf, accounted for 8 players (26.7%), while Hard Ground (HG) boots, intended for compact or older artificial surfaces, comprised 3 players (10.0%). Finally, Soft Ground (SG) boots, featuring interchangeable metal studs for wet or muddy natural pitches, were used by 3 players (10.0%). This distribution reflects the predominance of FG configurations in competitive squads, with a notable proportion of AG models aligned with the increasing use of artificial surfaces in football environments.

Although the use of SG stud configurations on artificial turf is generally discouraged due to increased injury risk and potential surface damage, players were permitted to wear their habitual footwear. However, given that the aim of this study was to reflect real competitive conditions and that all surfaces complied with FIFA Quality Programme requirements, players were allowed to use their habitual footwear. This information is reported to ensure full transparency regarding potential variations in traction.

Variables and instruments.

The 40-m sprint test was measured using a 1080 Sprint linear encoder (1080 Motion, Lidingö, Sweden). This device provides high temporal resolution (333 Hz) and validated against high-speed motion-capture systems for force–velocity profiling [25, 26]. RSA and COD tests were recorded using RaceTime photoelectric timing gates (Microgate, Bolzano, Italy) provide millisecond-level accuracy and consistent repeatability in sprint assessments. CMJ performance was assessed pre- and post-RSA using the Optojump laser measurement system (OptoJump-Microgate, Bolzano, Italy), which has shown high validity and reliability for jump-height assessment. For the CMJ assessment, participants completed 2 countermovement jumps before the RSA test (CMJ_pre) and two after the RSA test (CMJ_post). In each timepoint, the best of the 2 attempts was retained for analysis, and the RSACMJ-diff variable was calculated as the difference between the best CMJ_pre and the best CMJ_post.

Repeated sprint ability (RSA) was assessed using several key performance indicators: best sprint time (RSA_{Best-t}), percentage difference between first and last sprint times ($RSA_{Time-diff}$), velocity loss between the first and last sprints (RSA_{V-Loss}), difference in maximum acceleration between first and last sprint ($RSA_{Acc-diff}$), difference in maximum deceleration between first and last sprint ($RSA_{Dec-diff}$), and difference in maximum velocity between first and last sprint ($RSA_{Vmax-diff}$). Although these metrics assume a progressive decline in performance across sprints, occasional fluctuations were observed. The first–last comparison is widely used in RSA research because it reflects temporal fatigue patterns rather than isolated extremes. Using 'best minus worst' irrespective of trial order would not substantially alter the interpretation of our findings, but it could increase variability and reduce sensitivity to fatigue progression.

The speed and acceleration performance assessment included several key metrics derived from the 40-m sprint test: maximum velocity (V_{max}), maximum acceleration (ACC_{max}), theoretical maximum force (F_0), and theoretical maximum velocity (V_0). F_0 and V_0 were obtained using the linear force–velocity relationship derived from split-time and velocity data recorded during the 40-m sprint. This approach assumes that horizontal external force decreases linearly as running velocity increases. F_0 and V_0 were obtained from the linear force–velocity relationship derived from the sprint acceleration data. In this model, F_0 corresponds to the y-intercept, representing the theoretical maximal horizontal force at zero running velocity, and V_0 corresponds to the x-intercept, representing the theoretical maximal running velocity at zero horizontal force [25, 26].

Change of direction ability was evaluated using the 5-0-5 agility test, with performance expressed as total time ($5\text{-}0\text{-}5_{time}$). Each participant performed two trials with both the dominant and non-dominant leg, and for analysis purposes, the trial with the fastest time was selected. Furthermore, fatigue was assessed by calculating the difference in countermovement jump height before and after the test protocol ($RSA_{CMJ-diff}$).

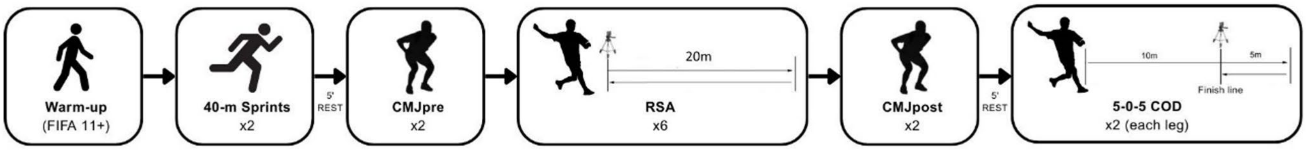


Fig. 2 Test procedure

2.4 Statistical analysis

Prior to hypothesis testing, the distribution of each dependent variable was examined using the Shapiro–Wilk test, grouped by field. All variables showed distributions approximating normality within each field condition. First, linear mixed-effects models (LMMs) were applied for each outcome variable within the vegetal infill fields, with field condition as a fixed effect and participant identifier as a random (to control for the effect of repeated measures as well as to capture unexplained variability). Pairwise comparisons between fields were performed using estimated marginal means with Tukey adjustment for multiple comparisons. All model outputs, including estimates (EST), standard errors (SE), confidence intervals, and p-values, were extracted and compiled for reporting. Descriptive statistics [mean ($\bar{x}$) and standard deviation (SD)] were also computed per field for all variables included in the analysis. Second, additional Linear Mixed-Effects Models (LMMs) were developed to compare each vegetal infill field with ELT infill and NG, respectively, setting either the ELT infill or NG as the reference level. One LMM was performed per outcome variable, with field condition as a fixed effect and participant identifier as a random effect.

3 Results

Table 3 shows $\bar{x}$± SD values of the outcome variables and pairwise comparisons resulted from the LMM within the vegetal infill fields.

When comparing the ELT field with the vegetal infills fields (Fig. 3), significant differences were found in $\text{RSA}_{\text{Best-t}}$. Higher times were observed in WC (EST=+0.14 s; SE=0.06; $p<0.05$) and PC (EST=+0.10 s; SE=0.04; $p<0.05$). Additionally, WC showed a smaller decrease in $\text{RSA}_{\text{Acc-diff}}$ compared to ELT (EST=+8.6%; SE=4.15; $p<0.05$). Compared to ELT, participants achieved better 5-0-5 performance on the OP (EST = −0.06 s; SE=0.02; $p<0.05$), PC (EST = −0.08 s; SE=0.02; $p<0.05$), Corn (EST = −0.07 s; SE=0.02; $p<0.05$), and Cork (EST = −0.05 s; SE=0.02; $p<0.05$) surfaces.

RSA: Repeated Sprint Ability; V_{max}: Max Speed (m/s); ACC_{max}: Maximal acceleration (m/s^2); DEC_{max}: Maximal deceleration (m/s^2); CMJ: Countermovement Jump; F_0: theoretical maximum force; V_0: theoretical maximum velocity. WC: Wood chips; OP: Olive pits; PC: Pine cone. * significant differences with the reference football field: ELT field ($p<0.05$). The black line represents the effect of the reference football field (ELT), while the red dashed lines indicate the standard error with respect to the reference field, and the vertical red lines represent the standard error bars.

When compared to NG (Fig. 4), WC showed reduced performance in $\text{RSA}_{\text{Best-t}}$ (EST=+0.09 s; Standard Error=0.04; $p<0.05$), ACC_{max} (EST=−0.55 m/s²; Standard

Table 3 Descriptive statistics and pairwise comparisons of performance and fatigue variables across vegetal infill fields

	Wood chips (a)		Olive pits (b)		Pine cone (c)		Corn (d)		Cork (e)	
	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
$\text{RSA}_{\text{Best-t}}$ (s)	7.34	0.25	7.23	0.30	7.25	0.30	7.15$^{a, c}$	0.25	7.20$^{a, c}$	0.28
$\text{RSA}_{\text{Time-diff}}$ (%)	4.17	3.69	6.01	1.58	2.11^{b}	5.14	4.74	3.83	5.55^{c}	3.50
$\text{RSA}_{\text{V-Loss}}$ (%)	3.58	1.53	3.64	0.72	4.44	1.63	3.88	1.25	4.08	1.39
$\text{RSA}_{\text{Acc-diff}}$ (%)	−3.40	14.01	−4.15	21.34	−2.82	19.77	−4.22	11.69	−5.19	11.35
$\text{RSA}_{\text{Dec-diff}}$ (%)	−3.84	16.37	1.99	19.22	−3.43	19.83	2.32	21.59	−1.75	13.68
$\text{RSA}_{\text{Vmax-diff}}$ (%)	−4.03	3.31	3.91	45.04	−4.90	6.51	−6.16	5.52	−7.37	5.80
40-m test: V_{max} (m/s)	8.34	0.41	8.38	0.37	8.35	0.37	8.34	0.46	8.31	0.37
40-m test: ACC_{max} (m/s^2)	7.16	0.93	6.98	1.23	7.61	1.22	7.28	1.31	7.28	1.68
40-m test: F_0 (N/kg)	7.24	0.66	7.24	0.74	7.46	1.22	7.46	0.94	7.74	0.74
40-m test: V_0 (m/s)	8.77	0.52	8.73	0.47	8.73	0.60	8.76	0.80	8.68	0.49
$\text{RSA}_{\text{CMJ-diff}}$ (%)	−0.04	0.06	−0.03	0.07	−0.02	0.08	−0.05	0.05	−0.06	0.07
5-0-5 $_{\text{time}}$ (s)	2.40	0.12	2.33	0.10	2.31^{a}	0.12	2.31^{a}	0.12	2.36	0.11

RSA: Repeated Sprint Ability; $\text{RSA}_{\text{Best-t}}$ best sprint time; $\text{RSA}_{\text{Time-diff}}$ percentage difference between first and last sprint times; $\text{RSA}_{\text{V-Loss}}$ velocity loss across sprints; $\text{RSA}_{\text{Acc-diff}}$ difference in maximum acceleration between first and last sprint; $\text{RSA}_{\text{Dec-diff}}$ difference in maximum deceleration between first and last sprint; $\text{RSA}_{\text{Vmax-diff}}$ difference in maximum velocity between first and last sprint; 40-m test: V_{max} maximum velocity in the 40-m sprint test; 40-m test: ACC_{max} maximum acceleration in the 40-m sprint test; 40-m test: F_0 theoretical maximum force in the 40-m sprint test; 40-m test: V_0 theoretical maximum velocity in the 40-m sprint test; $\text{RSA}_{\text{CMJ-diff}}$ difference in countermovement jump height before and after the test protocol; 5-0-5 time Total time (s) to complete the 5-0-5 agility test, assessing change of direction ability; $\bar{x}$ Mean; SD Standard Deviation.

a, b, c, d, e significant differences between groups ($p<0.05$).

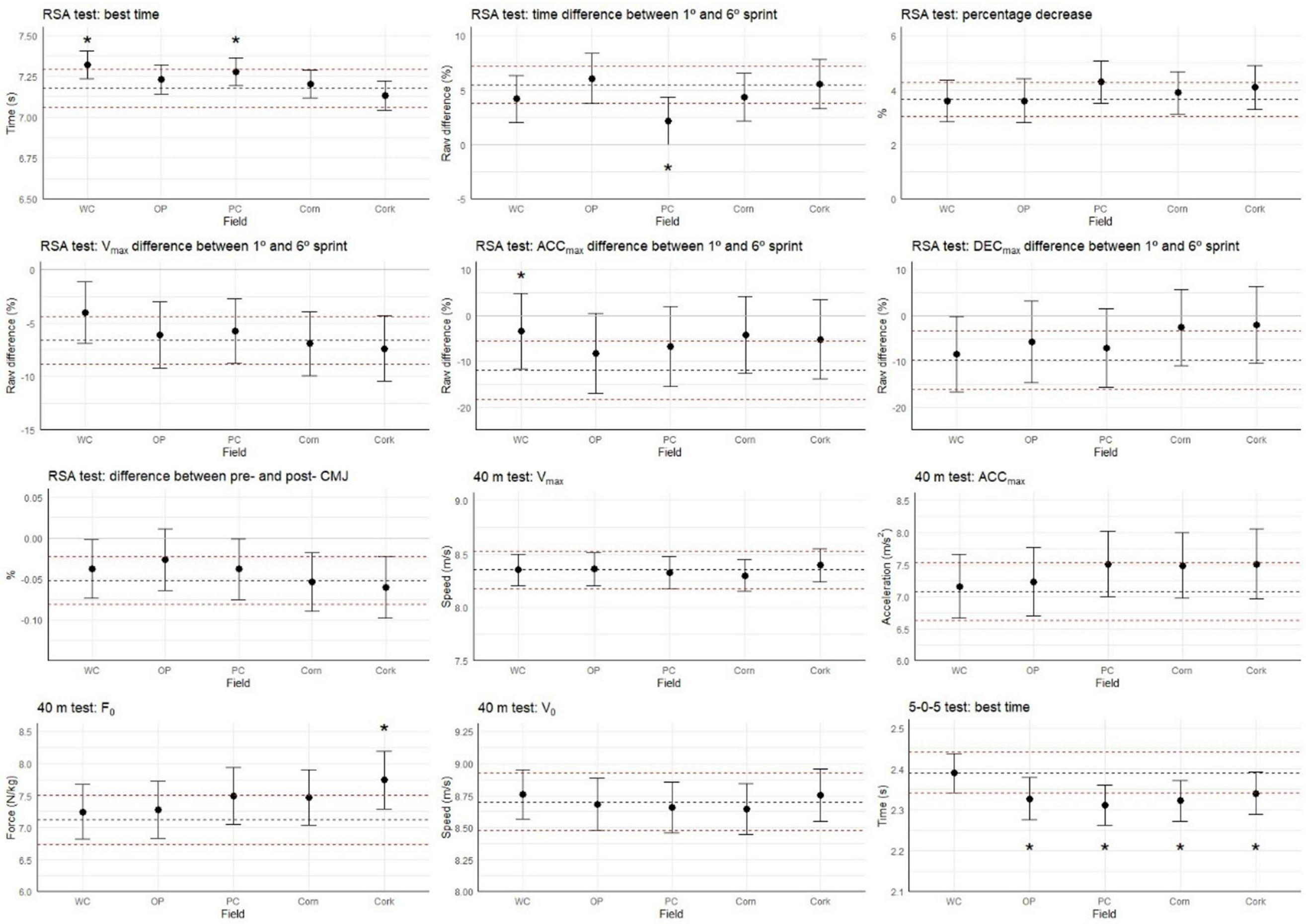


Fig. 3 Comparisons between vegetal infill fields and ELT field: estimated differences in RSA, sprint and COD performance

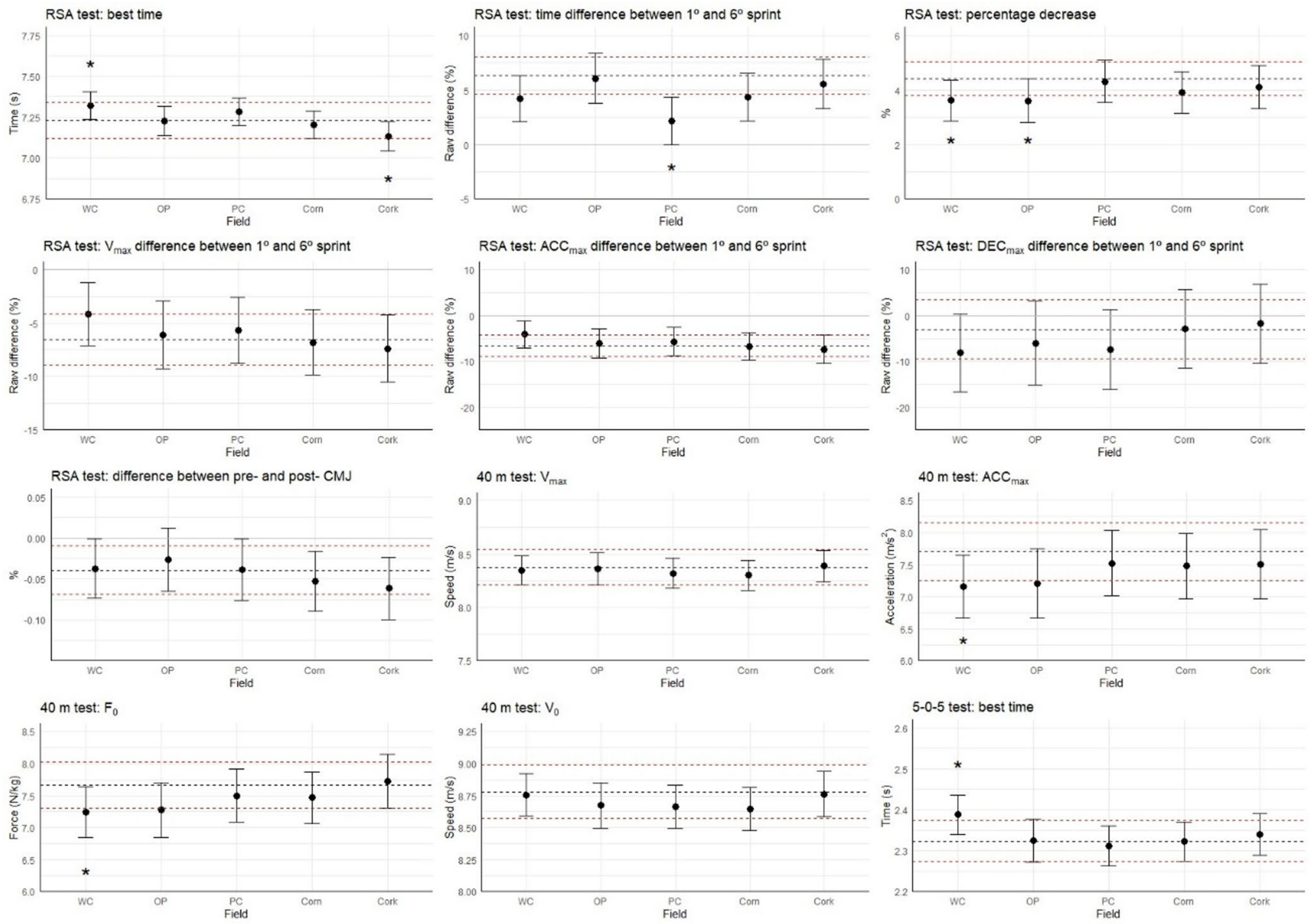
Error = 0.25; $p < 0.05$), F_0 (EST = −0.42 N/kg; Standard Error = 0.20; $p < 0.05$), and 5-0-5_{time} (EST = +0.06 s; Standard Error = 0.02; $p < 0.05$). However, in terms of RSA_{V-Loss}, WC exhibited a smaller decrement in performance compared to NG (EST = −0.8%; Standard Error = 0.40; $p < 0.05$). The Cork infill also showed improved performance in RSA_{Best-t} compared to NG (EST = −0.09 s; Standard Error = 0.05; $p < 0.05$).

RSA: Repeated Sprint Ability; V_{max}: Max Speed (m/s); ACC_{max}: Maximal acceleration (m/s^2); DEC_{max}: Maximal deceleration (m/s^2); CMJ: Countermovement Jump; F_0: theoretical maximum force; V_0: theoretical maximum velocity. WC: Wood chips; OP: Olive pits; PC: Pine cone. * significant differences with the reference football field: natural grass field ($p < 0.05$). The black line represents the effect of the reference football field (natural grass), while the red dashed lines indicate the standard error with respect to the reference field, and the vertical red lines represent the standard error bars.

4 Discussion

This study identified clear differences in players' kinetic performance across artificial turf systems with distinct vegetal infills, particularly in change-of-direction actions and fatigue-related responses. These variations highlight the influence of infill composition on player–surface interaction within FIFA-compliant installations.

The findings demonstrate that sprinting performance is largely unaffected by surface infill type. Across the seven surfaces, players achieved similar peak sprint velocities during the 40-m test, suggesting that surface infill type did not constrain the expression of maximal speed under these controlled conditions. For instance, the observed differences in mechanical properties and performance metrics across field types have practical relevance for training and injury prevention strategies in professional football. Players tended to exhibit higher acceleration-related outputs on the cork-based system, including greater values in the estimated theoretical maximum force (F_0), although this should be interpreted cautiously given the influence of other


RSA test: best time

RSA test: time difference between 1º and 6º sprint

RSA test: percentage decrease

RSA test: V_{max} difference between 1º and 6º sprint

RSA test: ACC_{max} difference between 1º and 6º sprint

RSA test: DEC_{max} difference between 1º and 6º sprint

RSA test: difference between pre- and post- CMJ

40 m test: V_{max}

40 m test: ACC_{max}

40 m test: F_0

40 m test: V_0

5-0-5 test: best time

Fig. 4 Comparisons between vegetal infill fields and NG: estimated differences in RSA, sprint and COD performance

surface components. However, this effect could also reflect the combined influence of other structural components, such as pile height, fibre density, and shock pad characteristics, which interact with the infill to determine overall surface behaviour. Conversely, the lower F_0 and ACCmax values observed on WC—and similarly on OP—compared to NG may indicate reduced mechanical efficiency, which could affect acceleration capabilities.

From a surface property perspective, ELT fields showed the highest values in deformation and energy behaviour, indicating lower stiffness but greater energy return. These characteristics are generally associated with improved performance in short, high-intensity actions, as supported by previous literature [4]. In line with these mechanical characteristics, the performance comparison between ELT and NG in the present study supports this relationship. As shown in Figs. 3 and 4, players tended to achieve better outcomes in short, high-intensity actions on the ELT surface, including faster RSABest-t times and higher ACCmax and F_0 values, whereas NG generally elicited lower force-production capabilities. These findings are consistent with the higher deformation and greater energy return observed on the ELT system, which facilitate force transmission during acceleration. This direct comparison reinforces the influence of surface stiffness and energy behaviour on short-duration, high-intensity performance profiles. In contrast, NG fields exhibited the lowest values in these parameters, which may reduce force transmission but could offer increased stability due to lower deformation [18].

Beyond the between-surface comparisons reported above, the lower force production and slower sprint performance observed on the WC and PC systems can be plausibly explained by their mechanical behaviour. Both infills showed characteristics consistent with greater compliance and lower effective energy restitution, implying that a larger fraction of the athlete's input is absorbed by the surface and not returned during propulsion. This increased energy dissipation during stance is compatible with the reduced F_0 and slower $RSA_{Best\text{-}t}$ values observed on WC and PC. Additionally, the irregular particle geometry and comparatively lower bulk density of these infills likely decrease infill stability under load, further limiting horizontal force transmission and acceleration. While isolating the specific contribution of individual structural components (e.g., infill depth, fibre support, shock-pad interaction) warrants future work, the combined profile of higher compliance and lower energy return provides a coherent explanation for the performance decrements on WC and PC in the present cohort.

Vegetal infill surfaces, which presented intermediate values, may offer a balance between performance and stability, potentially making them suitable for varied training demands. These findings highlight the importance of selecting appropriate surface types based on the specific physical demands of training sessions and match preparation, and they may inform decisions regarding field maintenance and surface design in elite football environments. Performance differences may not only reflect infill type but also the condition of structural components, which can change over time due to compaction and wear. Regular maintenance—such as infill decompaction and levelling—plays a critical role in preserving mechanical properties and ensuring consistent player–surface interaction.

The RSA test is widely recognized for its ability to reflect a player's capacity to sustain repeated high-intensity efforts under fatigue [27]. As the test progresses, performance naturally declines, offering a practical way to observe how fatigue accumulates across efforts [28]. In this context, our results revealed notable differences among vegetal infill surfaces. On WC and PC fields, players recorded their slowest sprint times and overall performance was lower compared to NG and ELT. These findings are consistent with the reduced force production observed in isolated sprints on WC surfaces. Interestingly, although WC and PC showed lower absolute performance, they exhibited more favourable values in metrics related to performance loss. This suggests that while these surfaces may limit the expression of maximal force, they could promote a more gradual decline in performance across repeated efforts—potentially indicating a different fatigue profile or mechanical demand. Regarding acute fatigue, measured through the CMJ_{diff} variable, across all surfaces no differences were found within vegetal infill and when comparing them to NG and ELT. This may be attributed to their capacity to reduce mechanical loading during repeated efforts, as supported by earlier findings on the role of surface compliance in modulating neuromuscular fatigue [29, 30]. While most players exhibited a progressive decline in performance, this pattern was not universal. Our metrics are based on first–last sprint comparisons, which are recommended for capturing fatigue trends. Alternative approaches, such as best–worst comparisons, would likely yield similar conclusions but with greater variability and less insight into fatigue progression.

Concerning the COD test, all vegetal fields showed lower times in the 5-0-5 test compared to the ELT field and similar times to the NG field, except for the WC, suggesting that these materials may provide traction levels closely aligned with NG. Excessive or insufficient traction has been associated with increased injury risk and impaired performance [13], highlighting the importance of achieving a functional balance in surface design. However, the rotational resistance properties appear inconsistent with these results, showing directional variability that does not align with the observed performance differences. While peak torque measured according to FIFA Test Methods 2015-06a and 2024-06 does not seem to correlate with performance outcomes, it remains unclear whether T10, a parameter included in the updated FIFA rotational resistance protocol, might show a stronger relationship. Given the known characteristics of the systems, estimating theoretical torque at 10º values could help clarify this discrepancy. None of the systems tested incorporated a stabilising sand layer, although previous research indicates that this component can influence rotational traction by altering fibre support and infill stability. Therefore, the rotational resistance values observed here reflect configurations without this component. Two mechanisms likely contributed to this behaviour: *(i)* the stronger dependence of vegetal infills on applied normal load for peak torque generation; and *(ii)* the fact that the rotational resistance test simulates foot rotation, whereas the COD test primarily reflects linear grip characteristics [16]. These findings also raise important considerations regarding the mechanical testing protocols used to evaluate artificial turf systems. While traditional parameters such as shock absorption (SA), vertical deformation (VD), and peak torque (PT) have been widely used, newer FIFA test methods—such as T10, rotational stiffness (RSS), peak shock absorption (PSA), and energy return (ER)—may offer more sensitive insights into how surface properties influence performance. For instance, T10 could be particularly relevant when comparing systems for specific performance outcomes, such as agility or traction, as it may better reflect the initial rotational resistance experienced during directional changes [17].

Taken together, these findings indicate that vegetal infills should not be treated as a homogeneous category but rather as distinct systems with unique mechanical and performance profiles. While certain infills may enhance specific performance outcomes—such as agility or fatigue resistance—others may underperform in key metrics like force production or acceleration compared to traditional systems. Although the mechanical properties of the field are essential to ensure minimum functionality and safety, the differences found may be attributable to specific characteristics of the player's interaction with each specific infill. It is even possible that current tests exhibit different behaviour depending on the type of infill, as is the case with rotational resistance [10, 16]. Recent studies have emphasized that even minor variations in infill composition and structure can alter mechanical behaviour and, consequently, athletic performance [2].

Therefore, it is more accurate to consider vegetal infills as differentiated alternatives to ELT, whose suitability must be evaluated in relation to the specific demands of the sport context and performance priorities.

This study offers preliminary field-based evidence regarding player–surface interaction on artificial turf systems with vegetal infills, in the context of ongoing regulatory changes on microplastics within the European Union [12]. Facility managers across Europe now face the challenge of adopting alternative materials under diverse financial constraints, climatic conditions, and with limited independent data on the performance of these new systems. To our knowledge, this is the first study to systematically evaluate the biomechanical and performance implications of vegetal infills in sub-elite male football players.

In this cohort and under the present testing conditions, participants achieved performance outcomes on certain vegetal-infill systems that were comparable to those observed on natural grass for sprint velocity and change-of-direction, alongside similar short-term fatigue responses. Moreover, structural components, mechanical wear, and environmental conditions may influence long-term performance and player–surface interaction. However, these aspects were not directly assessed in this study, and further longitudinal and multi-site research is needed to determine how such factors interact with different infill materials over time.

Finally, generalisation to youth and female cohorts should be made with caution. Female players often exhibit different neuromuscular and movement strategies in landing and cutting tasks and a higher non-contact ACL injury risk, which may alter how traction and compliance interact with performance and load on a given surface (e.g., knee valgus moments, trunk–hip–knee control) [31]. Likewise, maturation status in youth is associated with lower absolute force and power outputs and different stride and braking–propulsive profiles, which could change sensitivity to surface stiffness, deformation and energy return [32].

This study has several limitations that should be acknowledged. First, the sample consisted exclusively of sub-elite male football players competing at the highest regional amateur level. This restricts generalisability because female and youth cohorts often differ in anthropometric characteristics, strength profiles, and movement patterns, which can influence surface interaction and injury risk. For example, youth players typically exhibit lower absolute force and acceleration capacities, while female players may present different traction demands and fatigue responses, meaning that the effects observed here may not translate directly to those populations. Although all surfaces met FIFA Quality Programme requirements, differences in pile height and other structural components (e.g., fibre density, infill depth, presence of stabilising sand) may have influenced performance outcomes. Therefore, observed differences cannot be attributed solely to infill type, but rather to the entire surface system configuration.

Second, participants were recruited from different clubs, introducing heterogeneity in training routines, tactical approaches, and physical preparation. While this diversity enhances ecological validity by reflecting real-world conditions, it may also explain some variability in performance outcomes across surfaces.

Third, testing was conducted on a single field per infill type and under controlled weather conditions. This approach does not capture variability due to environmental factors such as rain or temperature extremes, which can alter infill compaction and mechanical properties.

Fourth, the study focused on short-term performance outcomes and did not assess long-term adaptations to repeated exposure. Future research should include more diverse cohorts, evaluate environmental variability, and examine chronic effects to provide a comprehensive understanding of surface–player interaction. Furthermore, although the possible differences produced by variability between players have been controlled with the random effect in the mixed model, there is always a possible bias, although unlikely, in the differences produced due to large spread in the players.

Additionally, players may have required extra time to acclimatise to the new vegetal infill surfaces. Most participants were accustomed to natural grass or ELT-based artificial turf, and unfamiliarity with alternative infills could have influenced performance or perception during testing. Future studies should consider incorporating an acclimatisation period to minimise this potential source of variability. Another aspect that should be acknowledged is that players may have required additional time to acclimatise to the new vegetal infill surfaces. Most participants were accustomed to natural grass or ELT-based artificial turf, and unfamiliarity with alternative infills could have influenced performance or perception during testing. Future studies should consider incorporating an acclimatisation period to minimise this potential source of variability [6, 9, 10].

Finally, the natural grass and ELT fields used as benchmarks were maintained to high standards and met all FIFA Quality Programme requirements for surface–player interaction. While this ensures that comparisons were made against representative, compliant systems, it also means that the findings may not fully reflect performance differences on lower-quality or poorly maintained fields, which are common in many contexts. Therefore, conclusions regarding whether a given vegetal infill performs ‘better’ or ‘worse’ than natural grass or ELT should be interpreted within the scope of high-quality reference surfaces.

Additionally, the study did not include repeated testing sessions or repeated mechanical characterisation of the surfaces, which would be valuable for assessing consistency, temporal variation, and the stability of the surface–player interaction.

5 Conclusions

This study provides novel insights into the physical performance and fatigue responses of amateur football players on artificial turf systems with different vegetal infills, compared to traditional ELT infill and NG. The results demonstrate that some vegetal infills can offer performance outcomes comparable to or even superior to ELT infill in short duration and high intensity actions, although maintaining speed during repeated efforts remains challenging. Compared to the NG field, the vegetal-infill surfaces tended to yield lower outcomes in short, high-intensity actions, whereas RSA-related indicators displayed greater variability, suggesting that fatigue responses may be more surface-dependent. However, no single vegetal infill consistently outperformed others across all variables, which reinforces the need for context-specific evaluation. Each infill system should be assessed individually, as their mechanical properties and the way players interact with them vary significantly. These findings highlight the importance of adopting a multidimensional approach when selecting infill materials, considering not only environmental sustainability but also athletic performance and safety.

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Author contributions A.A.-C., J.L.F., and J.G.-U. conceived and designed the study. A.A.-C. coordinated the data collection and led the methodological framework. J.L.F. conducted the statistical analysis and contributed to the interpretation of results. J.G.-U. and K.M. drafted the main manuscript text. M.B. and A.M.-S. supported the experimental design and field testing. J.B. prepared the figures and tables. L.G. contributed to the critical revision of the manuscript. All authors reviewed and approved the final version of the manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

References

1. Hughes MG, Birdsey L, Meyers R et al (2013) Effects of playing surface on physiological responses and performance variables in a controlled football simulation. J Sports Sci 31:878–886. https://doi.org/10.1080/02640414.2012.757340
2. Sanchez-Sanchez J, Garcia-Unanue J, Jimenez-Reyes P et al (2014) Influence of the mechanical properties of third-generation artificial turf systems on soccer players' physiological and physical performance and their perceptions. PLoS ONE 9:e111368. https://doi.org/10.1371/journal.pone.0111368
3. Cole D, Fleming P, Roberts J et al (2023) Comparison of player perceptions to mechanical measurements of third generation synthetic turf football surfaces. Sports Eng 26:5
4. Sanchez-Sanchez J, Garcia-Unanue J, Felipe JL et al (2016) Physical and physiological responses of Amateur football players on third-generation artificial turf systems during simulated game situations. J Strength Cond Res 30:3165–3177. https://doi.org/10.1519/JSC.0000000000001415
5. Garcia-Unanue J, Fernandez-Luna A, Burillo P et al (2020) Key performance indicators at FIFA Women's World Cup in different playing surfaces. PLoS ONE 15:e0241385. https://doi.org/10.1371/journal.pone.0241385
6. Sánchez-Sánchez J, García-Unanue J, Gallardo AM et al (2018) Effect of structural components, mechanical wear and environmental conditions on the player–surface interaction on artificial turf football pitches. Mater Des 140:172–178
7. Sánchez-Sánchez J, Haxaire P, García Unanue J et al (2018) Determination of mechanical properties of artificial turf football pitches according to structural components. Proc Inst Mech Eng P J Sports Eng Tech 232:131–139
8. Alcántara E, Gámez J, Rosa D et al (2009) Analysis of the influence of rubber infill morphology on the mechanical performance of artificial turf surfaces for soccer. Proc Inst Mech Eng P J Sports Eng Tech 223:1–9
9. Fleming PR, Forrester SE, McLaren NJ (2015) Understanding the effects of decompaction maintenance on the infill state and play performance of third-generation artificial grass pitches. Proc Inst Mech Eng P J Sports Eng Tech 229:169–182
10. McGowan H, Fleming P, Pak J-H et al (2023) The effect of rotational velocity on rotational traction across a range of artificial turf surface systems. Sci Rep 13:21631
11. Dickson KH, Straw CM, Thoms AW et al (2022) Impact of third generation synthetic turf athletic field age on surface hardness

and infill depth spatial variability. Proc Inst Mech Eng P J Sports Eng Tech 236:192–199

12. European Commission. EU action against microplastics. In: European Union (2023) : 67–88
13. Bø S, Bohne R, Lohne J (2024) Environmental impacts of artificial turf: a scoping review. Int J Environ Sci Technol 21(16):10205–10216
14. European Chemicals Agency. Commission Regulation (EU) 2023/2055—Restriction of microplastics intentionally added to products. In: European Commission (2023)
15. Russo C, Cappelletti GM, Nicoletti GM (2022) The product environmental footprint approach to compare the environmental performances of artificial and natural turf. Environ Impact Assess Rev 95:106800
16. McGowan H, Fleming P, James D et al (2025) Investigating normal stress effects on the shear and traction characteristics of performance infill materials used in artificial turf surfaces. Sports Eng 28:6
17. McGowan H, Fleming P, James D et al (2025) The development and validation of a performance infill tracking system to investigate rotational traction mechanisms on artificial turf surfaces. Sci Rep 15:9039
18. Colino E, Garcia-Unanue J, Gallardo L et al (2020) Mechanical properties of treadmill surfaces and their effects on endurance running. Int J Sports Physiol Perform 15:685–689. https://doi.org/10.1123/ijspp.2019-0539
19. Ammar A, Bailey SJ, Hammouda O et al (2019) Effects of playing surface on physical, physiological, and perceptual responses to a repeated-sprint ability test: natural grass versus artificial turf. Int J Sports Physiol Perform 14:1219–1226. https://doi.org/10.1123/ijspp.2018-0766
20. Brito J, Krustrup P, Rebelo A (2012) The influence of the playing surface on the exercise intensity of small-sided recreational soccer games. Hum Mov Sci 31:946–956. https://doi.org/10.1016/j.humov.2011.08.011
21. Impellizzeri FM, Rampinini E, Castagna C et al (2008) Effect of plyometric training on sand versus grass on muscle soreness and jumping and sprinting ability in soccer players. Br J Sports Med 42:42–46. https://doi.org/10.1136/bjsm.2007.038497
22. Lopez-Fernandez J, Sanchez-Sanchez J, Rodriguez-Canamero S et al (2018) Physiological responses, fatigue and perception of female soccer players in small-sided games with different pitch size and sport surfaces. Biol Sport 35:291–299. https://doi.org/10.5114/biolsport.2018.77829
23. Bizzini M, Dvorak J (2015) FIFA 11+: an effective programme to prevent football injuries in various player groups worldwide-a narrative review. Br J Sports Med 49:577–579. https://doi.org/10.1136/bjsports-2015-094765
24. Zivkovic A, Markovic S, Cuk I et al (2025) Reliability and validity of key performance metrics of modified 505 test. Life (Basel) 15. https://doi.org/10.3390/life15020198
25. Feser E, Lindley K, Clark K et al (2022) Comparison of two measurement devices for obtaining horizontal force-velocity profile variables during sprint running. Int J Sports Sci Coach 17:1455–1461
26. Komino P, Le Mat Y, Zadro I et al (2022) Sprint acceleration mechanical outputs: direct comparison between GPEXE Pro2 and 1080 sprint devices. Sci Rep 163:1–4
27. Bravo DF, Impellizzeri FM, Rampinini E et al (2008) Sprint vs. interval training in football. Int J Sports Med 29:668–674
28. Kyles A, Oliver JL, Cahill MJ et al (2023) Linear and change of direction repeated sprint ability tests: a systematic review. J Strength Cond Res 37:1703–1717
29. Alba-Jimenez C, Moreno-Doutres D, Pena J (2022) Trends assessing neuromuscular fatigue in team sports: a narrative review. Sports (Basel) 10. https://doi.org/10.3390/sports10030033
30. Miyama M, Nosaka K (2004) Influence of surface on muscle damage and soreness induced by consecutive drop jumps. J Strength Cond Res 18:206–211. https://doi.org/10.1519/R-13353.1
31. Hewett TE, Myer GD, Ford KR et al (2016) Mechanisms, prediction, and prevention of ACL injuries: cut risk with three sharpened and validated tools. J Orthop Res 34:1843–1855
32. Lloyd RS, Oliver JL (2012) The youth physical development model: a new approach to long-term athletic development. Strength Cond J 34:61–72. https://doi.org/10.1519/SSC.0b013e31825760ea