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A Network-Based Spatial Assessment of Road Accessibility and Logistics Vulnerability

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ABSTRACT

Road accessibility is a key determinant of logistics resilience, territorial connectivity, emergency response capability, and regional development. In geographically extensive countries with uneven settlement patterns, logistics vulnerability is influenced not only by travel distance but also by network topology, corridor dependency, and the availability of alternative routes. Despite Libya's strategic position within regional trade networks, a comprehensive network-based framework for evaluating municipal logistics vulnerability has been lacking. This study develops a spatial network assessment framework to analyze road accessibility and logistics vulnerability across Libya. The national road system is modeled as a strategic logistics network connecting twenty major municipalities with maritime gateways and inland logistics hubs. Six indicators are incorporated to capture complementary dimensions of accessibility and network performance: network distance to ports, network distance to logistics hubs, distance to the coastal corridor, road passability exposure, route criticality exposure, and network redundancy constraint. Objective indicator weights are determined using the CRITIC method, and a composite logistics vulnerability index is constructed to classify municipalities and identify critical transport corridors. The findings reveal two dominant drivers of logistics vulnerability: the geographical isolation of southern and peripheral municipalities from coastal gateways and the concentration of national freight flows along a limited number of highly critical corridors. Kufra, Ghadames, Murzuq, Nalut, Ajdabiya, Gharyan, Sirte, and Zliten are identified as the most vulnerable municipalities, while the Misrata–Sirte, Ajdabiya–Sirte, Ajdabiya–Benghazi, and Misrata–Sabha corridor systems emerge as the most critical network segments. The proposed framework provides a robust spatial decision-support tool for infrastructure investment prioritization, corridor resilience planning, logistics network management, and evidence-based regional development policy in Libya.

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1. Introduction

Road infrastructure is a central component of logistics performance and territorial development. It enables the movement of goods, people, humanitarian supplies, fuel, construction materials, agricultural products, and emergency services [1]. The spatial configuration of the road network influences transport cost, service reliability, market access, and the capacity of municipalities to respond to disruptions [2]. For this reason, road accessibility is not merely a transport indicator; it is a structural condition that shapes the economic and social resilience of municipalities [3].

Logistics vulnerability refers to the degree to which a location, corridor, or system is exposed to failure, delay, isolation, or performance degradation. A municipality may be vulnerable because it is far from ports, because it depends on one long corridor, because its road connections pass through difficult terrain, or because alternative routes are limited [4]. Vulnerability therefore depends on both spatial remoteness and network structure. A road system can appear geographically connected while still being operationally fragile if many municipalities depend on a small number of critical links [5].

Transport geography and spatial planning have long used accessibility measures to evaluate the relationship between locations and opportunities. In road-based systems, accessibility can be measured through travel time, road distance, network distance, proximity to gateways, and connectivity to service nodes [6]. These measures are especially important in countries where population, infrastructure, and economic activity are unevenly distributed [7]. A network-based approach improves on straight-line distance because it captures how locations are actually connected through corridors and nodes [8].

Road-network vulnerability studies emphasize the importance of link criticality and route redundancy. A road segment is critical when its disruption creates large increases in travel distance or isolates important locations [9]. A municipality is more resilient when it can reach ports, hubs, and markets through several alternative corridors. Measures such as edge betweenness, detour ratio, and network redundancy help identify which links carry a disproportionate share of connectivity. These measures are relevant for logistics planning because they reveal hidden dependencies that are not visible from distance alone [10, 11].

Libya provides a relevant case for road accessibility and logistics vulnerability assessment [7]. The country has a large territorial extent, while population, ports, and economic activity are concentrated mainly along the Mediterranean coast [12, 13]. The coastal corridor connects the main urban and port cities, including Tripoli, Misrata, Sirte, Benghazi, Derna, and Tobruk [14]. In contrast, southern and inland municipalities such as Sabha, Ubari, Murzuq, Kufra, Ghadames, Brak Al-Shati, and Jalu depend on long north-south and east-west road corridors to access coastal gateways and national markets.

Previous work on urban transportation in Libya has described the importance of transport infrastructure for mobility, safety, urban development, and economic activity [2, 7]. The Logistics Cluster assessment reported that Libya has an extensive road system and identified the coastal route from the Tunisian border to the Egyptian border as the main national artery. The same structure creates a strong coastal-inland contrast: coastal municipalities benefit from proximity to ports and dense activity, while inland municipalities depend on longer routes and fewer alternatives.

Recent disaster experiences further highlight the importance of transport resilience. The 2023 storm and flooding in eastern Libya showed how damage to infrastructure can affect service delivery, recovery, and emergency response [15]. The Libya Rapid Damage and Needs Assessment prepared by the World Bank, the United Nations, and the European Union identified transportation among the sectors strongly affected by the event. This reinforces the need to assess road networks not only by ordinary accessibility, but also by their capacity to maintain connectivity under disruption [16, 17].

Open geospatial data supports a direct network-based assessment of road accessibility and logistics vulnerability. In this study, roads, municipalities, ports, and logistics hubs are organised as an integrated transport network. This structure enables the measurement of shortest-path access, corridor dependence, route redundancy, and road-section criticality. These indicators provide a clear basis for comparing municipalities and identifying the most vulnerable logistics corridors in Libya.

Multi-criteria aggregation is useful when several spatial and network indicators must be combined into one interpretable assessment. Objective weighting methods such as CRITIC assign greater importance to criteria that contain stronger contrast and less redundancy [18]. This is suitable for municipal logistics vulnerability assessment because indicators such as port distance, hub distance, passability exposure, criticality, and redundancy capture different dimensions of the same spatial problem [19]. The resulting index supports comparison, classification, and prioritization.

This study develops a network-based spatial assessment of road accessibility and logistics vulnerability in Libya. The contribution is threefold. First, it shifts the analysis from city-point comparison to a strategic road-network structure. Second, it integrates accessibility, corridor criticality, route redundancy, passability exposure, and coastal-inland isolation in one model. Third, it produces layered maps and municipal rankings that support transport planning, road maintenance targeting, logistics-node development, and resilience-oriented policy decisions.

2. Methodology

2.1 Research design

The study applies a network-based spatial assessment design. The alternatives are twenty major Libyan municipalities represented by their municipal centres. The road system is represented as a strategic corridor network that connects municipalities with ports, reference logistics hubs, and inland regional nodes. The model measures vulnerability through accessibility, passability, criticality, and redundancy indicators. The final output is a composite municipal logistics vulnerability index and a classification of critical corridors.

2.2 Network construction

The network is formulated as a weighted graph G = (N, E), where N is the set of municipalities, ports, and logistics hubs, and E is the set of strategic road-corridor links. Each edge has a class and an impedance length. Coastal trunk corridors connect the principal coastal municipalities, inland strategic corridors connect coastal gateways with interior regions, regional connectors provide secondary inter-municipal connectivity, and secondary alternatives represent additional links that improve redundancy. The impedance length of each edge is calculated as L_e = d_e x alpha_e, where d_e is the geodesic distance between the connected nodes and alpha_e is a route factor that reflects corridor class and expected travel impedance. Figure 1 shows the Libyan road network.

2.3 Evaluation indicators

Six indicators are used to evaluate municipal logistics vulnerability, as shown in Table 1. Network distance to port measures the shortest impedance distance from each municipality to the nearest maritime gateway. Network distance to hub measures the shortest impedance distance to the nearest reference logistics hub. Distance to coastal corridor measures the degree of inland isolation from the national coastal axis. Passability exposure captures the effect of road class, long-distance inland movement, terrain conditions, and desert-route exposure. Route criticality exposure measures the average and maximum criticality of the road segments used to reach key logistics nodes. Network redundancy constraint reflects the availability and quality of alternative routes to the nearest port.

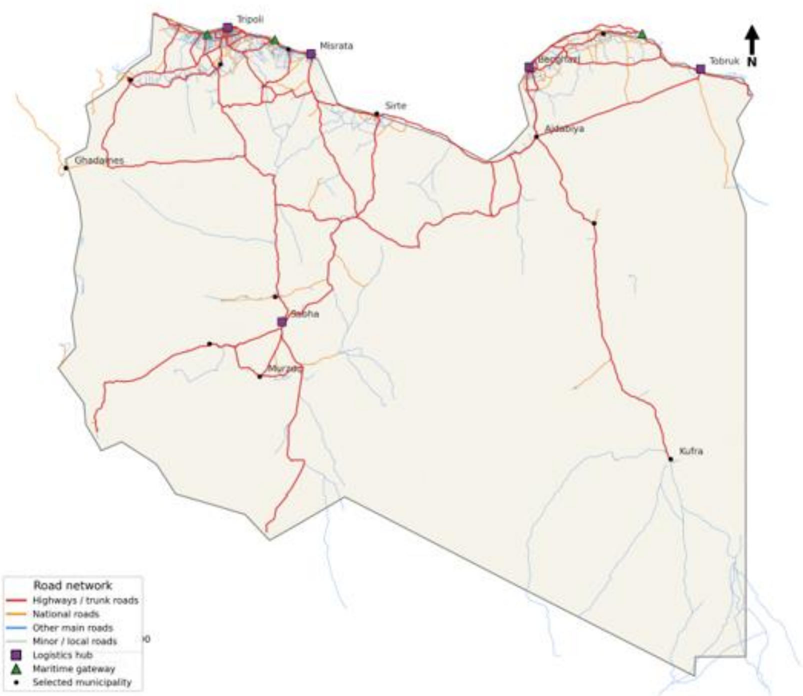

Fig. 1. Layered road network, logistics hubs, and maritime gateways

Table 1
Evaluation indicators used in the network-based vulnerability model

Code	Indicator	Measurement	Vulnerability direction
C1	Port access distance	Shortest network-impedance distance to nearest port	Higher = more vulnerable
C2	Hub access distance	Shortest network-impedance distance to nearest logistics hub	Higher = more vulnerable
C3	Coastal-corridor access	Network distance to nearest node on the coastal corridor	Higher = more vulnerable
C4	Passability exposure	Composite exposure score based on corridor class and inland/desert movement	Higher = more vulnerable
C5	Route criticality exposure	Criticality of segments used in shortest paths to ports and hubs	Higher = more vulnerable
C6	Network redundancy constraint	Constraint produced by limited alternative routes and high detour ratio	Higher = more vulnerable

2.4 Network accessibility and criticality measures

For each municipality i, port accessibility is defined as the minimum shortest-path distance from i to the set of ports P. Hub accessibility is calculated in the same way using the set of reference logistics hubs H. Edge criticality is calculated using weighted edge betweenness centrality, which indicates how frequently a corridor segment lies on shortest paths between municipalities. Route criticality exposure for each municipality is then calculated from the criticality of the segments located on its shortest paths to the nearest port and hub. This links municipal vulnerability with the importance of the corridors on which the municipality depends.

Network redundancy is evaluated by considering the number of edge-disjoint paths and the detour ratio between the shortest and second-shortest routes to the nearest port. A municipality with multiple route alternatives and a low detour ratio has stronger redundancy. A municipality with one dominant route or a much longer alternative route has higher redundancy constraint. This

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measure is important because logistics vulnerability often appears when a single corridor carries a large share of access to ports, hubs, and markets. Figure 2 shows the accessibility zones to the nearest logistics hub.

2.5 Objective weighting and composite index

The six indicators are normalized so that higher values represent greater vulnerability. The CRITIC method is then used to calculate objective indicator weights. For each indicator, CRITIC combines contrast intensity, represented by standard deviation, with conflict among indicators, represented by the correlation structure. Indicators that vary strongly across municipalities and add non-redundant information receive higher weights. The composite logistics vulnerability index is calculated as the weighted sum of normalized indicator values and then rescaled between 0 and 1. Municipalities are classified into five groups: very low, low, moderate, high, and very high vulnerability.

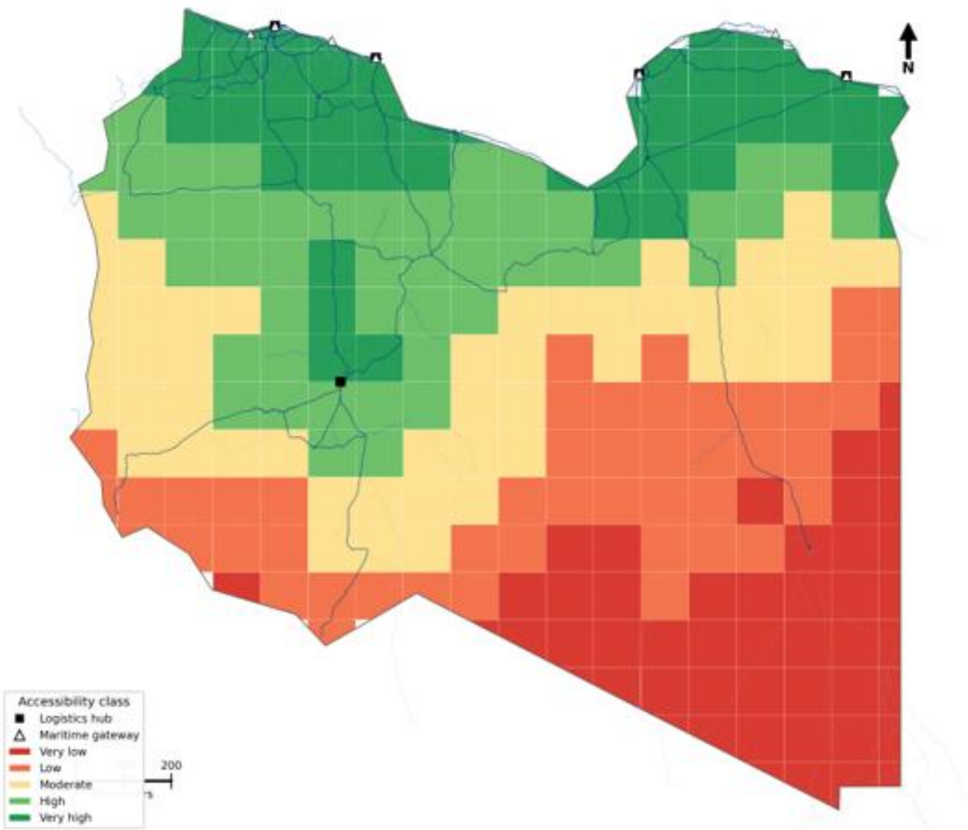

Fig. 2. Accessibility zones to the nearest logistics hub

3. Results

3.1 Study area and logistics structure

The case study covers twenty municipalities distributed across the main coastal axis, eastern urban centres, western border areas, mountain municipalities, central corridor nodes, and southern inland regions. The selected municipalities are Tripoli, Benghazi, Misrata, Sabha, Zawiya, Zliten, Al Khoms, Sirte, Tobruk, Derna, Bayda, Ajdabiya, Gharyan, Nalut, Ghadames, Ubari, Murzuq, Kufra, Jalu, and Brak Al-Shati. The reference logistics hubs are Tripoli, Misrata, Benghazi, Sabha, and Tobruk, while the maritime gateways are Tripoli, Zawiya, Al Khoms, Misrata, Benghazi, Derna, and Tobruk.

The spatial structure is dominated by the coastal trunk corridor and a smaller number of inland strategic links. The coastal corridor supports east-west national movement and access to ports, while inland corridors connect the coast to Sabha, Kufra, Ghadames, and the south-western municipalities. This configuration creates different forms of vulnerability. Some municipalities are vulnerable because of geographic remoteness. Others are vulnerable because they act as corridor gateways or depend on critical links with few alternatives.

3.2 Network indicators

Table 2 presents the main network indicators used in the assessment. The values show large variation in access to ports and hubs. Coastal and port municipalities have short network distances to logistics gateways, while Kufra, Ghadames, Murzuq, Ubari, Sabha, and Brak Al-Shati require long inland movement. The values also show that vulnerability is not limited to distance. Municipalities such as Sirte, Ajdabiya, Gharyan, Nalut, and Zliten appear as important network positions because they connect major corridors or lie on routes used by other municipalities.

Table 2
Network-based municipal logistics indicators

Municipality	Nearest port	Port dist.	Nearest hub	Hub dist.	Passability	Criticality	Redundancy constraint
Ajdabiya	Benghazi	167.3	Benghazi	167.3	1.00	0.311	0.725
Al Khoms	Al Khoms	0.0	Misrata	93.9	1.00	0.264	0.633
Bayda	Derna	90.7	Benghazi	191.4	1.00	0.225	0.725
Benghazi	Benghazi	0.0	Benghazi	0.0	1.00	0.000	0.633
Brak Al-Shati	Misrata	650.9	Sabha	70.8	3.90	0.118	0.415
Derna	Derna	0.0	Tobruk	161.6	1.50	0.105	0.633
Ghadames	Tripoli	618.4	Tripoli	618.4	3.70	0.128	0.564
Gharyan	Tripoli	97.5	Tripoli	97.5	3.20	0.063	0.725
Jalu	Benghazi	443.4	Benghazi	443.4	2.10	0.274	0.364
Kufra	Tobruk	1055.2	Tobruk	1055.2	4.40	0.016	0.485
Misrata	Misrata	0.0	Misrata	0.0	1.00	0.000	0.633
Murzuq	Misrata	894.1	Sabha	172.4	3.57	0.113	0.475
Nalut	Tripoli	331.6	Tripoli	331.6	3.70	0.130	0.659
Sabha	Misrata	721.7	Sabha	0.0	3.90	0.118	0.388
Sirte	Misrata	211.1	Misrata	211.1	1.00	0.337	0.633
Tobruk	Tobruk	0.0	Tobruk	0.0	1.50	0.000	0.633
Tripoli	Tripoli	0.0	Tripoli	0.0	1.00	0.000	0.633
Ubari	Misrata	884.5	Sabha	219.5	3.40	0.102	0.375
Zawiya	Zawiya	0.0	Tripoli	50.4	1.00	0.100	0.633
Zliten	Al Khoms	38.6	Misrata	55.2	1.00	0.264	0.725

3.3 Corridor criticality

The corridor criticality results identify the road segments and junction areas that concentrate the largest share of strategic corridor movement, Figure 3. The strongest concentrations appear along the coastal trunk corridor, around the Tripoli, Misrata, Ajdabiya, and Sabha junctions, and on the key inland axes linking coastal logistics platforms with southern municipalities, as shown in Table 3. The western inland route toward Nalut and Ghadames, the central-south corridor toward Sabha, Ubari, and Murzuq, and the eastern desert corridor toward Jalu and Kufra emerge as especially sensitive sections where disruption would have large territorial consequences.

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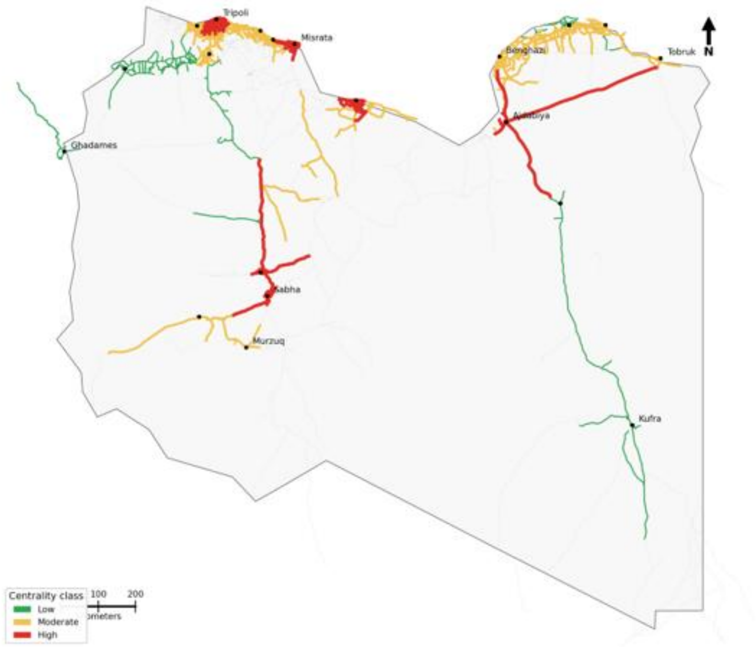

Fig. 3. Strategic road centrality based on corridor concentration

Table 3
Highest-criticality corridor segments

Rank	Corridor segment	Class	Betweenness
1	Ajdabiya - Sirte	coastal trunk	0.479
2	Misrata - Sirte	coastal trunk	0.337
3	Ajdabiya - Benghazi	coastal trunk	0.311
4	Misrata - Zliten	coastal trunk	0.274
5	Bayda - Benghazi	coastal trunk	0.242
6	Al Khoms - Zliten	coastal trunk	0.237
7	Al Khoms - Tripoli	coastal trunk	0.189
8	Bayda - Derna	coastal trunk	0.174

3.4 Indicator weights and vulnerability index

The vulnerability mapping confirms strong spatial differences across Libyan municipalities. Very high vulnerability is concentrated in remote or corridor-dependent municipalities such as Kufra, Ghadames, Nalut, and Murzuq. High vulnerability is also observed in Ajdabiya and Sirte because of their strategic dependence on a limited number of major connections. In contrast, the coastal metropolitan nodes and port-adjacent municipalities show lower vulnerability because of denser road structure, shorter access to gateways, and greater logistics concentration, Figure 4. Table 4 shows the indicator' weights obtained using CRITIC methodology.

Table 4
Objective indicators' weights obtained using CRITIC

Indicator	Weight
Network redundancy constraint	0.279
Route criticality exposure	0.196
Passability exposure	0.157
Coastal-corridor access	0.141
Port access distance	0.131
Hub access distance	0.097

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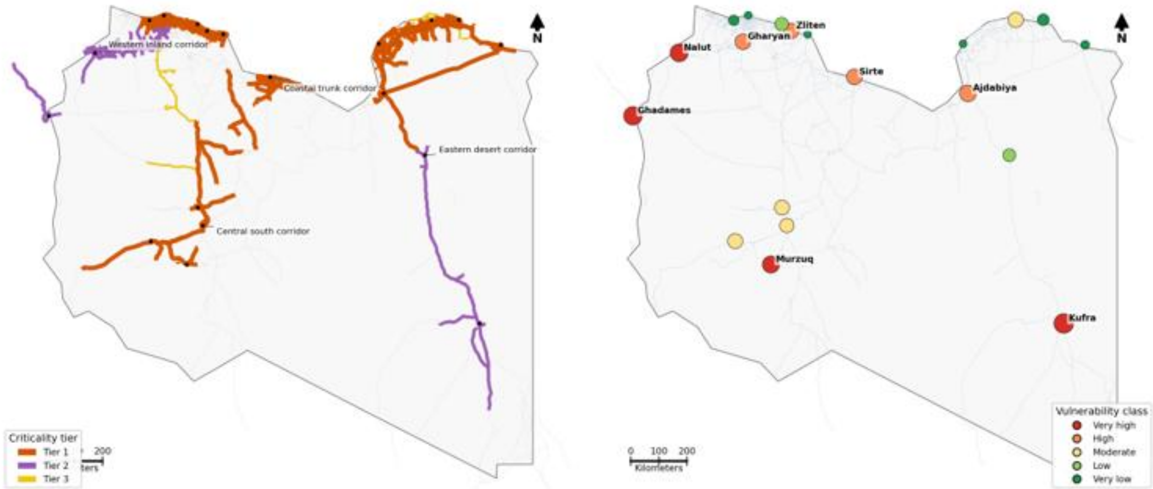

Figure 4. Critical road sections and municipal logistics vulnerability

3.5 Municipal ranking and spatial interpretation

The composite vulnerability ranking identifies Kufra, Ghadames, Nalut, and Murzuq as very high-vulnerability municipalities. These locations combine peripheral position, long network distances, route constraints, and exposure to difficult inland movement. Ajdabiya, Gharyan, Sirte, and Zliten form a second high-vulnerability group. Their ranking is explained less by distance and more by their role as corridor gateways and route-dependent nodes in the national network. This distinction is important because network vulnerability can affect both remote municipalities and strategically positioned municipalities that carry a high share of logistics connectivity.

Moderate-vulnerability municipalities include Bayda, Ubari, Brak Al-Shati, and Sabha. These locations have important regional functions and serve as connectors between coastal and inland areas, but they also face higher exposure to route length, corridor dependence, and passability constraints. Low and very low vulnerability values are recorded by municipalities with direct access to ports, hubs, or strong coastal connections, including Tripoli, Misrata, Benghazi, Tobruk, Zawiya, Derna, Al Khoms, and Jalu. Their lower values reflect stronger gateway access and stronger position within the strategic road network. Figure 5 and Table 5 show the ranking of municipalities by logistics vulnerability index.

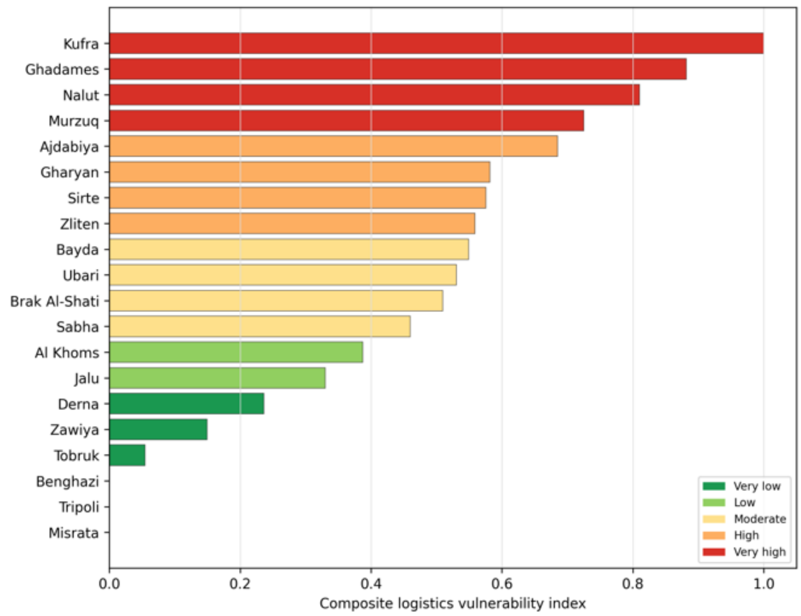

Fig. 5. Ranking of municipalities by logistics vulnerability index

Table 5
Municipal logistics vulnerability ranking

Rank	Municipality	Vulnerability index	Class
1	Kufra	1.000	Very high
2	Ghadames	0.882	Very high
3	Nalut	0.810	Very high
4	Murzuq	0.725	Very high
5	Ajdabiya	0.685	High
6	Gharyan	0.582	High
7	Sirte	0.575	High
8	Zliten	0.559	High
9	Bayda	0.549	Moderate
10	Ubari	0.530	Moderate
11	Brak Al-Shati	0.510	Moderate
12	Sabha	0.460	Moderate
13	Al Khoms	0.387	Low
14	Jalu	0.330	Low
15	Derna	0.236	Very low
16	Zawiya	0.150	Very low
17	Tobruk	0.055	Very low
18	Benghazi	0.000	Very low
19	Misrata	0.000	Very low
20	Tripoli	0.000	Very low

3.6 Planning implications

The results support four planning directions. First, very high-vulnerability municipalities require priority attention in inland corridor reliability, passability monitoring, fuel and maintenance support, and regional stock positioning. Second, high-vulnerability gateway municipalities require targeted investment because their performance affects other municipalities that depend on the same corridors. Third, critical corridor segments should be monitored as national logistics assets, especially where few alternative routes exist. Fourth, ports and inland hubs should be planned as an integrated logistics system rather than as isolated facilities, because accessibility depends on the continuity of the corridors that connect them.

The findings also show that vulnerability reduction cannot rely only on expanding road length. In several cases, improving redundancy, maintaining existing corridors, strengthening intermediate nodes, and creating operational contingency routes may produce greater resilience benefits than constructing new links. This is particularly relevant for Libya because inland municipalities depend on long-distance corridors whose performance affects territorial cohesion, emergency response, and market access.

4. Conclusions

This study developed a network-based spatial assessment of road accessibility and logistics vulnerability in Libya. The framework represented the national logistics system as a strategic corridor network connecting twenty municipalities with ports and reference logistics hubs. Six indicators were used to capture port access, hub access, coastal-corridor access, passability exposure, route criticality, and network redundancy. Objective weights were calculated using CRITIC, and the indicators were combined into a composite municipal logistics vulnerability index.

The results show that Libya's municipal logistics vulnerability is shaped by two main spatial mechanisms. The first is the coastal-inland accessibility gap, which increases vulnerability for municipalities located far from ports and coastal activity. The second is corridor dependence, which increases vulnerability for municipalities that rely on a limited number of high-criticality road segments. This explains why both remote municipalities and selected gateway municipalities appear as high-priority locations in the ranking.

The highest-priority municipalities are Kufra, Ghadames, Nalut, Murzuq, Ajdabiya, Gharyan, Sirte, and Zliten. Critical road segments are concentrated on the central coastal axis and on inland connections linking Misrata, Sabha, and western mountain municipalities. These results provide a spatial basis for road maintenance prioritization, logistics-node planning, emergency-route preparedness, and national corridor resilience. The framework can also be extended to sector-specific logistics applications such as food distribution, health-supply delivery, fuel supply, construction materials, agricultural transport, and free-zone connectivity.

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Conflicts of Interest
The authors declare no conflicts of interest.

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