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Data Analysis of Oil Palm (Elaeis Guineensis) Root Carrying Capacity in Mitigating Landslide Risk Due to Extreme Rainfall: A Comparative Literature Study

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Abstract: *This study examines the carrying capacity of oil palm (Elaeis guineensis) roots in mitigating landslide risk under extreme rainfall conditions in Indonesia. The research was motivated by increasing deforestation and the conversion of natural forests into oil palm monoculture plantations, which reduce slope stability and increase disaster vulnerability. The objective of this study was to analyze the effectiveness of oil palm root systems in maintaining soil stability using the Index of Root Anchoring (IRA) and Index of Root Binding (IRB) parameters. This research employed a qualitative descriptive method with a comparative literature study approach. The population consisted of scientific literature discussing root biomechanics, soil stability, and landslide mitigation, while the sample included selected journals, reports, and scientific references relevant to oil palm root characteristics. Data were collected through literature documentation techniques and analyzed descriptively by comparing IRA and IRB values from previous studies. The results showed that oil palm roots possess relatively strong horizontal binding capacity with an IRB value of approximately 0.0256, but very weak vertical anchoring capacity with an IRA value of approximately 0.004. The conclusion indicates that oil palm plantations can reduce surface erosion but are unable to provide adequate deep-soil reinforcement under extreme rainfall conditions, thereby increasing landslide susceptibility..*

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Introduction

Trees are plants that cannot be separated from living things. They are the lungs of the world, providing us with shelter with the shade of their leaves or trunks as basic building materials, and as a source of fiber and nutrition with their fruits. Beyond these benefits, trees play a crucial role in maintaining environmental stability through their root systems. The root network works actively to bind soil particles, increase cohesion, and prevent landslides, especially when there is an increase in pore water pressure due to heavy rainfall. As stated by Anwar Abbas, Head of the Environmental Division of PP Muhammadiyah, in the Tempo news page on December 10, 2025, "Dense forests will be able to reduce soil erosion and landslides so that when heavy rain occurs, the water flowing into the river will not be too muddy."

This ecological function is increasingly threatened by the massive deforestation of natural forests for monoculture plantations, particularly oil palm (Elaeis guineensis J.). This change has triggered a crisis that has a direct impact on the safety of residents in upstream and downstream areas. A Kompas (2025) report presented data on the impact of landslides in North Sumatra and its surroundings as of January 2026, where environmental degradation had caused more than 1,200 deaths and forced 1.1 million people to evacuate. This environmental damage was also explained by Tempo (2025) through the fact of massive infrastructure damage; in Aceh Province alone, at least 461 road points and 332 bridges were recorded as having suffered serious damage due to slope failure and flash floods.

The lower disaster mitigation capacity of oil palm plantations compared to natural forests is technically rooted in the biological differences between the two types of vegetation. Experts from the University of Muhammadiyah Malang (2024) explained that trees in natural forests can absorb 100-200 liters of water per day, while oil palm trees can only absorb 20-30 liters due to the smaller xylem structure and the presence of a wax layer on the trunk that inhibits the infiltration process. Furthermore, analysis from LindungiHutan (2024) shows that taproots in natural forests that can penetrate to a depth of 10 meters function as effective soil anchors, in contrast to the characteristics of oil palm roots which are shallow fibrous roots with an average reach of only 50-100 cm.

Recent weather instability, characterized by scorching heat and unpredictable rainstorms, has made land with single vegetation such as oil palms vulnerable to risks worthy of investigation. Based on these conditions, this study was conducted to comparatively analyze the carrying capacity of oil palm roots in mitigating landslide risks. This study is based on data and formulas regarding tree roots from the journal Hairiah et. al. which were then compared with data on oil palm tree roots from the journal Yahya et. al. The results of this study are expected to provide a scientific basis for more sustainable land management and soil conservation efforts in facing future disaster threats.

How effective is the root bearing capacity of oil palm (Elaeis guineensis) in mitigating the risk of landslides? Is there a correlation between the intensity and duration of extreme rainfall and the increased frequency of landslides in areas dominated by oil palm (Elaeis guineensis) trees? How do the results of the root bearing capacity analysis of oil palm (Elaeis guineensis) contribute to data and landslide mitigation strategies?

Analyzing the effectiveness of the root bearing capacity of oil palm (Elaeis guineensis) in mitigating the risk of landslides. To determine the correlation between the intensity and duration of extreme rainfall with the increasing frequency of landslides in areas dominated by oil palm (Elaeis guineensis) trees. To determine the results of the analysis of the root bearing capacity of oil palm (Elaeis guineensis) to contribute as data and landslide disaster mitigation strategies.

This research is expected to provide benefits from various aspects as follows: Academic Aspect, this research contributes to increasing knowledge and scientific references in the field of geotechnics and disaster mitigation, especially related to the role of the oil palm root system (Elaeis guineensis J.) in increasing soil bearing capacity and slope stability. Theoretical Aspect, this research aims to provide an understanding of the process of soil strengthening by plant roots in increasing soil cohesion and suppressing the potential for soil mass movement in high-intensity rainfall conditions. This research strengthens the understanding of the functional imbalance between the ability to bind the surface (binding) and the ability to anchor the deep soil structure (anchoring) in monoculture crops. Practical Aspect, this research can be a reference for plantation managers in mapping landslide risks based on the

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biological characteristics of shallow oil palm roots (80% biomass at a depth of <60 cm). In addition, this data can be used as a basis for calibrating soil moisture monitoring tools for early evacuation.

This research provides baseline data for determining mitigation methods for relevant agencies in developing plans to reduce landslide risk. The results can be used by policymakers to develop land use and soil conservation policies that prioritize environmental safety and regional sustainability.

Literature review

Tree

The most basic concept for defining a tree is a perennial, woody, large and tall plant, with a single, upright, unbranched trunk, and capable of supporting itself to support a separate crown of branches at the top, which can grow to a height of more than 10 feet (±3.05 meters) and a diameter of more than 3 inches (±7.6 cm.) said Coder (2024). A more practical definition of a tree is a woody plant that has a single, upright main stem (trunk) with a diameter of at least three inches at a point 4.5 feet (±1.37 meters) above the ground, has a clear foliage pattern, and reaches a mature height of at least 13 feet (±4 meters).

Root of the tree

Tree roots are the part of the tree that is usually located underground, growing toward the center of the earth (geotrope) or toward water (hydrotrope). The root body cannot support leaves or their parts because it lacks nodes and internodes. Unlike green plants, roots are whitish to yellowish in color, according to Nugroho (2006). The pointed tip of the root allows it to easily penetrate the soil mechanically and chemically. In addition, the stem grows more slowly than the root tip. Plant roots strengthen the plant body and transport water and nutrients to areas needed by the plant after absorbing them from the soil. According to Nugroho (2006), roots also function as a storage place for additional nutrients. Due to the diversity of root systems, there is a relationship between root properties and their function (Atkinson, 2000).

Oil Palm Tree

The oil palm is one of the world's most important plantation crops, primarily due to its ability to produce palm oil, an essential raw material for the food, cosmetics, and biodiesel industries. The plant originates from West Africa but is now widely cultivated in various tropical countries, including Indonesia and Malaysia, which are the world's leading palm oil producers. Palm oil is highly popular for various industrial applications due to its high productivity and low production costs. It is one of the most economically valuable plantation crops in the world due to its long life cycle and ability to produce products for many years (Prasvita, 2010).

The oil palm (Elaeis guineensis) is a plant of the caste Plantae, subdivision Magnoliophyta (flowering plants), class Liliopsida (monocotyledonous plants), order Arecales, and family Arecaceae. Due to its high oil productivity and ability to adapt to many tropical conditions, Elaeis guineensis is the most commonly cultivated species for palm oil production.

The oil palm is a type of tree that can grow up to 24 meters tall. Its flowers and fruit are clustered and have many branches. The fruit is small and reddish-black when ripe. Oil is found in the skin and leaves of the oil palm. Palm oil is used to make candles, soap, and cooking oil. The pulp is used as animal feed, especially for chickens. The physiological characteristics of the oil palm are as follows:

1. Leaf

   The oil palm's leaves are dark green, compound, with slightly lighter midribs. The thorns are not particularly hard or sharp, but their appearance is similar to that of the snake fruit.
2. Stem

   The stem of the plant is covered with midrib scars until it is plus or minus twelve years old. After the age of plus or minus twelve years, the dry fronds will fall off so that they resemble a coconut plant.
3. Root

   The roots of oil palm trees are fibrous. The fibrous roots of oil palm plants grow downward and to the sides, and some respiratory roots grow upward to the sides to access more air.
4. Flower

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Male and female flowers are distinct and mature at different times, making self-pollination extremely rare. Male flowers are smaller and more profuse than female flowers.

5. Fruit

   Depending on the seeds used, palm fruit can be black, purple, or red.

Land

The top layer of the earth's plate is land. Das (1995) states that soil is usually defined as material consisting of solid mineral aggregates (grains) that are not cemented (chemically bound) to each other and weathered organic matter. These solid particles are filled with liquid and gas, filling the empty spaces between the solid particles.

Soil types vary depending on location. According to Dokuchaev (1870) in Fauizek et al. (2018), soil is the surface layer of the earth derived from parent material that has undergone natural changes due to water, air, and various living and dead organisms. The composition, structure, and color of weathering undergo significant changes.

Soil Erosion (Landslide)

The process of eroding or moving topsoil from one location to another by natural means such as water, wind, or ice is known as soil erosion. Erosion is a major global problem that can threaten land productivity and environmental quality (Yibeltal et al., 2019). According to Hardiyatmo (2006), there are several types of erosion:

1. Splash erosion is erosion caused by splashes and/or rainwater.
2. Sheet erosion occurs on hillsides due to thin layers of erosion, like a sheet of paper being worn away.
3. Gully erosion is erosion caused by the erosion of water flow that forms small gullies or water channels.
4. Gully erosion occurs when the groove becomes wider and has almost the same process as gully erosion but with a depth of 1 to 2.5 meters.
5. Stream erosion, which occurs when the surface of a levees or watershed edge erodes, causes sediment to be washed away along the stream.

Soil Moisture

According to Ahmad Auhaz (2022), soil structure stores and regulates water within the soil. When rain falls or plants are watered, water seeps into the soil along with soil particles. In a process known as absorption, soil has the capacity to hold or bind water for a certain period of time..

Soil moisture is the amount of water held within the soil pores. It is a term used to describe water that partially or completely fills the soil pores above the water table. Soil moisture is highly dynamic due to the processes of evaporation, transpiration, and percolation. Soil moisture is an important variable in the exchange of water and heat energy between the surface and the atmosphere through evaporation and transpiration. It provides important information on issues such as runoff potential and flood control, soil erosion and slope failure, water resource management, geotechnical engineering, and water quality.

IRA and IRB Index

1. *Index of Root Anchoring*(IRA):

a. Definition:

   Hairiah et al. (2020) stated that this index measures how roots spread vertically. The IRA serves as a benchmark for how well roots can dig deep to anchor the soil structure. It's like an anchor thrown from a ship to the seabed, acting as a barrier against horizontal pull. A ship with a strong anchor will remain anchored even when strong waves push against it. When combined with the concept of roots, the IRA is an index of how strong a tree is at preventing it from being swept away and falling.

b. Calculation Basis:

$$IRA = \frac{\Sigma D_V^2}{dbh^2}$$

ΣD_V^2: The sum of the squares of the diameters of all vertical roots.

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dbh^2: The sum of the squares of the stem diameters at breast height.

2. *Index of Root Binding*(IRB):

a. Definition:

Hairiah et al. (2020) stated that this index measures how far roots stretch horizontally. The IRB defines how much a tree's roots, particularly fibrous and lateral-branching roots, can form a network that holds the topsoil together. Imagine building a house floor; if we simply pour cement without any reinforcing steel, the floor will be very fragile and easily crack under load. However, when the reinforcing steel is installed horizontally, it binds the cement granules together into a solid whole. In the roots, the IRB is an index of how trees can maintain the strength of the soil structure.

b. Calculation Basis

$$IRB = \frac{\Sigma D_H^2}{dbh^2}$$

ΣD_H^2: Sum of the squares of the diameters of horizontal roots (proximal roots with a growth angle of less than 45° to the soil surface).

dbh^2: The sum of the squares of the diameters of the tree trunk at breast height.

***Proximal Root*(Proximal Root)**

Proximal roots are defined as the roots that form the first branch and emerge directly from the base of the tree trunk (Van Noordwijk et al., 2001). In the application of Functional Branch Analysis (FBA), the diameter of the proximal root is a key parameter for estimating the total biomass of the root system without causing land destruction (non-destructive), where measurements are made by digging the soil around the tree until the first branching point is clearly visible. This diameter data is then used in an allometric equation through a support program to estimate the biomass weight of an entire root system and all its subroots fractal (Van Noordwijk and Mulia, 2001).

Method

Time and Place

This research was conducted from February 3, 2026 to May 10, 2026, which included searching for references, collecting data, and compiling journals on the campus of the Indonesian University of Education, and online from the researcher's location.

Types of research

The type of research the researcher conducted was descriptive qualitative research. Descriptive qualitative research utilizes a library research approach, also known as a literature study. This approach is used to collect literature study data on relevant themes by reviewing books, research journals, scientific articles, and previous research (Meleong, 2010). Research that describes the results of the research conducted is called descriptive research. Descriptive research, as the name suggests, aims to provide descriptions, explanations, and validation of the phenomena being studied (Ramdhan, 2021).

Results and Discussion

Oil Palm Root Data

Based on a journal study of the root characteristics of oil palm (Elaeis guineensis), several technical parameters were identified that influence the plant's ability to support soil stability. Data extracted from the research (Yahya et al., 2010) regarding root response to environmental and technical conditions are presented as follows:

1. **Mechanical Characteristics and Root Architecture. Oil palm root systems are technically classified into four levels based on their diameter:**
   A. Primary roots are 5–10 mm in diameter.
   B. Secondary roots are 2–4 mm in diameter.
   C. Tertiary roots are 0.7–1.2 mm in diameter.
   D. Quaternary roots are 0.1–0.3 mm in diameter.

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2. **Biomass Distribution and Root Depth. The ability of roots to bind soil mass is greatly influenced by their depth distribution:**
   A. About 80% of the total root biomass is found only in the topsoil at a depth of up to 60 cm.
   B. The densest concentration of roots is found at shallow depths, namely 0–20 cm from the soil surface.
   C. Primary roots can grow vertically to a depth of more than 5 meters and horizontally up to 6 meters from the base of the tree.
   D. The total dry root biomass of a mature oil palm tree is estimated to reach 22.5 kg.

3. **Root Response to External Factors.PRoot growth shows heterogeneity according to the distance and activities around the land area:**
   A. The highest root density is near the base of the trunk and tends to decrease with increasing distance from the tree.
   B. Root growth in certain areas increases significantly in locations containing abundant organic matter, for example in areas located under piles of fronds.
   C. Mechanization activities or the use of heavy equipment result in soil compaction which inhibits root growth, and this is evident from the lower biomass produced by primary and secondary roots in vehicle paths.
   D. The root-to-shoot ratio of oil palm is relatively low, ranging from 0.15 to 0.20.

4. **Evaluation Parameters (IRA and IRB Index)**

This study divides the mechanical function of roots into two main indices:

A. *Index of Root Anchoring*(IRA):

Calculation Basis:

$$IRA = \frac{\Sigma D_V^2}{dbh^2}$$

ΣD_V^2: The sum of the squares of the diameters of all vertical roots.
dbh^2: The sum of the squares of the stem diameters at breast height.

B. *Index of Root Binding*(IRB):

Basis of calculation:

$$IRB = \frac{\Sigma D_H^2}{dbh^2}$$

ΣD_H^2: Sum of the squares of the diameters of horizontal roots (proximal roots with a growth angle of less than 45° to the soil surface).
dbh^2: The sum of the squares of the diameters of the tree trunk at breast height.

Through these two indexes, researchers can assess the carrying capacity of tree roots, from the balance between binding soil structure (IRA), and holding the top layer of soil (IRB).

Discussion

1. Evaluation of Mechanical Support Capacity of Oil Palm Roots Based on IRA and IRB Index

Based on mechanical analysis using the Index of Root Anchoring (IRA) and Index of Root Binding (IRB) parameters, significant functional imbalances were found in the oil palm root system. With an average stem diameter of 0.5 meters and the presence of thousands of proximal roots, the effectiveness of this vegetation's bearing capacity on slope stability can be described as follows:

A. Basic Data

Trunk Diameter (dbh): Average 0.5 meters (50 cm)

Proximal Roots: Oil palms have approximately 2,000 to 4,000 primary roots extending from their trunks. However, they have only a few vertical roots.

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B. IRA (Index of Root Anchoring) Calculation

IRA measures downward-sloping roots (angle >45°). Oil palm root biomass data at a depth of >60 cm.

Estimate: If there are 10 vertical primary roots with an average diameter of 1 cm.

ΣD_V^2: $=10 \times (1^2) 10\ cm^2$

Calculation:

$$IRA = \frac{10}{50^2} = \frac{10}{2500} = \mathbf{0{,}004}$$

The calculation results show that the IRA value for oil palm is only 0.004, a figure far below the ideal standard for slope shade trees (0.1 to 1.0). Technically, this demonstrates that oil palms lack strong vertical anchorage. Oil palm roots fail to function as ground anchors due to their limited penetration and inability to bind the soil structure below 60 cm.

C. IRB (Index of Root Binding) Calculation

IRB measures horizontal roots (angle <45°). Oil palms have thousands of lateral roots and fibrous roots on the surface.

Estimate: There are approximately 100 horizontal (proximal) primary roots with an average diameter of 0.8 cm around the base.

$\Sigma D_H^2 : 100 \times (0{,}8^2) = 100 \times 0{,}64 = 64\ cm^2$

Calculation:

$$IRB = \frac{64}{50^2} = \frac{64}{2500} = \mathbf{0{,}0256}$$

In contrast, the IRB value was found to be 0.0256, or approximately six times greater than the IRA value. This indicates that oil palms have a fairly strong soil binding capacity. Their roots act like rebar, binding the topsoil together, effectively preventing light sheet erosion on the surface.

D. Conclusion

The effectiveness of oil palm (Elaeis guineensis) root support in maintaining soil structure can be evaluated using two parameters: the Index of Root Anchoring (IRA) and the Index of Root Binding (IRB), which are mechanical. Analyzing biomass data reveals a highly unbalanced root system.

It was found that for oil palm, the highest root concentration was detected at shallow depths, namely in the 0-20 cm layer, and at depths of less than 60 cm, 80% of the root biomass accumulated. Referring to the parameters set by Hairiah et al. (2020), this characteristic obtained a relatively high IRB (Root Binding) value, but produced a very low IRA (Root Anchoring) value.

In other words, the supporting capacity of oil palm roots is excellent at forming a horizontal network to bind the soil surface structure, preventing light sheet erosion. However, the IRA value is below the ideal standard, indicating the absence of structural binding in the root's supporting capacity. The binding function is to penetrate soil volumes deeper than 1 meter and to hold the soil structure together to prevent trees from falling or being swept away during soil erosion (landslides).

2. Causal Mechanism of Landslides in Oil Palm Plantations Due to Extreme Rainfall

The interaction between the characteristics of oil palm stem roots and extreme rainfall creates a specific mechanism for landslides. During heavy rainfall events, water absorption increases water pressure in the soil. In oil palm monocultures, the topsoil (0-60 cm) may be tightly bound by a network of intertwined roots (high IRB), but the underlying layers remain vulnerable due to the lack of vertical root penetration that serves as support.

When the soil below the root zone (below 60 cm) becomes saturated, the soil's shear strength is drastically reduced. Because oil palms have a low soil water retention index, there are no elements that can firmly lock the structure of the saturated soil mass. As a result, the soil mass is likely to experience deep landslides, where the soil mass bound by oil palm roots collapses and is dragged away. This explains why oil palm plantations on hillsides are at high risk of landslides even though the surface of

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the soil is densely covered by trees.

Conclusion

Based on a comparative literature analysis of the Index of Root Anchoring (IRA) and Index of Root Binding (IRB) parameters, the main findings of this study indicate a functional imbalance in the oil palm root system, which has implications for landslide risk during extreme rainfall. The relatively high IRB value indicates the ability of oil palm fibrous roots to form a horizontal network that effectively resists surface erosion and reduces sheet erosion; however, the IRA value is very low, so that vertical roots do not act sufficiently as anchors to hold the soil mass at a depth of more than 60 cm. The combination of a dense surface network and lack of root penetration explains the mechanism of slope failure in oil palm plantations when the subsoil reaches water saturation; the bound top layer can be cut off from the support of the subsoil, triggering severe landslides. These findings strengthen the hypothesis that oil palm monoculture provides surface stability but does not guarantee the structural stability of slopes under extreme rainfall conditions.

Limitations of this study include the nature of the literature study that relies on secondary data from previous studies so that local variations, soil heterogeneity, plant age, cultivation practices, and the influence of mechanization are not fully quantified; in addition, the estimates of root number and diameter used in the IRA and IRB calculations are approximate, thus creating uncertainty in the index values. For further research, it is recommended to conduct quantitative field studies including direct measurements of vertical and horizontal root diameters, soil moisture profiling at depths greater than 60 cm, and numerical modeling of slope stability that incorporates extreme climate variability and land management practices. Practically, the results of this study recommend the implementation of mixed planting systems that include taproot species to improve anchoring, the placement of natural forest buffer zones on vulnerable contours, and the installation of soil moisture sensors at depths below the main root zone of oil palms as an early warning tool to reduce landslide risk.

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