STUDIES ON THE PHYSICAL AND MECHANICAL PROPERTIES OF TEFF [*ERAGROSTIS TEF*] SEEDLING RELEVANT TO TRANSPLANTER DEVELOPMENT
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የጤፍ ፊዚካል እና መካኒካል ባህሪያት [Eragrostis tef (Zucc.) Trotter] ከችግኝ ትራንስፕላንተር ልማት ጋር የሚዛመዱ ጥናቶች

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ABSTRACT

Teff (Eragrostis tef), a staple crop in Ethiopia and an emerging global superfood, is increasingly being cultivated through transplanting to improve yield and resource efficiency. The development of efficient teff transplanting machinery requires a thorough understanding of the physical and mechanical properties of teff seedlings. This study investigated the physical and mechanical characteristics of four teff varieties (Quncho, Dukem, Tseday, and the local variety Gemechis) at 20, 25, and 30 days after sowing. The analyzed parameters included seedling weight, height, stem diameter, moisture content, tensile strength, shear stress, and coefficient of friction. Descriptive statistical analyses were conducted using Statistix 10 and MATLAB 2024b, and results were expressed as mean values for each parameter. The findings revealed that as the seedlings matured, their weight, height, stem diameter, tensile strength, and shear stress increased, whereas moisture content decreased. The measured tensile strength values were as follows: Quncho (12.17±0.053 N, 14.46±0.964 N, and 18.297±0.577 N), Dukem (12.36±0.058 N, 14.597±1.11 N, and 18.763±0.57 N), Tseday (12.66±0.057 N, 14.097±0.81 N, and 17.9±1.155 N), and Local (Gemechis) (12.18±0.057 N, 14.32±0.764 N, and 19.12±0.012 N) for 20-, 25-, and 30-day-old seedlings, respectively. All tensile strength values exceeded the forces applied by the transplanter, indicating that seedlings of these four teff varieties possess adequate strength and resilience, making them suitable for the design and development of mechanical teff transplanters.

አህፅርኦት

ጤፍ [Eragrostis tef (Zucc.) Trotter], በኢትዮጵያ ውስጥ ዋነኛ ሰብል እና ታዳጊ ዋና ምግብ፣ የምርት እና የሀብት ቅልጥፍናን ለማሳደግ በመትከል የተሻለ ምርት እያስገኘ ነው። ለጤፍ ንቅለ ተከላ ቀልጣፋ ማሽነሪ የጤፍ ችግኞችን መሰረታዊ አካላዊ እና ሜካኒካል ባህሪያት መረዳትን ይጠይቃል። ይህ ጥናት ከተዘራ በኋላ ባሉት 20፣ 25 እና 30 ቀናት ውስጥ የአራት የጤፍ ዝርያዎችን (ቁንጮ፣ ዱከም፣ ፀደይ እና የአካባቢ ዝርያ" ገመቺስ) አካላዊ እና መካኒካል ባህሪያትን በመገምገም ክብደትን፣ ቁመትን፣ ግንድ ዲያሜትርን፣ የእርጥበት መጠንን፣ የመሸከም አቅምን፣ የመቆራረጥን እና የግጭት መጠንን ይገመግማል። ገላጭ ስታቲስቲካዊ ትንታኔ በስታቲስቲክስ 10 እና ማትላብ 2024b ሶፍትዌር በመጠቀም የተከናወነ ሲሆን ውጤቶቹ ለተለያዩ መለኪያዎች እንደ አማካይ እሴቶች ቀርበዋል ። የዚህ ጥናት ውጤት እንደሚያሳየው ችግኞች እየበሰለ ሲሄዱ ክብደታቸው፣ ቁመታቸው፣ ዲያሜትራቸው፣ የመሸከም አቅማቸው እና የመቁረጥ ውጥረታቸው እየጨመረ ሲሄድ የእርጥበት መጠን እየቀነሰ ነው። የጤፍ ችግኝ የመሸከም ጥንካሬ 12.17±0.053 N, 14.46±0.964 N, እና 18.297±0.577 N በ20, 25, እና 30 ቀናቶች ለቁንቾ ዝርያ; 12.36 ± 0.058 N, 14.597 ± 1.11 N, እና 18.763 ± 0.57 N በ 20, 25 እና 30 ቀናት ውስጥ ለዱከም ልዩነት; 12.66±0.057 N, 14.097±0.81 N, እና 17.9±1.155 N በ 20, 25 እና 30 ቀናት ውስጥ ለጸደይ ልዩነት; እና 12.18±0.057 N፣ 14.32±0.764 N፣ እና 19.12±0.012 N በ20፣ 25 እና 30 ቀናት ለአካባቢው ልዩነት። እነዚህ ሁሉ እሴቶች በማሽኑ ከተተገበረው ኃይል የሚበልጡ ሲሆን ይህም የአራቱ የጤፍ ዝርያዎች ችግኞች ደህንነቱ የተጠበቀ እና ተመሳሳይ የጥንካሬ ባህሪ ያላቸው በመሆናቸው የጤፍ ሰብሎችን ንቅለ ተከላ ለመንደፍ ምቹ ያደርጋቸዋል።

INTRODUCTION

Teff *[Eragrostis tef (Zucc.) Trotter]* is a unique, gluten-free crop that serves as a staple for the Ethiopian population and is increasingly recognized as a health food in western markets (*Spaenij-Dekking, et al., 2005*). Ethiopia is the largest Tef producer in the world, it accounts for 24% of the grain area, followed by maize 17% and sorghum 15% (*CSA, 2018*). Teff is nutritious due to its high protein and mineral content, and the absence of gluten makes it an alternative food for people suffering from coeliac disease. It has become globally known,

Yonas Lemma, PhD student; Kishor Purushottam Kolhe, Main Supervisor and Professor; Amana Wako, Associate Professor and various products are available in Europe and North America as health foods especially for persons with gluten intolerance. In South Africa, India, Pakistan, Uganda, Kenya and Mozambique teff is mainly grown as a forage or pasture crop (*Worku K. et al., 2022*). In addition to its nutritional value, teff straw is also used to strengthen mud for wooden house construction and is also an excellent livestock feed (*Spaenij-Dekking, et al., 2005*). Teff cultivation is labor-intensive, with most pre-harvest and post-harvest processes following traditional methods *(Zewdie GT. et al., 2010*). The productivity of this sector is closely related to the timing and execution of pre- and post-harvest tasks. Many farmers rely on manual or animal labor for field preparation, highlighting their dependence on conventional cultivation practices (*Geta K. et al., 2020*). Tef grows under a wide range of ecological conditions from sea level up to 3000 meters above sea level (m.a.s.l) (*Seyfu K., 1997*). It is annually cultivated on over three million hectares of land, and as such it accounts for about 30% of the total area and 20% of the gross grain production of cereals grown in the country *(Welteji, 2018) (CSA, 2020)*

Historically, teff has been cultivated using the broadcasting method, with seed rates of 25–50 kg/ha (*ATA, 2018*). This practice can result in excessive plant density, leading to issues like lodging and poor yields. Lodging is one the most yield limiting factors, which occurs when plants grow long in height and fail to hold the panicle *(Kidu G.. et al., 2025)* High plant densities can also cause problems such as insect infestations, nutrient and sunlight competition, weeding challenges, and irregular seed placement. However, research indicates that improved agronomic practices and innovative cultivation techniques, such as row planting at 20 to 25 cm apart or transplanting seedlings at 10 to 15 cm intervals, can reduce lodging (*Tareke, 2013*). Despite the potential benefits of these newer methods, the absence of a suitable transplanter specifically designed for teff cultivation remains a significant limitation. While some initiatives have attempted to transplant teff seedlings, resulting in yield increases, these methods are often labor-intensive and costly, making them impractical for larger operations. Studies have explored the mechanical properties of various seedling types, revealing critical insights into the design of effective transplanting systems. However, a focused examination of teff seedlings remains underexplored, leaving a gap in understanding how their unique properties can influence transplanting efficiency. Developing a machine for transplanting teff seedlings requires an in-depth exploration of their physical and mechanical properties such as moisture content, weight, stem diameter, height, tensile strength shear stress, coefficients of static friction. This research provided valuable insights into these characteristics teff seedling, producing the first comprehensive dataset to the design of specialized transplanters that could enhance the efficiency and effectiveness of teff cultivation practices.

Studying teff seedling properties such as moisture content, weight, height, stem diameter, tensile force, shear forces, and coefficient of friction is vitally important for the design and development of agricultural machinery *(Kumar, U., & Thomas, E.V et al, 2015)*. Here's how each property relates to machinery design and agricultural practices of teff crop: Understanding moisture content helps in designing of planting and transplanting machinery that maintain optimal water levels in the soil. Equipment like seed drills and irrigation systems can be tailored to ensure proper soil moisture is maintained, reducing water wastage and promoting seedling health. Seedling weight influences how they respond to handling, planting, transplanting, and transportation. Heavier seedlings might be more resilient but also require more careful handling, machinery (such as planting and transplanting machines) must be capable of accommodating varying weights to prevent damage during transplanting or transport, enhancing operational efficiency. The height of seedlings can affect transplant spacing, depth of transplanting and row width in machinery operations. Designing transplanter, planters and cultivators requires knowledge of height to ensure adequate space for growth and to optimize the harvesting process without damaging the crop *(Kumar, U., & Thomas, E.V et al, 2015*).

Stem diameter plays a crucial role in the design of planting and transplanting machineries. A thicker stem indicates a stronger seedling. Understanding this can aid in selecting the right machinery for planting, transplanting, and will help in determining the appropriate force needed for tasks like detaching the seedling from the seedling mat, soil penetration. Equipment design needs to accommodate variations in stem diameter to minimize damage during transplanting, planting, while also ensuring effective seedling support and growth (*Hearn, 2000*). Tensile Force is a key property that helps assess how seedlings respond to pulling forces, which is vital during operations such as transplanting or mechanized harvesting. Machines need to be designed to exert the right amount of tensile force to avoid uprooting or damaging seedlings, enhancing success rates in transplant operations. Shear forces affect the seedling's ability to remain upright under mechanical processes and environmental stresses (like wind). Machines such as transplanter, harvesters might need to be designed mitigate shear forces when cutting or pulling plants, ensuring that they do not uproot or damage adjacent seedlings. The coefficient of friction determines how well seedlings can anchor in the soil and resist being displaced or uprooted.

Machinery Implications: The design of furrows, seed placement mechanisms, and soil types must be considered to optimize the coefficient of friction, ensuring that seedlings are securely embedded in the soil, reducing the chances of dislodgement during mechanized operations (*Kumar, U., & Thomas, E.V et al, 2015*).

In general, studying these seedling properties is essential for creating agricultural machinery that is not only efficient in operations but also fosters healthy plant growth and minimizes damage during planting, transplanting, transportation, and harvesting. Understanding these characteristics leads to better designs that improve agricultural productivity, enhance teff crop yields, and support sustainable farming practices.

The aim of this article is to find out how the physical and mechanical properties of the selected teff seedling influence the design of a transplanter. This will help to establish the convenient reference data required to develop equipment for handling, planting, transplanting, transportation, and other processes involving teff seedlings.

2. MATERIALS AND METHODS

2.1. MATERIALS

2.1.1 Study location

This study was conducted at the Ethiopian Institute of Agricultural Research, Melkasa Agricultural Research Center, which is located in the Central Valley of Ethiopia. The place is at an altitude of 1466 m above sea level and lies on the geographical coordinates of 8° 24' 0" N, 39° 20 0" E, Latitude and Longitude respectively. It receives 763 mm of mean annual rainfall, of which 70% falls during the major cropping season: June to September. The dominant soil type in the area is sandy loam.

2.1.2 Materials

The materials selected for the development of the transplanter were chosen based on durability, availability, strength, and weight. Standard components such as chains and sprockets, belts and pulleys, bearings, nuts, and bolts were considered during the design process. Structural steel square pipes with an outer width of 40 mm and a wall thickness of 3 mm were used for frame fabrication. Five shafts were employed to transmit power from the engine to the wheel and crank mechanism; these shafts were made of mild steel. The design was based on ductile materials, with strength governed by the maximum shear stress theory. The weight of each component was calculated analytically.

The devices used to measure the physical and mechanical properties of teff seedlings are shown in Fig. 1, and include the following: an FH 50K force gauge; a sensitive electronic balance; an oven dryer; a Vernier caliper (0–150 mm, 0.01 mm precision); and a bench-type universal testing machine (Hounsfield, England) with a capacity of 5 kN, used to measure seedling tensile strength. Shear (cutting force) tests were conducted using a texture analyzer with the following specifications: force capacity of 50 kgf (500 N), force resolution of 0.1 g, speed range of 0.01–40 mm/s, maximum aperture of 370 mm/590 mm, and distance resolution of 0.001 mm.

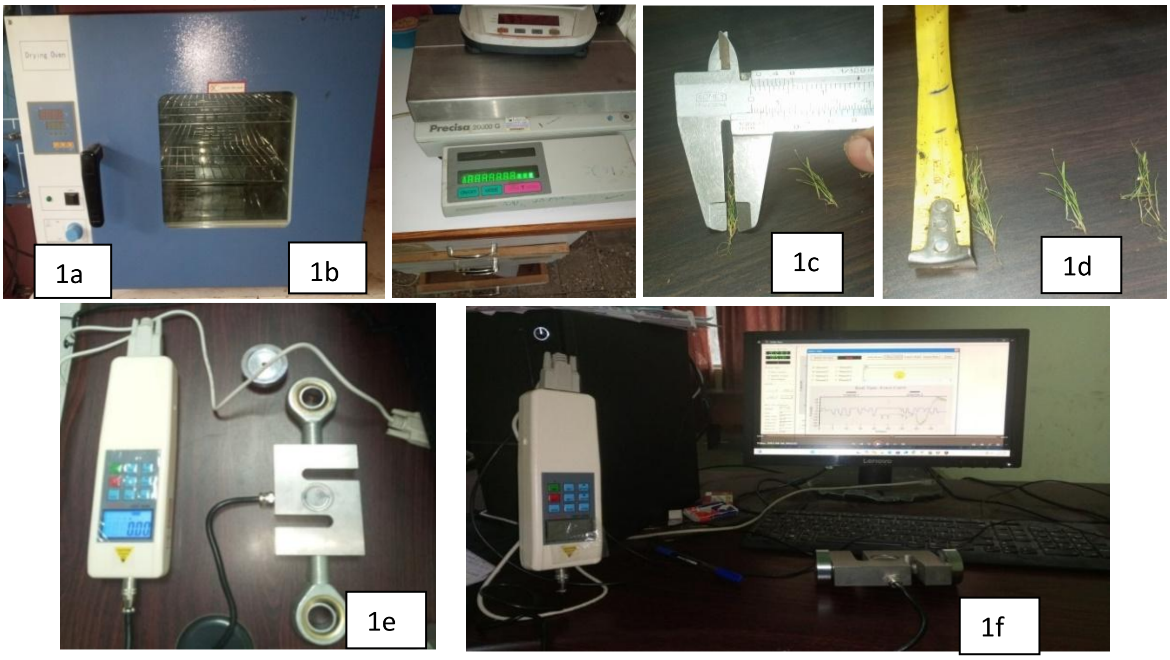


Fig. 1(a, b, c, d, e, f): Instruments used for measuring the physical and mechanical properties of seedlings
(1a) Oven dryer; (1b) Electronic balance; (1c) Vernier caliper; (1d) Measuring tape; (1e) FH 50K Force Gauge used for measuring tensile and shear forces; (1f) Real-time force curve display and computer–instrument setup during testing.

2.2 METHODS

All properties were assessed for 20, 25, and 30-day-old teff seedlings, focusing on four varieties: Quncho, Dukem, Tseday, and the local Gemechis variety. Each measurement was replicated three times for accuracy. Table 1 outlines the combinations of teff varieties and seedling ages used to evaluate their physical and mechanical properties. A total of 36 teff seedlings were randomly sampled from the nurseries of the four varieties. The data were analyzed using Statistix 10 and MATLAB 2024b software. Descriptive statistical analysis was conducted with Statistix 10, presenting results as mean values along with standard deviations for various parameters. Figure 2 illustrates the relationship between the physical and mechanical properties of teff seedlings and the prototype teff transplanter design. The overall methodology was depicted in Fig. 2 below.

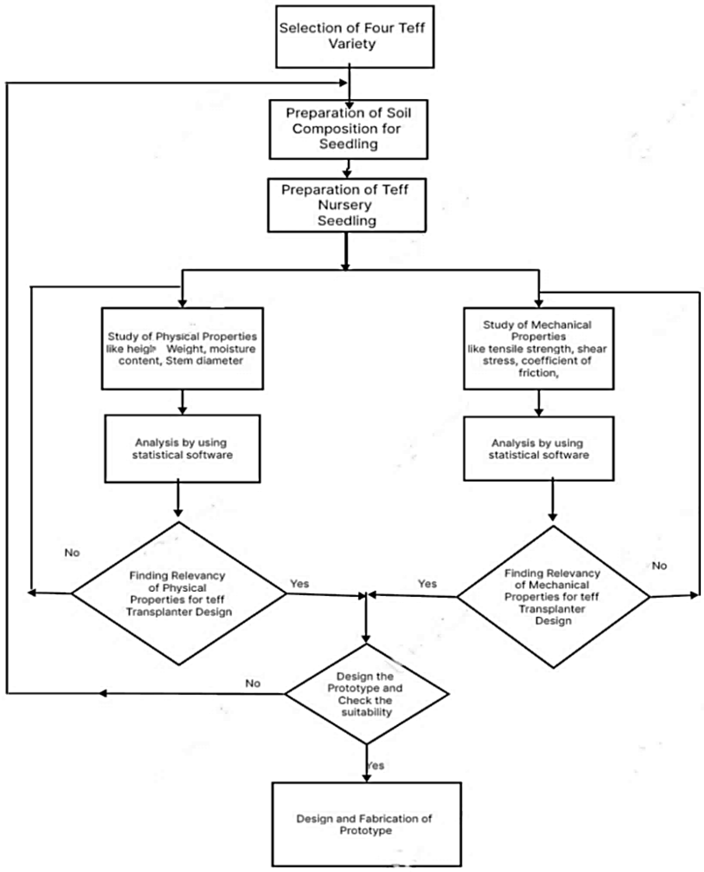


Fig. 2 - Overall methodology and relevance of the physical and mechanical properties of teff seedlings to the design of the teff transplanter prototype

Ethiopia boasts a diverse array of teff varieties adapted to various agricultural conditions, but our research specifically targeted four selected varieties. These are Dz-Cr-387/RIL-355 (Quncho), DZ-01-974 (Dukem), DZ-Cr-37 (Tseday), and DZ-Cr-387RIL#127 (Gemechis), sourced directly from local farmers (Fig 3). The selection was based on key criteria like productivity, grain quality, local farmer preference, and dissemination rates in Ethiopia. This decision followed thorough discussions with researchers at the Debre Zeit and Melkassa Agricultural Research Centers, who offered valuable insights into the most promising teff varieties relevant to our research objectives.

To ensure that mechanically transplanted seedlings met the standard requirements, they needed uniform distribution and intertwining roots. A suitable soil mix was essential for growing teff seedlings, allowing us to explore mat thickness, rolling quality, and the seedlings' physical and mechanical properties. After mixing, the soil was sterilized in an oven to prevent contamination.

Table 1

Details of the teff variety and seedling age combinations used for measuring physical and mechanical properties

SN	Teff Variety	20-day seedling age	25-day seedling age	30-day seedling age
1	V1 (Quncho)	V1S2	V1S3	V1S4
2	V2 (Dukem)	V2S2	V2S3	V2S4

SN	Teff Variety	20-day seedling age	25-day seedling age	30-day seedling age
3	V3 (Tseday)	V3S2	V3S3	V3S4
4	V4 (Local)	V4S2	V4S3	V4S4

where: V1, V2, V3, V4 represent Teff varieties: Quncho, Dukem, Tseday, and Local (Gemechis), respectively. S1, S2, S3, S4 correspond to different seedling ages.

Table 2

Detailed information of the selected teff varieties for seedlings

SN	Variety	Year Released	Center Released	Altitude	RF, mm	DM, days	Productivity (t/ha)	
							On station	On Farm
1	Quncho	2006	DZARC	1500-2500	300-700	80-113	2.4-2.8	2-2.2
2	Dukem	1995	DZARC	1400-2400	150-700	76-138	2.4-3.4	2-2.5
3	Tseday	1984	DZARC	500-700	300-700	82-90	1.8-2.8	1.4-1.9
4	Local (Gemechis)	2007	Melkassa	1450-1695	690-965	76-138	2.8-3.3	2.2-2.6

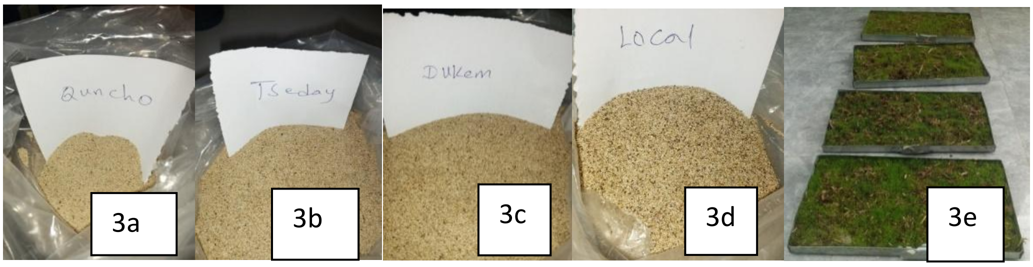


Fig. 3(a, b, c, d, e) - Teff varieties used for seedling cultivation

(a)*Quncho*, (b) *Dukem*, (c) *Tseday*, (d) Local (*Gemechis*), (e) Teff seedling growth on each plate

2.2.1 Study of the physical properties of teff seedlings

The detailed study of the physical properties of teff seedlings was conducted on four varieties of teff developed at the Melkassa research center. Seedlings were procured at the experimental nursery raised at the Melkassa site, Division of Agricultural Engineering Research, with the standard agronomic practice of nursery. The seedlings were raised in the nursery (tray) by the recommended seed rate and cultural practices.

According to the cultivation technology, the teff seedlings are transplanted at 20 to 30 days after sowing. Therefore, physical properties for the teff seedling transplanter design were considered at 20, 25, and 30 days after sowing.

The studies on different Physical properties of 36 randomly selected samples of all four varieties at 20, 25, and 30 days of teff seedlings were conducted in the Division of Agricultural Engineering laboratory as: 1) Weight of seedlings-Teff seedlings are generally raised for 20, 25, and 30 days, then uprooted as a whole seedling and put into an electronic weighing balance. Thus, thirty-six randomly selected seedlings were weighed with the root system with the help of an electronic weighing balance with a least count of 0.001 g. The weight of seedlings is an important parameter because teff seedlings are lighter than other crop seedlings. The ease with which seedlings flow in different components of the machine is affected by the weight of seedlings, as heavier seedlings drop better than the lighter seedlings due to the gravitational effect. 2) Moisture content**:** The moisture content of teff seedlings was determined at the transplanting stage. The standard method given by the Association of Official Agricultural Chemists (AOAC) to determine seedlings moisture content was used. The teff seedlings were cut into 3-4 thin slices, weighed, and oven dried to constant weight at 60 ± 2°C (*Stroshine, 1998*). 3) Stem diameter of teff seedlings**:** The stem diameter of teff seedlings was measured using a vernier caliper with a least count of 0.1 mm. These dimensions help determine the details of the metering mechanism, like determining the size of the finger groove in the finger planting mechanism. 4) Height of seedlings: The height of seedlings was measured through the longest dimension with the help of a steel tape (*Mohsenin, 1986*). It helps to determine the length of fingers and the height of the seedling tray.

2.2.2 Mechanical properties of the teff seedling

Identifying the mechanical properties of teff seedlings involves several methods and tests to assess characteristics such as strength, elasticity, toughness, and stiffness. For the mechanical properties, the tests conducted are: 1) Coefficient of friction: The coefficient of friction of teff seedlings on commonly used materials in fabrication, such as mild galvanized iron surfaces, was measured by using a calibrated tilting table (*Stroshine, 1998*). The teff seedling was kept on horizontal plane sheets of these materials, and inclination was gradually raised. The angle of impending slip was recorded. The coefficient of static friction was the tangent of the angle measured. The coefficient of static friction was computed using the formula: $\mu = \tan \delta$, where μ = Coefficient of friction and δ = Angle at impending slip, degrees. 2) Tensile force and shear force: The FH 50K Force Gauge, part of the FH-M Series of digital force gauges, is a versatile device designed to measure tensile and compressive forces using an external measuring cell. This handheld instrument integrates a load cell, electronics, and a display. At the core of the digital force gauge is the load cell, which functions as a spring that flexes under applied force (Fig.1). As the load increases and deflection occurs, the internal conductor is "stretched," resulting in a longer, thinner current path with increased internal resistance. This leads to a reduction in "signal voltage," and the display, whether analog or digital, indicates the increased load as a rise in weight. Force gauges, commonly referred to as "push-pull gauges" or "push-pull scales," measure the force acting on a sample and can assess tension, compression, bending, shear, as well as peel, adhesion, and friction. These tests provided critical data on the tensile force, shear force, and coefficient of friction of the seedlings, which are essential for designing a transplanter that can handle teff seedlings without damage.

3. RESULTS AND DISCUSSION

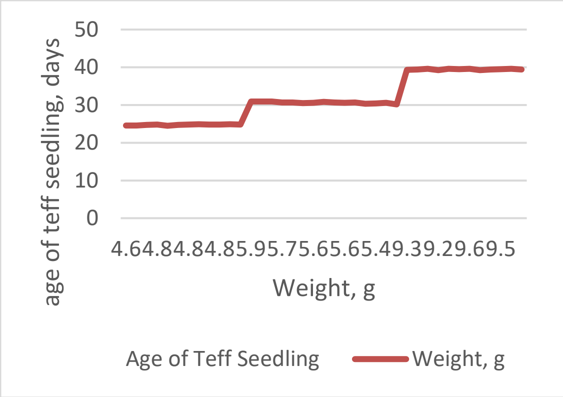
3.1 RESULTS

Table 3 presents the analysis results of the physical and mechanical properties of four teff seedling varieties.

Table 3

Physical and mechanical properties of *Quncho, Dukem, Tseday* and Local (*Gemechis*) teff seedlings at 20, 25, and 30 days of age

Age of Seedlings, (Days)	MC, (%)	Weight, (g)	Height, (cm)	Stem Diameter, (mm)	Tensile Force, (N)	Shear Force, (N)	Coefficient of static friction, (%)
				Quncho			
20	87.57±1a.520	4.63±0.152a	12.3± 0.265a	1.15±0.03a	12.17±0.053a	15.93±0.404a	0.87±0.01a
25	72.71±0.997b	5.65±0.252b	15.93±0.479b	1.165±0.03b	14.46±0.964b	17.3±0.469b	0.703±0.032b
30	66.27±0.577c	9.43±0.153c	34.83±0.577c	1.223±0.006c	18.297±0.577c	20.53±0.153c	0.527±0.0153c
				Dukem			
20	87.13±1.762a	4.7±0.1a	12.63±0.116a	1.153±0.0153a	12.36±0.058a	15.97±0.473a	0.88±0.01a
25	73.2±0.854b	5.6±0.265b	16.33±0.64b	1.18±0.053b	14.597±1.11b	17.367±0.116b	0.707±0.0462b
30	65.17±0.58c	9.467±0.058c	32.93±0.578c	1.227±0.012c	18.763±0.57c	20.567±0.116c	0.53±0.011c
				Tseday			
20	87.43±1.69a	4.8±0.11a	12.8±0.61a	1.143±0.015a	12.66±0.057a	15.33±0.473a	0.863±0.012a
25	73.33±1.704b	5.73±0.153b	16±0.854b	1.177±0.05b	14.097±0.81b	17.33±0.503b	0.673±0.0058b
30	67.53±1.155c	9.6±0.00c	33.43±0.231c	1.24±0.012c	17.9±1.155c	20.47±0.153c	0.55±0.021c
				Local (*Gemechis*)			
20	88.13±0.643a	4.83±0.058a	12.03±1.102a	1.13±0.027a	12.18±0.057a	15.53±0.751a	0.867±0.0058a
25	75.8±0.53b	5.567±0.322b	15.3±0.578b	1.15±0.053b	14.32±0.764b	17.4±0.173b	0.627±0.06b
30	67.9±5.196c	9.267±0.116c	31.27±0.289c	1.213±0.0057c	19.12±0.012c	21.03±0.38c	0.56±0.0173c



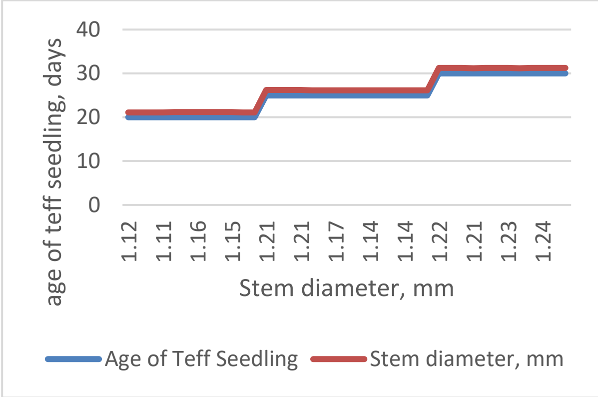
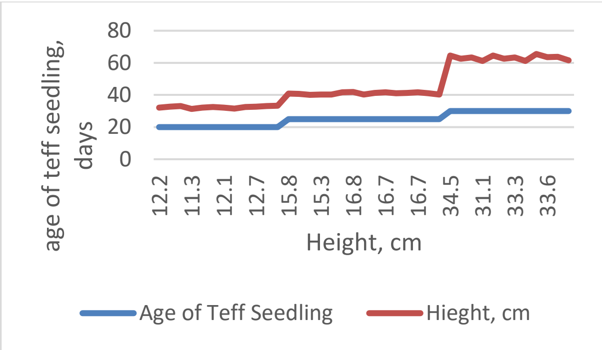


Fig. 4 - Influence of seedling age on the weight (left) and stem diameter (right) of teff seedlings for the Quncho, Dukem, Tseday, and Local (Gemechis) varieties at 20, 25, and 30 days of age



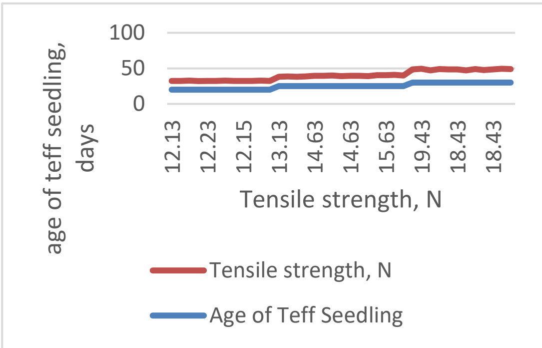


Fig. 5 - Influence of seedling age on the height (left) and tensile strength (right) of teff seedlings for the Quncho, Dukem, Tseday, and Local (Gemechis) varieties at 20, 25, and 30 days of age

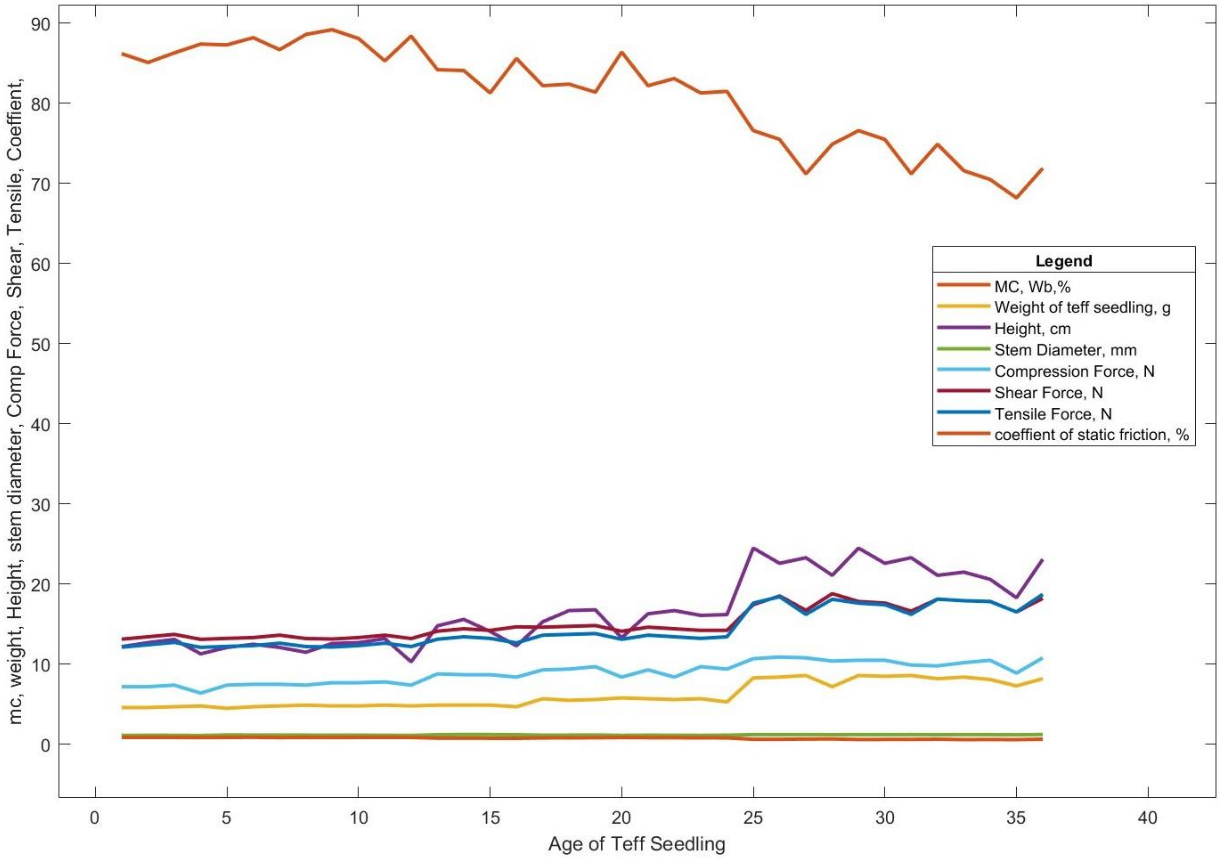


Fig. 6 - Influence of seedling age on the moisture content, weight, stem diameter, height, compressive force, shear stress, and tensile strength of teff seedlings for the Quncho, Dukem, Tseday, and Local (Gemechis) varieties at 20, 25, and 30 days of age

Table 4

Force required to detach the seedlings from the seedling mat

SN	Types of force	15 mm mat thickness		20 mm mat thickness	
		min	max	min	max
1	Tangential force at the tip of the finger, N	3.68	4.70	3.11	5.32
2	Radial force at the tip of the finger, N	4.05	7.53	5.85	9.06
3	Resultant force of finger, N	6.07	9.38	7.48	10.72

3.2 DISCUSSIONS

The analysis of the data presented in Table 3 reveals that the mean moisture content (MC) values of the *Quncho* teff variety seedlings were 87.57±1.52%, 72.71±0.997%, 66.27±0.577% at 20, 25, and 30 days of age, respectively, showing significant differences among the seedling ages *(Nazari G., et al., 2008)*. Similarly the mean values for weight (g), height (cm), stem diameter (mm), tensile force (N), shear force (N), and coefficient of static friction (%) for Quncho seedlings were 4.63±0.152 g, 5.65±0.252 g, 9.43±0.153 g; 12.3±0.265 cm, 15.93±0.479 cm, 34.83±0.577 cm; 1.15±0.03 mm, 1.165±0.03 mm, 1.223±0.006 mm; 12.17±0.053 N, 14.46±0.964 N, 18.297±0.577 N; 15.93±0.404 N, 17.3±0.469 N, 20.53±0.153 N; 0.87±0.01, 0.703±0.032, 0.527±0.0153 at 20, 25, and 30 days of age respectively. Each parameter showed a statistically significant difference among seedling ages, indicating that physical and mechanical properties change notably as seedlings mature. Similar results were reported for the biometric properties of onion seedlings at different ages (*Pandirwar A, 2015*), and by *Pandirwar (2016)* in a study on onion seedling properties for transplanter design.

Table 3 also presents the analysis results of the *Dukem* teff variety seedling properties at 20, 25, and 30 days of age. The measured parameters - moisture content, weight, height, stem diameter, tensile force, shear force, and coefficient of static friction - were found to be 87.13±1.762%, 73.2±0.854%, 65.17±0.58%; 4.7±0.1 g, 5.6±0.265 g, 9.467±0.058 g; 12.63±0.116 cm, 16.33±0.64 cm, 32.93±0.578 cm; 1.153±0.0153 mm, 1.18±0.053 mm, 1.227±0.012 mm; 12.36±0.058 N, 14.597±1.11 N, 18.763±0.57 N; 15.97±0.473 N, 17.367±0.116 N, 20.567±0.116 N; 0.88±0.01, 0.707±0.0462, 0.53±0.011, respectively (*Eshetie A., et al., 2023*). The results show that as the age of the seedlings increased, both tensile and shear forces also increased, consistent with findings reported by *Geta K. et al., (2020)*.

Similarly, Table 3 shows the results of the *Tseday* teff variety seedling properties at 20, 25, and 30 days of age. The measured parameters - moisture content, weight, height, stem diameter, tensile force, shear force, and coefficient of static friction - were 87.43±1.69%, 73.33±1.704%, 67.53±1.155%; 4.8±0.11 g, 5.73±0.153 g, 9.6±0.00 g; 12.8±0.61 cm,16±0.854 cm, 33.43±0.231 cm; 1.143±0.015 mm, 1.177±0.05 mm, 1.24±0.012 mm; 12.66±0.057 N, 14.097±0.81 N, 17.9±1.155 N; 15.33±0.473 N, 17.33±0.503 N, 20.47±0.153 N; 0.863±0.012, 0.673±0.0058, 0.55±0.021, respectively. Similar results were reported by *Pandirwar A (2015)*.

Table 3 also presents the results of the *Local (Gemechis)* teff variety seedling properties at 20, 25, and 30 days of age. The measured parameters - moisture content, weight, height, stem diameter, tensile force, shear force, and coefficient of static friction - were 88.13±0.643%, 75.8±0.53%, 67.9±5.196%; 4.83±0.058 g, 5.567±0.322 g, 9,267±0.116 g, 12.03±1.102 cm, 15.3±0.578 cm, 31.27±0289 cm; 1.13±0.027 mm, 1.15±0.053 mm, 1.213±0.0057 mm, 12.18±0.057 N, 14.32±0.764 N, 19.12±0.012 N; 15.53±0.751 N, 17.4±0.0173 N, 21.03±0.038 N; 0.867±0.0058, 0.627±0.06, 0.56±0.0173, respectively (*Pandirwar, 2015; Khadatkar, 2020*).

Figures 4, 5, and 6 illustrate the relationships among key physical and mechanical properties of *Quncho, Dukem, Tseday*, and *Local (Gemechis)* teff seedlings. As the seedlings aged (20, 25, and 30 days after planting), distinct trends were observed over time. Specifically, the weight, height, stem diameter, tensile strength, and shear stress of the seedlings increased with age, whereas the moisture content and coefficient of static friction exhibited an inverse relationship. As the seedlings matured, their moisture content and coefficient of static friction decreased, likely due to tissue densification and lignification during growth, which reduce the proportion of water relative to dry matter.

According to Table 4, the force required to detach a seedling was at least 10.72 N for a 20 mm-thick mat and 9.38 N for a 15 mm-thick mat. Comparing the results presented in Tables 3 and 4 shows that the teff seedlings can withstand these forces without sustaining damage such as breakage or shearing. If the applied force falls below the threshold values indicated in Table 4, the seedlings are more likely to break during handling. Specifically, the transplanter applies forces ranging from 6.07 to 9.38 N for the 15 mm mat and 7.48

to 10.72 N for the 20 mm mat. The tensile strengths of the teff seedlings were measured as follows: *Quncho* (12.17±0.053 N, 14.46±0.964 N, and 18.297±0.577 N), *Dukem* (12.36±0.058 N, 14.597±1.11 N, and 18.763±0.57 N), *Tseday* (12.66±0.057 N, 14.097±0.81 N, and 17.9±1.155 N), and *Local (Gemechis)* (12.18±0.057 N, 14.32±0.764 N, and 19.12±0.012 N) for 20-, 25-, and 30-day-old seedlings, respectively. All measured tensile strength values exceeded the detachment forces applied by the transplanter, indicating that the seedlings of all four teff varieties can withstand the mechanical stress during transplantation. This confirms that the seedlings possess sufficient strength and structural integrity, making them suitable for the design and development of a mechanical transplanter for teff crops.

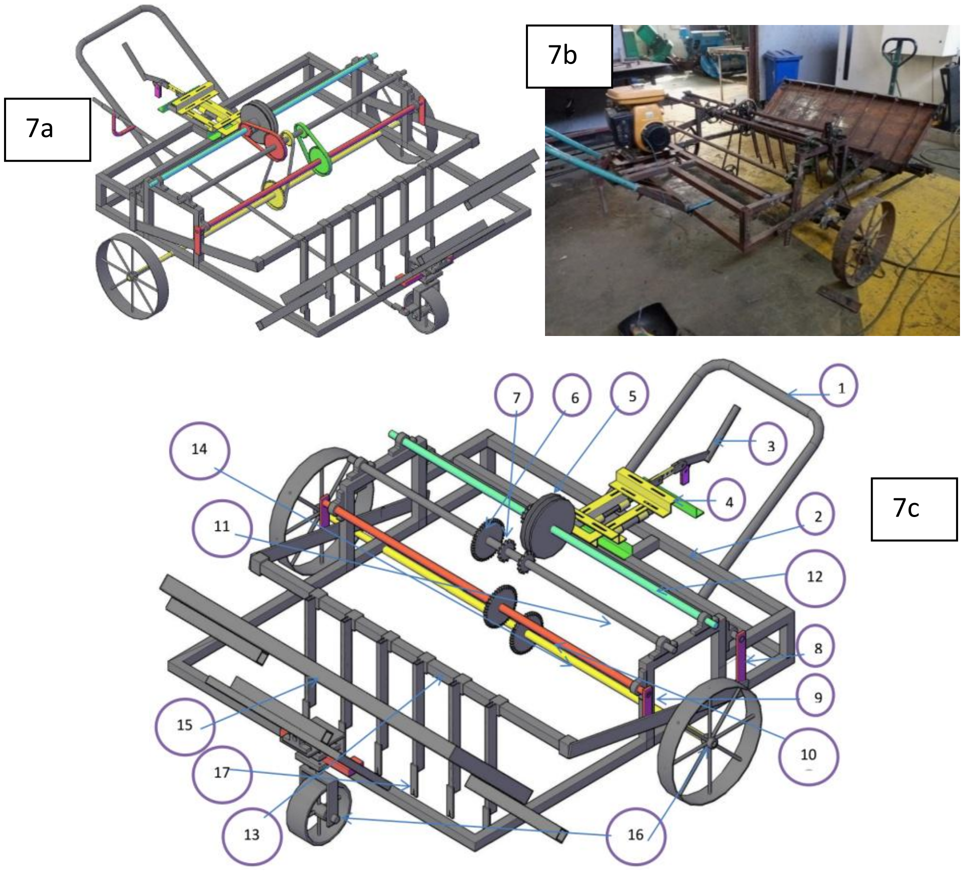


Fig. 7 (a, b, c) - (a) CAD design and (b) the developed prototype;
(c): CAD model of Teff transplanter and its components:
1 - handle, 2 - frame, 3 - engine engaging and disengaging arm, 4 - engine stand, 5 - large pulley, 6 - large sprocket from the main shaft to third shaft, 7 - small sprocket, 8 - large connecting rod, 9 - small cranking rod, 10 - third shaft, 11 - secondary shaft, 12 - main shaft, 13 - finger arm cranking bar, 14 - wheel shaft, 15 - seedling tray, 16 - wheels, 17 - finger arm or fork.

The mechanical properties of crops are not only important for developing new varieties and genetically improved breeds but are also essential for designing and optimizing agricultural machinery. These properties are critical for the development of various pre-harvest technologies, such as transplanters and harvesting equipment, as well as post-harvest technologies, including threshing and processing machines used in teff production. To design a suitable and efficient transplanter for teff, it is crucial to understand the physical and mechanical properties of teff seedlings.

Therefore, knowing the coefficient of friction of the seedlings is essential for designing the tray components of the prototype. From Table 3, the coefficient of static friction for the seedlings was found to range from 0.52 to 0.88%, which corresponds to an angle of inclination ($\tan^{-1}$) of approximately 27-45°. Based on this result, the prototype seedling tray was designed using the maximum inclination angle to ensure the continuous downward movement of teff seedlings along the tray. Similarly, the seedling stem diameter is an important parameter for designing the finger arm of the transplanter. The spacing between the fingers must be sufficient to hold at least three seedlings at a time. According to Table 3, the average stem diameter of teff seedlings ranged from 1.13 to 1.2367 mm; therefore, to accommodate three seedlings simultaneously, the slot width of the finger arm was calculated as 3.71 mm, and a practical design width of 4 mm was adopted.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

In conclusion, the study demonstrated that teff seedlings possess robust tensile strength and shear resistance that exceed the forces typically applied during transplanting, thereby minimizing the risk of mechanical damage during operation. As the seedlings matured, their weight, height, stem diameter, and overall mechanical strength increased, while moisture content decreased. Among the tested varieties, the *Local (Gemechis)* variety exhibited superior mechanical performance, making it particularly suitable for specific agricultural applications. Overall, understanding the physical and mechanical properties of teff seedlings is essential for optimizing transplanter design. However, further research is recommended to evaluate additional teff varieties.

The physical and mechanical properties of the teff varieties played a crucial role in shaping the design of the main components of the transplanter, particularly the seedling tray. These parameters provided essential input data for the prototype design, ensuring that the tray could securely hold and transport the seedlings without causing damage. Furthermore, the design of other mechanical components, such as the finger arm and crank mechanism, was influenced by the seedling diameter and the force requirements associated with mat resistance and seedling extraction during the planting process. By incorporating the physical dimensions and mechanical behavior of the seedlings, the design ensured effective engagement with each seedling while minimizing the risk of mechanical failure or damage. The overall system was developed using a comprehensive design approach that considered multiple factors, including the weight and strength of construction materials, component load capacity, the weight of the seedlings, and soil reaction forces during planting operations.

4.2 RECOMMENDATIONS

Based on the findings of this study, future research should encompass a wider range of teff varieties to gain a comprehensive understanding of their mechanical properties and growth dynamics. Further studies are recommended to investigate the effects of environmental factors, such as soil type, moisture levels, and temperature, on the tensile and shear strength of teff seedlings. Long-term investigations examining the evolution of seedling growth and mechanical behavior over extended periods could also provide valuable insights into optimal transplanting and harvesting practices. In addition, evaluating the mechanical performance of hybrid or genetically improved teff varieties may offer important information for improving agricultural efficiency and minimizing seedling damage during mechanized transplanting operations.

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