Mühendislik ve Doğa Bilimleri

Editör: Prof. Dr. Murat HATİPOĞLU

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ÖZGÜR YAYINLARI

Ön Söz

Bu kitapta yayınlanan bölümler, mühendislik alanını tanımlayan tüm bilimsel disiplinler ile doğa ve temel bilimleri tanımlayan jeoloji, biyoloji, zooloji, fizik, kimya ve matematik disiplinlerinde teorik ve uygulamalı ve de özellikle yapay zeka modüllü bilimsel bulguları içeren çalışmaları kapsamaktadır. Mühendislik ve doğa bilimleri aslında odaklanma noktaları oldukça farklı olan bilimin ta kendisi ve iki temel disiplinidir.

Doğa bilimleri dünyamızın oluşumsal ve yaşamsal süreçlerini konu edinir, dünyamızı (gerektiğinde evreni) yöneten kuralları keşfetmek için, gözlem, deney ve nihayetinde teorik kuramları ortaya koyarak bu doğal işleyişi çözmeye çalışır. Jeoloji, biyoloji, zooloji, matematik, fizik, kimya temel uğraşı alanları olarak sınıflandırılabilir.

Mühendislik bilimleri ise bu bilgileri insanlık yararına nasıl kullanılabilirliğinin açıklaması ve uygulamaları ile uğraşmaktadır. Bu bakımdan ele alındığında Mühendislik Bilimleri doğa bilimleri, uygulamalı fen bilimleri, yaşam bilimleri ve temel bilimlerin adeta uygulama ve pratiğe geçirme alanıdır. Bilimsel prensipleri kullanarak ekonomik ve güvenli insan yaşamına dair her türlü yapı, makine ve sistemler üretmeyi hedefler.

İçindekiler

Bölüm 1

Plant-Parasitic Nematodes Associated with Olive Trees and Management Strategies

Ayşenur Yılmaz[1]

Uğur Gözel[2]

Abstract

Olive (*Olea europaea* L.) is a crop of significant economic and cultural importance, particularly in the Mediterranean region. Its cultivation, however, is frequently challenged by various stress factors, among which plant-parasitic nematodes (PPNs) are recognized as major threats to root health, plant growth, and overall yield. This study reviews the plant-parasitic nematode species reported on olive trees worldwide, highlighting their distribution, biology, and the types of damage they cause. Furthermore, it examines current management strategies, including chemical, biological, and cultural control measures, as well as integrated approaches aimed at sustainable nematode management. By synthesizing global findings, the study underscores the necessity of effective nematode monitoring and control in olive orchards and provides recommendations for future research to support sustainable olive production systems.

1. INTRODUCTION

The olive tree (*Olea europaea* L.) is a long-cultivated species in the Mediterranean basin, with a history spanning several millennia, and has held considerable cultural, economic, and nutritional significance throughout human civilization (Zohary and Spiegel, 1975). Well-suited to the Mediterranean climate, this durable and long-living tree has become emblematic of prosperity

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and vitality, forming a fundamental component of the regional diet through the production of both table olives and olive oil.

The genus *Olea* includes roughly 27 species and approximately 600 cultivars globally. Olive cultivation occurs in nearly 40 countries across five continents; however, only around 30 of these engage in commercial-scale production (Efe et al., 2011). Among the leading producers are Tunisia, Türkiye, Italy, Greece, Spain, Morocco, Portugal and Syria.

The origin of the olive remains a debated topic; however, the most widely accepted hypothesis proposes that cultivation began with wild olives (*Olea europaea* L.) naturally occurring in the forests of Anatolia, from which the species subsequently spread throughout the Mediterranean basin (Liphschitz et al., 1991). *Olea europaea* L., belonging to the Oleaceae family, is thought to have originated in Southeastern Anatolia, Upper Mesopotamia, and Southwestern Asia (Owen et al., 2000). Other studies suggest that olives first appeared in South Asia, were later introduced to the Mediterranean via the Middle East and represent one of the earliest domesticated fruit tree species (Somova et al., 2003).

Historically, olive oil, leaves, and fruits have been widely utilized for nutritional, medicinal, and ritual purposes (Soni et al., 2006). Currently, nearly 97% of global olive production is concentrated within the Mediterranean basin (COI, 1991). The olive tree is considered the second most significant oil-producing fruit tree worldwide, following the palm (Baldoni and Belaj, 2010).

Evidence indicates that olives have been part of the Mediterranean flora for approximately 10,000 years, with some fossil records suggesting up to 12,000 years of history (Ünsal, 2023). Today, olive cultivation extends over more than 10 million hectares globally, primarily between latitudes 30° and 45°. According to FAO (2022), total production amounts to 21.4 million tons, with Spain producing 3.9 million tons, Türkiye 2.9 million tons, and Italy 2.1 million tons. Approximately 93% of the world's olive trees are found within Mediterranean countries (FAO, 2022).

In recent years, global olive production has risen substantially, rendering both productivity and product quality critical factors for sustainable cultivation. However, the presence of various diseases, pests, and weeds in olive orchards adversely affects production, leading to notable reductions in yield and quality.

Among the principal species causing damage within the olive ecosystem are the olive fruit fly (*Bactrocera oleae* Rossi) (Diptera: Tephritidae), the olive leafroller (*Palpita unionalis* (Hübner)) (Lepidoptera: Pyralidae), the olive scale insect (*Parlatoria oleae* (Colvée)) (Hemiptera: Diaspididae), and the olive moth (*Prays oleae* (Bernard)) (Lepidoptera: Yponomeutidae). These pests inflict both direct and indirect economic losses, primarily through feeding fruit and leaf tissues.

Among the major biotic constraints on olive production, plant-parasitic nematodes (PPN) are particularly important. These nematodes are estimated to account for approximately 12.6% of crop losses in cultivated plants worldwide (Lopes-Caitar et al., 2019). Specifically, over 70 species from 33 different plant-parasitic nematode genera have been reported in association with olive trees (Lamberti and Vovlas, 1993).

These nematode species impair water and nutrient uptake by causing structural damage to the root system, disrupting the plant's physiological balance and thereby leading to significant losses in both yield and quality. Additionally, the feeding injuries in root tissues facilitate the entry of pathogens such as fungi and bacteria, increasing the host plant's susceptibility to secondary infections (Özdemir, 2022). This further exacerbates the detrimental effect of plant-parasitic nematodes on olive trees and negatively affects overall olive productivity.

2. PLANT-PARASITIC NEMATODES: GENERAL OVERVIEW

Nematodes are microscopic, cylindrical organisms belonging to the subphylum Nematoda, exhibiting remarkable adaptability in both terrestrial and aquatic environments. Approximately 25% of nematodes are free-living, 1% are plant-parasitic, 6% are aquatic, and 15% are animal-parasitic (Ayyoub, 1980). Free-living nematodes contribute significantly to the decomposition and cycling of organic matter, whereas plant-parasitic nematodes (PPNs) feed on roots, stems, leaves, and tubers, causing substantial economic losses across a wide variety of products (Djian-Caporalino et al., 2009; Ecevit and Akyazı, 2010; Kepenekci, 2012).

Plant-parasitic nematodes utilize needle-like mouthparts called stylets to withdraw sap from plant cells. In the process, they secrete toxic compounds that induce symptoms such as galls, wilting, chlorosis, stunted growth, and root deformities (Gaugler and Anwar, 2004; Decraemer and Hunt, 2006; Kepenekci, 2012). Furthermore, the feeding injuries created by these nematodes facilitate the penetration of pathogens, including fungi, bacteria, and viruses, resulting in indirect damage to the host plant (Gaugler and Anwar, 2004).

The majority of economically important plant-parasitic nematode species belong to the order Tylenchida, with roughly 4,305 species identified to date (Maggenti, 1991; Nicol et al., 2011). Globally, the annual economic losses attributed to these nematodes are estimated to range from 78 to 157 billion US dollars (Barker et al., 1981; Sasser and Carter, 1985; Sasser and Freckman, 1987; Nicol et al., 2011).

Nematodes exhibit a remarkable tolerance to environmental stress. In the absence of a suitable host, the eggs of certain species can enter a dormant state, remaining viable in the soil for prolonged periods. This adaptive capability facilitates the persistence of plant-parasitic nematode populations in agricultural ecosystems and constitutes a critical biological characteristic that significantly complicates their management.

3. PLANT-PARASITIC NEMATODES in OLIVE TREES

Olive trees host numerous widely distributed plant-parasitic nematodes, including spiral nematodes (*Helicotylenchus* spp.), root lesion nematodes (*Pratylenchus* spp.), root-knot nematodes (*Meloidogyne* spp.), and *Mesocriconema xenoplax* (Raski) Loof & De Grisse, 1989 (Lamberti and Vovlas, 1993; McLeod et al., 1994; Nejad et al., 1997; Kepenekci, 2001; Nico et al., 2002; Nico et al., 2003b; Peña Santiago et al., 2004; Castillo et al., 2010; Sanei and Okhovvat, 2011; Ali et al., 2014). In contrast, the cyst-forming nematodes (*Heterodera mediterranea* Vovlas, Inserra & Stone, 1981) and citrus nematode (*Tylenchulus semipenetrans* Cobb, 1913) exhibit a more confined distribution in olive trees (Vlachopoulos, 1991; McKenry, 1994; Castillo et al., 1999; Castillo and Vovlas, 2002).

To date, more than 150 nematode taxa reported to infest or be linked with olive cultivation have been documented (McKenry, 1994; Nico et al., 2002; Nico et al., 2003a; Ali et al., 2014). In addition to the previously mentioned species, other genera reported in association with olive trees include *Amplimerlinius* spp., *Paratrichodorus* spp., *Aorolaimus* spp., *Paratylenchus* spp., *Trichodorus* spp., *Pratylenchoides* spp., *Xiphinema* spp., and *Tylenchorhynchus* spp. (Hashim, 1982; Roca and Lamberti, 1988; Lamberti and Vovlas, 1993; Decraemer, 1994; Nico et al., 2002).

Most endoparasitic nematodes, including *Pratylenchus, Tylenchulus*, *Heterodera*, and *Meloidogyne,* are considered infecting olive tree roots (Castillo et al., 2010; Sanei and Okhovvat, 2011; Ali et al., 2014). These nematodes interfere with the normal formation and functioning of roots, ultimately leading to diminished plant growth and lower yields (Karssen and Moens, 2006).

For instance, in Argentina, *Meloidogyne javanica* (Treub, 1885) Chitwood, 1949, has been reported as a major pathogen, causing widespread wilting problems in young, recently planted olive groves (Pérez et al., 2001). Similarly, in the USA, olive losses attributed to *Tylenchulus semipenetrans* and *Meloidogyne* spp. are estimated to range between 5% and 10% (Koenning et al., 1999).

Nematode damage is significantly pronounced in seedling production facilities, where optimal irrigation promotes root development and consequently increases nematode populations, adversely affecting the performance of mature trees (Diab and El-Eraki, 1968; Castillo et al., 1999; Nico et al., 2002; El-Borai and Duncan, 2005; Aït Hamza et al., 2017).

Olive trees serve as hosts for these parasites; yet current knowledge regarding the PPN communities linked to olive cultivation is quite limited (Nico et al., 2002). The first record originated in the USA, where root-knot nematodes (*Meloidogyne* spp.) were detected (Buhrer et al., 1933). Since then, studies on olive-associated PPNs have been conducted in various countries, particularly in Italy (Scognamiglio et al., 1968; Inserra and Vovlas, 1981), Chile (Jimenez, 1982), Jordan (Hashim, 1983), Libya (Edongali, 1989), Spain (Peña-Santiago, 1990; Nico et al., 2002), Portugal (Isabel and de A Santos, 1991), Egypt (Ibrahim, 1990; Ibrahim et al., 2000; Ibrahim et al., 2010), Iran (Sanei and Okhovvat, 2011), Türkiye (Kepenekci, 2001; Cilbircioğlu, 2007), Argentina (Pérez et al., 2001), and Syria (Ayoub and Ghaoui, 2011).

Previous research has largely focused on the definition of PPN without examining its possible effects on the product (Hashim, 1982). Studies have mainly concentrated on nematode groups regarded as posing substantial risks to olive cultivation, especially in the Mediterranean region, with particular focus on root-knot nematodes (*Meloidogyne* spp.) (Lamberti and Lownsbery, 1968; Jimenez, 1982; Sasanelli et al., 1997; Sasanelli et al., 2002), lesion nematodes *Pratylenchus* (Lamberti and Baines, 1969b), spiral nematodes *Helicotylenchus* (Graniti, 1955; Tarjan, 1964; Diab and El-Eraki, 1968), kidney-like nematodes *Rotylenchulus* (Philis and Siddiqi, 1976; Inserra and Vovlas, 1980; Hashim, 1983; Castillo et al., 2003a), cyst nematodes *Heterodera* (Hirschmann et al., 1966; Vovlas and Inserra, 1983; Castillo et al., 1999), and dagger nematodes *Xiphinema* (Minz et al., 1963; Diab and El-Eraki, 1968) (Tablo 1).

Other studies, particularly in Iran (Sanei and Okhovvat, 2011) and Spain (Nico et al., 2002), have primarily investigated the effects of these parasites on olive nurseries.

Tablo 1. Reported plant-parasitic nematodes of olive worldwide

Species	Country	Reference
Aphelenchus avenae Bastian 1865	Greece	Hirschmann et al., 1966
	Iran	Sanei and Okhovvat, 2011
	Jordan	Hashim, 1983
	Spain	Peña-Santiago, 1990
	Türkiye	Kesici, 2022
	Türkiye	Öztürk, 2020
	Türkiye	Yıldırım, 2023
Aphelenchus sp. Bastian 1865	Iran	Hosseininejad et al., 1996
	Italy	Scognamiglio et el., 1968
Paraphelenchus pseudoparietinus Micoletzky 1921	Spain	Peña-Santiago, 1990
Aphelenchoides sacchari Hooper 1958	Türkiye	Öztürk, 2020
A. clarus Thorne and Malek, 1968	Türkiye	Öztürk, 2020
Continued from Table 1.		
A. confuses Thorne and Malek, 1968	Türkiye	Öztürk, 2020
Aphelenchoides sp. Fischer 1984	Egypt	Ibrahim et al., 2010
	Italy	Scognamiglio et el., 1968
	Italy	Fiume, 1978
	Jordan	Hashim, 1983
	Spain	Peña-Santiago, 1990
	Syria	Ayoub and Ghaoui, 2011
	Türkiye	Aktürk and Gözel, 2025
Aprutides guidettii Scognamiglio 1974	Spain	Peña-Santiago, 1990
Longidorus africanus Merny 1966	Egypt	Tarjan, 1964
L. belloi Andres and Arias 1988	Portugal	Bravo and Roca, 1998
L. closelongatus Stoyanov 1964	Greece	Lamberti et al., 1996
L. cretensis Tzortzakakis et al., 2001	Greece	Tzortzakakis et al., 2008
L. elongatus De Man 1876	Egypt	Ibrahim et al., 2010
	Türkiye	Öztürk, 2023
L. macrosoma Hooper 1961	Spain	Peña-Santiago, 1990
L. siddiqii Aboul-Eid 1970	Jordan	Hashim, 1979
L. vinearum Bravo and Roca 1995	Portugal	Bravo and Roca, 1998
L. magnus Lamberti, Bleve-Zacheo & Arias, 1982	Spain	Castillo et al., 2010
L. attenuatus Hooper,1961	Türkiye	Öztürk, 2020
Longidorus sp. Micoletzky 1922	Egypt	Diab and El-Eraki, 1968
	Italy	Scognamiglio et el., 1968
	Spain	Nico et al., 2002
	Syria	Ayoub and Ghaoui, 2011
	Spain	Castillo et al., 2010
	Spain	Ali et al., 2014
Paralongidorus sp. Siddiqi et al., 1963	Italy	Fiume, 1978
Xiphinema adenohystherum Lamberti, Castillo, Gomez-Barcina et al., 1992	Spain	Castillo et al., 2010
Xiphinema aequum Roca and Lamberti, 1988	Italy	Roca and Lamberti, 1988
X. barense Lamberti et al., 1986	Italy	Lamberti et al., 1986

X. californicum Lamberti and Bleve-Zacheo 1979	USA	Lamberti, 1969c
X. diversicaudatum Micoletzky, 1927	Portugal	Navas et al., 1988
X. elongatum Schuurmans Stekhoven and Teunissen, 1938	Egypt	Diab and El-Eraki, 1968
X. index Thorne and Allen 1950	Greece	Vlachopoulos, 1991
	Italy	Sasanelli et al., 1999
	Jordan	Hashim, 1983
	Türkiye	Öztürk, 2020
X. ingens Luc and Dalmasso 1964	Italy	Lamberti et al., 1975b
	Jordan	Hashim, 1979
X. italiae Meyl 1953	Italy	Martelli and Taylor, 1990
	Spain	Castillo et al., 2010
	Spain	Nico et al., 2002
	Spain	Ali et al., 2014
	Türkiye	Öztürk, 2020
	Türkiye	Akdemir, 2022
X. lusitanicum Sturhan, 1983	Portugal	Bravo and Roca, 1998
X. macroacanthum Lamberti et al., 1990	Italy	Lamberti et al., 1989
X. nuragicum Lamberti et al., 1992	Spain	Palomares-Rius et al., 2012
	Spain	Castillo et al., 2010
X. pachtaicum Tulaganov 1938	Italy	Castillo et al., 2010
Continued from Table 1.		
	Spain	Castillo et al., 2010
	Spain	Nico et al., 2002
	Spain	Ali et al., 2014
	Jordan	Hashim, 1979
	Portugal	Bravo and Roca, 1998
	Spain	Palomares-Rius et al., 2012
	Spain	Nico et al., 2002
	Türkiye	Kesici, 2022
	Türkiye	Öztürk, 2020
	Türkiye	Öztürk, 2023
	Türkiye	Satmaz, 2012
X. sahelense Dalmasso, 1969	Spain	Arias, 1975
X. turcicum Luc and Dalmasso, 1964	Spain	Peña-Santiago, 1990
X. vuittenezi Luc et al., 1964	Spain	Arias, 1975
Xiphinema sp. Cobb, 1913	Chile	Gallo and Jimenez, 1976
	Egypt	Ibrahim et al., 2010
	Iran	Hosseininejad et al., 1996
	Israel	Minz et al., 1963
	Italy	Scognamiglio et el., 1968
	Jordan	Anon, 1970
	Spain	Tobar-Jimenez, 1964
Paratrichodorus alleni Siddiqi, 1974	Italy	Decraemer, 1994
P. minor Colbran 1956	Spain	Nico et al., 2002
P. teres Hooper 1962	Spain	Nico et al., 2002
Paratrichodorus sp. Siddiqi 1974	Jordan	Hashim, 1983

Trichodorus aequalis Allen 1957	Spain	Peña-Santiago, 1990
T. andalusicus Decraemer et al., 2012	Spain	Decraemer et al., 2013
	Spain	Nico et al., 2002
	Spain	Castillo et al., 2010
T. iliplaensis Decraemer et al., 2012	Spain	Decraemer et al., 2013
T. giennensis Decraemer et al., 1993	Spain	Nico et al., 2002
	Spain	Nico et al., 2002
	Spain	Castillo et al., 2010
T. lusitanicus Siddiqi, 1974	Portugal	Sturhan, 1989
T. parasilvestris Decraemer et al., 2012	Spain	Decraemer et al., 2013
T. primitivus De Man 1880	Portugal	Sturhan, 1989
	Portugal	Almeida et al., 1989
T. silvestris Decraemer et al., 2012	Spain	Decraemer et al., 2013
T. taylori Mancine 1980	Italy	De Waele et al., 1982
T. variopapillatus Hooper, 1972	Italy	Decraemer, 1994
Trichodorus sp. Cobb 1913	Chile	Gallo and Jimenez, 1976
	Italy	Scognamiglio et el., 1968
Ditylenchus anchiliposomus Tarjan 1958	Spain	Peña-Santiago, 1990
D. parvus Zell, 1988	Türkiye	Öztürk, 2020
D. valveus Thorne and Malek, 1968	Türkiye	Öztürk, 2020
D. dipsaci Kuhn 1857	Jordan	Hashim, 1983
	Spain	Talavera and Tobar Jimenez, 1997
	Türkiye	Öztürk, 2023
D. virtudesae Tobar-Jimenez 1964	Spain	Tobar-Jimenez, 1964
D. destructor Thorne, 1945	Türkiye	Kepenekci, 2001
D. myceliophora Goodey, 1958	Türkiye	Öztürk, 2020
Ditylenchus sp. Filipjev 1936	Italy	Scognamiglio et el., 1968
	Jordan	Anon, 1970
	Spain	Peña-Santiago, 1990

Continued from Table 1.

Criconema annuliferum De Man 1921	Spain	Peña-Santiago, 1990
	Spain	Castillo et al., 2010
	Spain	Nico et al., 2002
C. princeps Andra´ ssy 1962	Portugal	Castillo et al., 2010
Criconema sp. Hofma¨ nner and Menzel 1914	Greece	Vlachopoulos, 1991
Criconemella informis Micoletzky 1922	Spain	Peña-Santiago, 1990
C. sphaerocephala Taylor 1936	Spain	Peña-Santiago, 1990
C. xenoplax Raski 1952	Jordan	Hashim, 1983
	Spain	Nico et al., 2002
C. rosmarini Castillo et al., 1988	Spain	Castillo et al., 2010
C. sicula (Vovlas, 1982) Raski & Luc, 1987	Italy	Vovlas, 1982
Criconemella sp. De Grisse and Loof 1965	Spain	Peña-Santiago, 1990
Criconemoides informis Micoletzky 1922	Jordan	Hashim, 1979
	Spain	Hashim, 1979
	Spain	Castillo et al., 2010
	Spain	Nico et al., 2002

Criconemoides amorphus De Grisse, 1967	Spain	Castillo et al., 2010
	Spain	Nico et al., 2002
Criconemoides sphaerocephalum Taylor, 1936	Spain	Castillo et al., 2010
	Spain	Nico et al., 2002
Criconemoides sp. Taylor 1936	Chile	Gallo and Jimenez, 1976
	Egypt	Diab and El-Eraki, 1968
	Greece	Hirschmann et al., 1966
	Italy	Scognamiglio et al., 1968
	Jordan	Anon, 1970
	Greece	Vlachopoulos, 1991
Crossonema multisquamatum Kirjanova 1948	Zimbabwe	Mehta and Raski, 1971
Hemicriconemoides gaddi Loos 1949	Türkiye	Cilbircioğlu, 2007
	Türkiye	Öztürk, 2023
	Türkiye	Kepenekci, 2001
Mesocriconema curvatum Raski 1952	Spain	Castillo et al., 2010
M. onoense Luc 1959	Brazil	Rossi and Ferraz, 2005a
M. sicula Loof and De Grisse 1989	Italy	Vovlas, 1982
M. siculum (Vovlas, 1982) Loof & De Grisse, 1989	Italy	Vovlas, 1982
M. sphaerocephalum Taylor 1936	Spain	Castillo et al., 2010
M. xenoplax Raski 1952	Spain	Nico et al., 2002
	Türkiye	Öztürk, 2023
Neolobocriconema olearum Hashim 1984	Jordan	Hashim, 1984b
Nothocriconema princeps De Grisse and Loof 1965	Portugal	Decraemer, 1994
	Portugal	Abrantes et al., 1987
Ogma civellae Steiner 1949	Zimbabwe	Mehta and Raski, 1971
Macroposthonia xenoplax, Raski, 1922, Loof and De Grisse, 1989	Türkiye	Öztürk, 2020
O. rhomobosquamatum Mehta and Raski 1971	Spain	Peña-Santiago, 1990
	Spain	Castillo et al., 2010
	Spain	Nico et al., 2002
	Spain	Ali et al., 2014
	Portugal	Abrantes et al., 1987
	Italy	Vovlas and Inserra, 1981b
O. seymouri Wu 1965	Jordan	Hashim, 1983
Continued from Table 1.		
	Italy	Vovlas and Inserra, 1981b
	Portugal	Abrantes et al., 1987
	Spain	Castillo et al., 2010
Ogma sp. Mehta and Raski 1971	Italy	Fiume, 1978
Dolichodorus heterocephalus Cobb 1911	Italy	D'Errico et al., 1977
Dolichodorus sp. Cobb 1915	Italy	Fiume, 1978
Trophurus sp. Loof 1956	Italy	Scognamiglio et al., 1968
Hemicycliophora sturhani Loof 1984	Türkiye	Cilbircioğlu, 2007
	Türkiye	Kepenekci, 2001
Hemicycliophora sp. De Man 1921	Chile	Gallo and Jimenez, 1976

	Spain	Nico et al., 2002
Heterodera avenae Filipjev 1934	Spain	Nico et al., 2002
	Greece	Hirschmann et al., 1966
H. mediterranea Vovlas et al., 1981	Italy	Vovlas and Inserra, 1983
	Spain	Castillo et al, 1999
	Spain	Castillo et al, 2010
	Spain	Ali et al., 2014
Heterodera sp. Filipjev and Schuurmans Stekhoven 1941	Italy	Scognamiglio et al., 1968
Heteroderinae Filipjev and Schuurmans Stekhoven 1941	Spain	Peña-Santiago, 1990
Aorolaimus perscitus Doucet 1980	Spain	Santiago and Geraert, 1990
Helicotylenchus digonicus Perry 1959	Cyprus	Philis and Siddiqi, 1976
	Greece	Hirschmann et al., 1966
	Jordan	Bridge, 1978
	Jordan	Hashim, 1983
	Spain	Palomares-Rius et al., 2012
	Spain	Nico et al., 2002
	Türkiye	Cilbircioğlu, 2007
	Türkiye	Kepenekci, 2001
	Türkiye	Öztürk, 2020
	Türkiye	Öztürk, 2023
	Türkiye	Kesici, 2022
	Spain	Castillo et al., 2010
	Spain	Ali et al., 2014
	Spain	Nico et al., 2003a
H. multicinctus (Cobb, 1893) Golden, 1956	Türkiye	Yıldız, 2012
	Türkiye	Öztürk, 2020
	Türkiye	Kesici, 2022
H. dihystera Cobb 1893	Brazil	Rossi and Ferraz, 2005b
	Cyprus	Philis and Siddiqi, 1976
	Egypt	Tarjan, 1964
	Italy	Vovlas and Inserra, 1981a
	Jordan	Bridge, 1978
	Spain	Nico et al., 2002
	Spain	Romero and Arias, 1969
	Spain	Ali et al., 2014
	Spain	Diab and El-Eraki, 1968
	Zimbabwe	Sher, 1966
	Türkiye	Öztürk, 2020
	Türkiye	Öztürk, 2023
H. erythrinae Zimmermann 1904	Italy	Graniti, 1955
H. minzi Sher 1966	Jordan	Hashim, 1983
H. neopaxili Inserra et al., 1979	Italy	Inserra et al., 1979

Continued from Table 1.

H. oleae Inserra et al., 1979	Italy	Inserra et al., 1979

	Spain	Castillo et al., 2010
	Spain	Ali et al., 2014
H. pseudorobustus Steiner 1914	Greece	Hirschmann et al., 1966
	Iran	Sanei and Okhovvat, 2011
	Italy	Castillo et al., 2010
	Jordan	Hashim, 1979
	Spain	Nico et al., 2002
	Spain	Nico et al., 2002
	Spain	Castillo et al., 2010
	Spain	Ali et al., 2014
	Spain	Nico et al., 2003a
H. tunisiensis Siddiqi 1963	Israel	Sher, 1966
	Jordan	Hashim, 1979
	Portugal	Abrantes et al., 1987
	Spain	Talavera and Tobar Jimenez, 1997
	Türkiye	Cilbircioğlu, 2007
	Türkiye	Öztürk, 2020
	Türkiye	Öztürk, 2023
H. vulgaris Yuen 1964	Jordan	Hashim, 1983
	Portugal	Abrantes et al., 1987
	Spain	Nico et al., 2002
	Spain	Talavera and Tobar Jimenez, 1997
	Türkiye	Cilbircioğlu, 2007
	Türkiye	Kepenekci, 2001
	Spain	Castillo et al., 2010
	Spain	Ali et al., 2014
H. canadensis Waseem, 1961	Spain	Castillo et al., 2010
	Türkiye	Öztürk, 2020
H. exallus Sher, 1966	Spain	Castillo et al., 2010
H. cavanessi Waseem, 1961	Türkiye	Satmaz, 2012
	Türkiye	Öztürk, 2020
H. varicaudatus Yuen, 1964	Türkiye	Öztürk, 2020
	Türkiye	Öztürk, 2023
Helicotylenchus sp. Steiner 1945	Algeria	Lamberti et al., 1975a
	Chile	Gallo and Jimenez, 1976
	Egypt	Ibrahim et al., 2010
	Greece	Hirschmann et al., 1966
	Greece	Vlachopoulos, 1991
	Iran	Hosseininejad et al., 1996
	Italy	Scognamiglio et al., 1968
	Jordan	Anon, 1970
	Syria	Ayoub and Ghaoui, 2011
	Türkiye	Aktürk and Gözel, 2025
Hoplolaimus aorolaimoides Siddiqi 1972	Portugal	Abrantes et al., 1987
H. galeatus Cobb 1913	Türkiye	Cilbircioğlu, 2007
	Türkiye	Kepenekci, 2001

Hoplolaimus sp. Daday 1905	Egypt	Diab and El-Eraki, 1968
	Syria	Ayoub and Ghaoui, 2011
Plesiorotylenchus striaticeps Vovlas et al., 1993	Türkiye	Cilbircioğlu, 2007
	Türkiye	Kepenekci, 2001
Rotylenchus buxophilus Golden 1956	Türkiye	Cilbircioğlu, 2007
	Türkiye	Kepenekci, 2001

Continued from Table 1.

R. cypriensis Antoniou 1980	Jordan	Hashim, 1983
	Türkiye	Cilbircioğlu, 2007
	Türkiye	Kepenekci, 2001
	Türkiye	Öztürk, 2020
	Türkiye	Öztürk, 2023
R. robustus De Man 1876	Portugal	Decraemer, 1994
	Portugal	Abrantes et al., 1987
	Spain	Ali et al., 2014
Rotylenchus sp. Filipjev 1936	Cyprus	Philis and Siddiqi, 1976
	Greece	Hirschmann et al., 1966
	Greece	Vlachopoulos, 1991
	Italy	Scognamiglio et al., 1968
	Spain	Nico et al., 2002
Aorolaimus perscitus (Doucet, 1980)	Spain	Nico et al., 2002
	Spain	Castillo et al., 2010
Hoplolaiminae Filipjev 1934	Spain	Peña-Santiago, 1990
Meloidogyne acrita Chitwood 1949	China	Yang and Zhong, 1980
M. arenaria Neal 1889	Chile	Jimenez, 1982
	China	Yang and Zhong, 1980
	Spain	Nico et al., 2002
	Spain	Ali et al., 2014
	Spain	Castillo et al., 2010
	Spain	Nico et al., 2003a
M. baetica Castillo et al. 2003b	Spain	Castillo et al., 2003b
M. hapla Chitwood 1949	Chile	Jimenez, 1982
	Israel	Minz, 1961
	Portugal	Santos, 1982
M. incognita Kofoid and White 1919	Argentina	Castillo et al., 2010
	Brazil	Rossi and Ferraz, 2005b
	Chile	Jimenez, 1982
	China	Yang and Zhong, 1980
	Egypt	Ibrahim et al., 2000
	India	Sethi et al., 1988
	Israel	Minz, 1961
	Italy	Lamberti and Vito, 1972
	Italy	Inserra and Vovlas, 1981
	Jordan	Abu-Gharbieh et al., 1978
	Jordan	Hashim,1979
	Lebanon	Saad and Nienhaus, 1969
	Lybia	Edongali, 1989

	Portugal	Abrantes, 1981
	Spain	Nico et al., 2002
	Türkiye	Çetintaş, 2017
M. javanica Treub 1885	Argentina	Pérez et al., 2001
	Chile	Jimenez, 1982
	China	Yang and Zhong, 1980
	Egypt	Diab and El-Eraki, 1968
	Greece	Hirschmann et al., 1966
	Iran	Sanei and Okhovvat, 2011
	Israel	Tarjan, 1953
	Italy	Lamberti and Vito, 1972
	Italy	Inserra and Vovlas, 1981
	Jordan	Hashim, 1979
	Lybia	Edongali, 1989

Continued from Table 1.

	Pakistan	Castillo et al., 2010
	Portugal	Castillo et al., 2010
	Spain	Nico et al., 2002
	USA	Lamberti and Lownsbery, 1968
	Türkiye	Özarslandan and Elekcioğlu, 2010
M. lusitanica Abrantes and Santos 1991	Portugal	Isabel and de A Santos, 1991
	Spain	Nico et al., 2002
Meloidogyne sp. Goeldi 1887	Chile	Gallo and Jimenez, 1976
	Chile	Jimenez, 1982
	China	Yang and Zhong, 1980
	Cyprus	Philis and Siddiqi, 1976
	Iran	Hosseininejad et al., 1996
	Israel	Tarjan, 1953
	Italy	Graniti, 1955
	Jordan	Anon, 1970
	Portugal	Macara, 1971
	Portugal	Santos and Abrantes, 1980
	Syria	Ayoub and Ghaoui, 2011
	USA	Buhrer et al., 1933
Gracilacus peratica Raski 1962	Italy	Vovlas and Inserra, 1983
	Italy	Inserra and Vovlas, 1977
	Portugal	Abrantes et al., 1987
	Italy	Scognamiglio et al., 1968
	Spain	Castillo et al., 2010
G. teres Raski 1976	Spain	Santiago and Geraert, 1990
Gracilacus latescens Raski, 1976	Türkiye	Kesici et al., 2022
Gracilacus sp. Raski 1962	Italy	Scognamiglio et al., 1968
	Spain	Peña-Santiago, 1990
Paratylenchus arculatus Luc and de Guiran 1962	Spain	Nico et al., 2002
	Türkiye	Cilbircioğlu, 2007

	Türkiye	Kepenekci, 2001
P. nawadus Khan, Prasad and Mathur, 1967	Türkiye	Öztürk, 2023
P. baldacii Raski 1975	Spain	Peña-Santiago, 1990
P. ciccaronei Raski 1975	Spain	Palomares-Rius et al., 2012
	Spain	Nico et al., 2002
	Spain	Castillo et al., 2010
P. microdorus Andrassy 1959	Spain	Talavera and Tobar Jimenez, 1997
	Spain	Palomares-Rius et al., 2012
	Spain	Nico et al., 2002
	Spain	Castillo et al., 2010
P. nanus Cobb 1923	Spain	Talavera and Tobar Jimenez, 1997
P. sheri Raski 1973	Spain	Talavera and Tobar Jimenez, 1997
	Spain	Nico et al., 2002
	Spain	Castillo et al., 2010
P. vandenbrandei De Grisse 1962	Italy	Inserra et al., 1976
	Spain	Nico et al., 2002
	Spain	Castillo et al., 2010
Paratylenchus sp. Filipjev 1936	Italy	Vovlas and Inserra, 1983
	Italy	Scogniamiglio et al., 1968
	Jordan	Anon, 1970
	Syria	Ayoub and Ghaoui, 2011
Pratylenchoides erzurumensis Yüksel 1977	Türkiye	Cilbircioğlu, 2007
	Türkiye	Kepenekci, 2001

Continued from Table 1.

P. ritteri Sher 1970	Spain	Nico et al., 2002
	Iran	Inserra et al., 1979
	Türkiye	Kepenekci, 2001
P. alkani Yüksel, 1977	Türkiye	Öztürk, 2023
Pratylenchoides sp. Winslow 1958	Jordan	Anon, 1970
Pratylenchus coffeae Zimmerman 1898	Australia	Colbran, 1964
	Jordan	Hashim, 1983
P. crenatus Loof 1960	Italy	Inserra et al., 1979
	Spain	Nico et al., 2002
	Spain	Castillo et al., 2010
P. fallax Seinhorst 1968	Spain	Nico et al., 2002
P. mediterraneus Corbett 1983	Türkiye	Cilbircioğlu, 2007
	Türkiye	Kepenekci, 2001
P. musicola Cobb 1919	USA	Condit and Horne, 1938
P. neglectus Rensch 1924	Greece	Hirschmann et al., 1966
	Italy	Inserra et al., 1976
	Iran	Zari et al., 2011
	Jordan	Hashim, 1983
	Spain	Talavera and Tobar Jimenez, 1997
	Spain	Nico et al., 2002

	Türkiye	Kepenekci, 2001
	Türkiye	Öztürk, 2023
P. penetrans Cobb 1917	Australia	McLeod et al., 1994
	Italy	Inserra et al., 1976
	Jordan	Hashim, 1983
	Spain	Peña-Santiago, 1990
	Spain	Ali et al., 2014
	Spain	Nico et al., 2002
	Spain	Nico et al., 2003a
P. thornei Sher and Allen 1953	Iran	Sanei and Okhovvat, 2011
	Jordan	Hashim, 1979
	Spain	Nico et al., 2002
	Türkiye	Satmaz, 2012
P. vulnus Allen and Johnson 1951	Algeria	Lamberti et al., 1975a
	Australia	McLeod et al., 1994
	Italy	Lamberti and Baines, 1969b
	Spain	Nico et al., 2002
	USA	Condit and Horne, 1938
	USA	Serr and Day, 1949
	Türkiye	Kepenekci, 2001
P. zeae Graham 1951	Türkiye	Cilbircioğlu, 2007
	Türkiye	Kepenekci, 2001
Pratylenchus sp. Thorne 1949	Algeria	Lamberti et al., 1975a
	Chile	Gallo and Jimenez, 1976
	Egypt	Ibrahim et al., 2010
	Greece	Hirschmann et al., 1966
	Iran	Hosseininejad et al., 1996
	Italy	Vovlas and Inserra, 1983
	Jordan	Anon, 1970
	Spain	Peña-Santiago, 1990
	Syria	Ayoub and Ghaoui, 2011
Radopholus sp. Thorne 1949	Greece	Hirschmann et al., 1966
	Greece	Vlachopoulos, 1991
Zygotylenchus guevarai Tobar-Jimenez 1963	Spain	Peña-Santiago, 1990

Continued from Table 1.

	Spain	Nico et al., 2002
	Türkiye	Cilbircioğlu, 2007
	Türkiye	Kepenekci, 2001
Psilenchus hilarulus De Man 1921	Iran	Sanei and Okhovvat, 2011
	Türkiye	Öztürk, 2023
P. iranicus Kheiri 1970	Jordan	Hashim, 1983
	Spain	Peña-Santiago, 1990
Psilenchus sp. De Man 1921	Greece	Vlachopoulos, 1991
	Iran	Hosseininejad et al., 1996
Rotylenchulus macrodoratus Dasgupta et al., 1968	Greece	Koliopanos and Vovlas, 1977
	Italy	Vovlas and Inserra, 1976
	Italy	Vovlas and Lamberti, 1974

R. macrosoma Dasgupta et al., 1968	Israel	Dasgupta et al., 1968
	Jordan	Hashim, 1983
	Spain	Castillo et al., 2003a
	Türkiye	Cilbircioğlu, 2007
	Türkiye	Öztürk, 2020
	Türkiye	Öztürk, 2023
R. reniformis Linford and Oliveira 1940	Egypt	Badra and Khattab,1980
	Greece	Hirschmann et al., 1966
Rotylenchulus sp. Linford and Oliveira 1940	Algeria	Lamberti et al., 1975a
	Syria	Ayoub and Ghaoui, 2011
Amplimerlinius amplus Siddiqi 1976	Portugal	Siddiqi, 1976
A. longicauda Castillo & al., 1990	Spain	Castillo et al., 2010
A. magnistylus Castillo et al., 1991	Spain	Castillo et al., 2010
A. dubius Steiner 1914	Türkiye	Cilbircioğlu, 2007
	Türkiye	Kepenekci, 2001
A. macrurus Goodey 1932	Jordan	Hashim, 1979
A. paraglobigerus Castillo et al., 1990	Spain	Nico et al., 2002
	Spain	Castillo et al., 2010
Amplimerlinius sp. Siddiqi 1976	Spain	Peña-Santiago, 1990
Bitylenchus goffarti Sturhan 1966	Türkiye	Cilbircioğlu, 2007
	Türkiye	Kepenekci, 2001
Bitylenchus hispaniensis Handoo et al., 2014	Spain	Castillo et al., 2010
Merlinius brevidens Allen 1955	Cyprus	Philis and Siddiqi, 1976
	Greece	Hirschmann et al., 1966
	Iran	Sanei and Okhovvat, 2011
	Jordan	Hashim, 1979
	Spain	Peña-Santiago, 1990
	Spain	Castillo et al., 2010
	Spain	Palomares-Rius et al., 2012
	Türkiye	Yıldırım, 2023
M. microdorus Geraert 1966	Jordan	Hashim, 1983
	Spain	Talavera and Tobar Jimenez, 1997
	Türkiye	Yıldırım, 2023
M. nothus Allen 1955	Jordan	Hashim, 1983
	Spain	Castillo et al., 2010
Merlinius leptus (Allen, 1955) Siddiqi, 1970	Spain	Castillo et al., 2010
Merlinius obscurus	Spain	Castillo et al., 2010
Merlinius nanus (Allen 1955) Siddiqi 1970	Spain	Castillo et al., 2010
Quinisulcius acutus Allen 1955	Türkiye	Cilbircioğlu, 2007
	Türkiye	Kepenekci, 2001
Paratrophurus loofi Arias 1970	Spain	Peña-Santiago, 1990

Continued from Table 1.

	Türkiye	Öztürk, 2020
Scutylenchus lenorus Brown 1956	Türkiye	Cilbircioğlu, 2007
	Türkiye	Kepenekci, 2001

Telotylenchus sp. Siddiqi 1960	Greece	Hirschmann et al., 1966
Trophurus sp.	Italy	Vovlas and Inserra, 1983
Tylenchorhynchus aduncus De Guiran 1967	Spain	Nico et al., 2002
T. clarus Allen 1955	Jordan	Hashim, 1979
	Spain	Nico et al., 2002
	Spain	Castillo et al., 2010
T. claytoni Steiner 1937	Cyprus	Castillo et al., 2010
	Türkiye	Cilbircioğlu, 2007
	Türkiye	Kepenekci, 2001
T. cylindricus Cobb 1913	Türkiye	Cilbircioğlu, 2007
	Türkiye	Kepenekci, 2001
	Türkiye	Öztürk, 2020
	Türkiye	Öztürk, 2023
T. dubius Buetschli 1873	Greece	Hirschmann et al., 1966
	Spain	Peña-Santiago, 1990
	Spain	Nico et al., 2002
	Spain	Castillo et al., 2010
T. goffarti Sturhan 1966	Jordan	Hashim, 1979
T. huesingi Paetzold 1958	Spain	Nico et al., 2002
T. mamillatus Tobar-Jimenez 1966	Spain	Nico et al., 2002
T. penniseti Gupta and Uma 1980	Türkiye	Cilbircioğlu, 2007
	Türkiye	Kepenekci, 2001
T. striatus Allen 1955	Greece	Hirschmann et al., 1966
T. tenuis Micoletzky 1922	Jordan	Hashim, 1984a
T. tritici Golden et al., 1987	Türkiye	Cilbircioğlu, 2007
	Türkiye	Kepenekci, 2001
T. maximus Allen, 1955	Spain	Nico et al., 2002
	Spain	Castillo et al., 2010
T. mediterraneus Handoo, 2014	Spain	Castillo et al., 2010
T. ventrosignatus Tobar Jiménez, 1969	Spain	Castillo et al., 2010
T. zeae Sethi & Swarup, 1968	Spain	Castillo et al., 2010
Tylenchorhynchus sp. Cobb 1913	Algeria	Lamberti et al., 1975a
	Chile	Gallo and Jimenez, 1976
	Egypt	Ibrahim et al., 2000
	Greece	Hirschmann et al., 1966
	Iran	Hosseininejad et al., 1996
	Italy	Vovlas and Inserra, 1983
	Jordan	Anon, 1970
	Spain	Nico et al., 2002
	Syria	Ayoub and Ghaoui, 2011
Aglenchus agricola De Man 1884	Spain	Peña-Santiago, 1990
Basiria duplexa Hagemeyer and Allen 1952	Spain	Peña-Santiago, 1990
	Türkiye	Kepenekci, 2001
Basiria sp. Siddiqi 1959	Jordan	Hashim, 1983
Boleodorus thylactus Thorne 1941	Iran	Sanei and Okhovvat, 2011
	Türkiye	Kepenekci, 2001
	Türkiye	Öztürk, 2020

	Türkiye	Öztürk, 2023
Boleodorus sp. Thorne 1941	Iran	Hosseininejad et al., 1996
	Jordan	Hashim, 1983
	Spain	Peña-Santiago, 1990

Continued from Table 1.

Coslenchus cancellatus Cobb 1925	Spain	Peña-Santiago, 1990
C. costatus De Man 1921	Greece	Hirschmann et al., 1966
C. lateralis Andrassy 1982	Spain	Peña-Santiago, 1990
C. diversus Lal and Khan, 1988	Türkiye	Kepenekci, 2001
	Türkiye	Kesici et al., 2022
C. franklinae Siddiqi, 1981	Türkiye	Öztürk, 2020
C. turkeyensis Siddiqi, 1981	Türkiye	Kepenekci, 2001
	Türkiye	Öztürk, 2023
Coslenchus sp. Siddiqi 1978	Spain	Peña-Santiago, 1990
Discotylenchus discretus Siddiqi 1980	Jordan	Hashim, 1983
Filenchus discretus Siddiqi 1979	Spain	Peña-Santiago, 1990
F. filiformis Buetschli 1873	Greece	Hirschmann et al., 1966
	Türkiye	Öztürk, 2023
F. sandneri Wasilewska 1965	Spain	Palomares-Rius et al., 2012
F. thornei (Andrassy, 1954) Andrassy, 1963	Türkiye	Satmaz, 2012
	Türkiye	Öztürk, 2020
	Türkiye	Öztürk, 2023
F. sheri (Khan and Khan, 1978) Siddiqi 1986	Türkiye	Öztürk, 2023
F. cylindricus (Thorne and Malek, 1968) Niblack and Bernard, 1958	Türkiye	Öztürk, 2023
Filenchus sp. Andra´ ssy 1954	Jordan	Hashim, 1983
	Spain	Palomares-Rius et al., 2012
Irantylenchus clavidorus (Kheiri) Sumenkova, 1984	Türkiye	Kepenekci, 2001
Irantylenchus sp. Kheiri 1972	Iran	Sanei and Okhovvat, 2011
Neopsilenchus magnidens Thorne 1949	Spain	Peña-Santiago, 1990
N. peshawarensis Shahin and Maqbool, 1994	Türkiye	Kepenekci, 2001
Tylenchus arcuatus Siddiqi 1963	Spain	Peña-Santiago, 1990
T. davainei Bastian 1865	Spain	Palomares-Rius et al., 2012
	Türkiye	Öztürk, 2023
Tylenchus sp. Bastian 1865	Chile	Gallo and Jimenez, 1976
	Greece	Hirschmann et al., 1966
	Iran	Hosseininejad et al., 1996
	Italy	Vovlas and Inserra, 1983
	Jordan	Hashim, 1979
	Spain	Palomares-Rius et al., 2012
	Türkiye	Aktürk and Gözel, 2025
Trophotylenchulus saltensis Hashim 1983	Jordan	Hashim, 1983
Tylenchulus semipenetrans Cobb 1913	Australia	Colbran, 1964
	Chile	Castillo et al., 2010
	Egypt	Yang and Zhong, 1980
	Greece	Vlachopoulos, 1991

	Italy	Inserra and Vovlas, 1981
	USA	Baines, 1951
Tylenchulus sp. Cobb 1913	Chile	Gallo and Jimenez, 1976
	Italy	Fiume, 1978
	Syria	Ayoub and Ghaoui, 2011
Geocenamus brevidens (Allen, 1955) Siddiqi, 1970	Türkiye	Öztürk, 2023
Lelenchus leprosoma de Man, 1880	Türkiye	Öztürk, 2023
Sauertylenchus maximus Allen, 1955	Türkiye	Öztürk, 2023

Meloidogyne spp. are recognized as some of the most destructive plant pathogens worldwide (Karssen and Moens, 2006). The root-knot nematode (*Meloidogyne* spp.) species that damage olive trees are well adapted to temperate and subtropical climates, and among them is *M. acrita, M. arenaria, M. baetica, M. hapla, M. incognita, M. javanica*, and *M. lusitanica* (Yang and Zhong, 1980; Jimenez, 1982; Santos, 1982; Isabel and de A Santos, 1991; Ibrahim et al., 2000; Pérez et al., 2001; Castillo et al., 2003b; Nico et al., 2003b; Castillo et al., 2010; Çetintaş, 2017; Özarslandan and Elekcioğlu, 2010; Sanei and Okhovvat, 2011; Ali et al., 2014).

These species exhibit sporadic distribution in naturally growing olive trees, seedling production facilities and cultivated orchards, where they induce distinct gall formation on roots and cause stunted plant growth (Lamberti and Baines, 1969a; Sasanelli et al., 1997; Nico et al., 2002; Castillo et al., 2003a). As a result of infection, formationos sustained feeding sites structures known as "giant cells" develop in the root tissues, accompanied by damage to the vascular cylinder (stele). Under controlled conditions, low to moderate levels of infection have been shown to cause moderate galling in most olive cultivars (Sasanelli et al., 2002; Nico et al., 2003b).

Pratylenchus spp. are obligate migratory endoparasites that feed on the cortical parenchyma cells of olive roots. This parasitic activity causes severe tissue death in both the cortex and endodermis, accompanied by a decline in the number and lenght of lateral roots and the formatin of lesions along the root surface (Castillo and Vovlas, 2007).

The *Pratylenchus* species known to cause damage to olive trees include *P. coffeae, P. crenatus, P. fallax, P. mediterraneus, P. musicola, P. neglectus, P. penetrans, P. thornei, P. vulnus,* and *P. zeae* (Condit and Horne, 1938; Colbran, 1964; Inserra et al., 1979; McLeod et al., 1994; Kepenekci, 2001; Nico et al., 2002; Cilbircioğlu, 2007; Castillo et al., 2010; Sanei and Okhovvat, 2011; Satmaz, 2012; Öztürk, 2023).

The penetration of root tissues and subsequent migration of the nematode within the host occur through an integration of mechanical pressure exerted by its stylet and enzymatic degradation of the cell wall (Zunke, 1990).

Several genera of reported plant-parasitic nematodes of olive worldwide, including *Helicotylenchus, Longidorus, Xiphinema, Gracilacus*, and *Rotylenchulus*, are capable of damaging olive roots through a variety of feeding strategies (Diab and El-Eraki, 1968; Scognamiglio et al., 1968; Lamberti et al., 1975b; Gallo and Jimenez, 1976; Philis and Siddiqi, 1976).

In particular, nematodes belonging to the genus *Helicotylenchus*, commonly known as spiral nematodes, are associated with root necrosis and can negatively influence plant growth under specific environmental conditions (Inserra et al., 1979). *Helicotylenchus* species generally exhibits semi-endoparasitic feeding behavior, targeting the fine roots of olive trees. In contrast, *Xiphinema* and *Longidorus* species feed directly on root cells, resulting in tissue damage.

Moreover, certain nematode species have been reported to transmit plant viruses, causing diseases in various fruit and vegetable crops (Martelli and Taylor, 1990). For instance, SLRV has been shown to induce leaf and fruit deformities in the olive cultivar *Ascolana tenera* (Marte et al., 1986). Additionally, *Xiphinema elongatum* Schuurmans Stekhoven & Teunissen, 1938, was reported to reduce above-ground biomass in olive seedlings by up to 65% in Egypt (Lamberti and Vovlas, 1993).

4. GENERAL CONTROL METHODS FOR PLANT-PARASITIC NEMATODES

4.1. Quarantine Measures

Quarantine measures are a fundamental strategy for the control of plant-parasitic nematodes in olive trees. Since nematode infestations usually occur during the early stages of production, preventing their establishment is particularly important in nurseries (Stukenbrock et al., 2008). Although the use of sterile growing media in modern seedling production minimizes the risk of infestation, the application of sterile soil in subsequent stages is also essential for effective quarantine. Pathogen-free certification programs for olive seedlings have been developed in the European Union and Spain; however, since their implementation is not mandatory, producers are strongly advised to obtain propagation material from certified or reputable nurseries (EPPO/OEPP, 1993; BOJA, 1997; Lorrain, 1998; BOE, 1999). Whitehead (1998) recommends control efficiency levels of 95% for *Pratylenchus* spp. and 99.9% for *Meloidogyne* spp.. In addition, species such as *X. Californicum*, *X. americanum*, *Longidorus diadecturus, Xiphinema italiae* and *Heterodera mediterranea* (Ministerio de Agricultura, Servicio Agrícola y Ganadero, 2007) have been designated as quarantine pests.

4.2. Cultural Control Methods

4.2.1. Use of resistant cultivars

Host plant resistance represents an environmentally friendly, economical, and long-term control strategy against plant-parasitic nematodes. While the use of resistant rootstocks is widely applied against root-knot nematodes in *Prunus* species (Pinochet et al., 1991), its application in olive trees remains limited, primarily because olives are generally propagated by cuttings rather than grafting. Nevertheless, encouraging results achieved with the clonal rootstock 'Allegra' in California indicate that this strategy may also be effective for managing nematodes in olive cultivation (McKenry, 1994).

The susceptibility of olive cultivars to nematodes varies according to genotypic differences and species-specific traits. In a study conducted in Egypt, the cultivars Meashon and Tofany were reported to be resistant to *Meloidogyne incognita* but moderately susceptible to *Rotylenchulus reniformis*, whereas the cultivars Manzanillo and Egazi exhibited the opposite tolerance pattern (Al-Sayed and Abdel-Hameed, 1991). Similarly, studies in Italy revealed that the cultivar Coratina was resistant to both root-knot nematode species, while Leccino and Yusti showed resistance only to *M. javanica*. In contrast, the rootstock DA 12 1 was found to be highly susceptible (Sasanelli et al., 1997; Sasanelli et al., 2002). Moreover, the use of in vitro explants has been demonstrated to be an efficient method for rapidly evaluating nematode resistance in olive genotypes (Sasanelli et al., 2000).

4.2.2. Organic material applications

One of the environmentally friendly approaches in soil disinfection is the addition of organic materials (e.g., organic manure or compost) (Akhtar and Alam, 1993). Although various agricultural and industrial by-products have been tested for this purpose (D'Addabbo, 1995), composts recommended for the suppression of soil-borne fungi have been found to be insufficiently effective in nematode control.

In a study investigating the suppression of *M. incognita*, different proportions of dry mushroom shell compost were incorporated into the olive growing medium. The results demonstrated a pronounced reduction in nematode populations as compost ratios increased, with the most significant suppressive effect observed in the treatment utilizing pure compost (Nico et al., 2004).

4.2.3. Biofumigation

Biofumigation is an environmentally sustainable approach for controlling soil-borne pathogens, involving the incorporation of specific organic materials into the soil (Kierkegaard et al., 1993). This method exploits the biocidal volatile compounds released during the decomposition of tissues from *Brassica* and *Sorghum* species. When applied under plastic cover, the retention of these volatiles enhances the overall effectiveness of the treatment. Under laboratory conditions, leaf tissues of *Sorghum sudanense* were observed to suppress *Meloidogyne incognita*; however, effective control was achieved only after prolonged treatments lasting 30–60 days (A. Nico, R. M. Jiménez-Díaz, and P. Castillo, unpublished data). Therefore, while biofumigation can contribute to nematode suppression, its efficacy is generally lower than that of soil solarization.

4.3. Physical Control

Increasing concerns regarding the environmental consequences of pesticide use have prompted the development of non-chemical soil disinfection methods in agriculture. Among these, soil solarization is recognized as one of the most effective strategies. Solarization is a hydrothermal technique in which moist soil, covered with transparent plastic sheets, is heated by solar radiation to temperatures lethal to soil-borne pathogens (Katan, 1981).

Olive cultivation in Mediterranean climate regions provides favorable conditions for soil solarization due to elevated summer temperatures. Solarizing nursery substrates, such as peat or perlite, in small piles under greenhouse conditions has been demonstrated as an effective approach for controlling soil-borne pathogens (Nico et al., 2003b). A ten-day solarization treatment led to a substantial reduction of *M. incognita* eggs and egg masses down to a soil depth of 40 cm (Nico et al., 2003b). Furthermore, these high temperatures can inactivate other nematode species detrimental to olive trees, including *Pratylenchus vulnus* and *P. penetrans* (Nico et al., 2003a).

Soil solarization has been successfully applied not only to manage nematode infestations in established olive groves but also to control other soil-borne pathogens. For example, Tjamos (1983) and López-Escudero & Blanco-López (2001) reported that solarization markedly reduced the incidence of *Verticillium* wilt in olive trees infected with *Verticillium dahliae*.

4.4. Chemical Control

Although soil fumigation prior to planting is commonly employed for nematode management in certain fruit crops, its use in olive production remains limited. In nursery settings, chemical control methods are considered an effective approach for producing nematode-free planting material.

Research on the post-planting application of non-fumigant nematicides (NFNs) in olive groves is still scarce. In a field trial conducted in Chile, Jiménez et al. (2002) compared fenamiphos fumigation, a biocontrol formulation, and organic fertilizer applications in olive trees naturally infected with *Tylenchulus semipenetrans*. No significant differences were observed in root biomass, and both the biocontrol and organic fertilizer treatments were found to be as effective as fenamiphos. Similarly, in Egypt, Shawky et al. (2004) evaluated the efficacy of fenamiphos, ethoprop, carbofuran, oxamyl, and aldicarb against *M. incognita*. All nematicides effectively reduced nematode populations, with fenamiphos showing the highest efficacy and carbofuran the lowest.

Furthermore, Lamberti and Baines (1969b) reported that incorporating fenamiphos into the growing medium effectively reduced root-knot nematode infections in olive trees.

Among the NFNs licensed worldwide are ethoprophos, fosthiazate, fenamiphos, and oxamyl, but none of these substances are authorized for use on olive trees (Sobreiro and Reis, 2008; APVMA, 2009; CASAFE, 2009; MARM, 2009; Ministero delle politiche agricole, alimentari e forestali, 2009).

4.5. Biological Control

Arbuscular mycorrhizal fungi (AMF) enhance phosphorus uptake by forming symbiotic associations with plant roots and protect plants against soil-borne diseases and pests by competing with pathogens for infection sites and nutrient resources (Azcón-Aguilar and Barea, 1996). The effectiveness of AMF in suppressing plant-parasitic nematodes has been demonstrated in various pathosystems, including *Meloidogyne* species and olive trees (Castillo et al., 2006).

Early inoculation with *Glomus viscosum*, *G. intraradices*, and *G. mosseae* in the Arbequina and Picual olive varieties promoted plant growth and conferred significant protection against *Meloidogyne javanica* and *M. incognita* infections. This protective effect has been attributed to the suppression of nematode reproduction and a reduction in root gall formation (Castillo et al., 2006).

Consequently, the use of seedlings grafted with arbuscular mycorrhizal fungi (AMF) during the nursery stage can be regarded as an effective biological strategy for mitigating damage caused by root-knot nematodes and promoting long-term resilience in olive groves.

6. RESULTS

Host suitability for plant-parasitic nematodes (PPNs) is generally evaluated by assessing the level of nematode reproduction in the plant following artificial inoculation (Lewis, 1987). In nematological research, the reproduction factor (Rf) is the most commonly employed parameter for this purpose (Marull and Pinochet, 1991; Pinochet et al., 1991). When a compatible host–parasite interaction occurs, nematode infection induces pathogenesis by disrupting normal physiological processes within the plant (Melakeberhan and Webster, 1993).

Beyond the phytopathogenic effects of PPN populations in olive soils, limited information exists regarding their potential use as bioindicators for soil health or for guiding olive grove management practices (Bongers and Ferris, 1999). Studies have reported a positive correlation between soil degradation and PPN abundance, species diversity, and the Plant Parasite Index (PPI) (Freckman and Ettema, 1993). Additionally, enhanced plant nutrition has been shown to influence the composition and structure of PPN populations (Bongers et al., 1997).

Consequently, examining the distribution, density, and community structure of plant-parasitic nematodes (PPNs) in relation to various agricultural management systems is essential for both controlling nematode-associated diseases and developing sustainable production strategies.

Growing concerns regarding environmental and human health have led to the prohibition of many nematicides, highlighting the need for alternative approaches to manage PPNs in crops, including olives. Given the limited availability of nematode-resistant olive rootstocks, quarantine measures remain one of the most critical control strategies. In this context, the use of pathogen-free seedling material and nematode-free soil is vital for minimizing early-stage infections, thereby reducing growth losses and yield declines.

In certified seedling production, grafting and cutting materials should be obtained exclusively from rootstocks with equivalent or higher certification levels. Production soils must be free of harmful nematode species, including *Xiphinema diversicaudatum*, *Meloidogyne arenaria*, and *Pratylenchus vulnus*, as well as other quarantine organisms (Anonymous, 2006).

The insufficient nematode resistance in olive trees can be offset through non-chemical alternatives, particularly soil solarization, biofumigation, and biological control applications. This integrated approach supports both the economic and ecological sustainability of olive cultivation in Mediterranean agricultural systems.

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Chapter 2

Evaluation of Corundum and Rock Dust Waste as Cement-Based Concrete Material

Emre Karakaya[1]

Abstract

This study focuses on the recovery and reuse of corundum and rock dust waste generated as by-products during abrasion tests using the Bohme abrasion device. These tests, commonly applied to assess the wear resistance of natural stones, produce significant amounts of corundum and rock dust waste. Improper disposal of these fine particulate wastes may cause environmental problems such as air and soil pollution. To address this issue within the framework of sustainable construction practices, waste particles sized between 200 and 500 μm were ground in a laboratory rod mill for 10 minutes to obtain finer fractions ranging from 75 to 150 μm. The resulting powder was mixed with Portland cement at fixed water-to-cement ratio of 0.45 and cement contents of 5%, 7%, and 10%. Concrete specimens were produced and tested for physical and mechanical properties including dry density (ρd), porosity (n), Leeb rebound hardness (LRH), uniaxial compressive strength (UCS), and point load strength (PLT). The results showed improved mechanical performance with increasing cement content. Dry density ranged from 2.45 to 2.48 g/cm^3, while porosity slightly decreased from 34.78% to 33.52%. LRH increased from 170.08 to 211.70, UCS rose from 3.00 MPa to 7.55 MPa, and PLT improved from 0.21 MPa to 0.50 MPa. These findings suggest that corundum and rock dust waste can enhance the performance of cementitious composites and be effectively utilized as secondary raw materials. This study highlights a sustainable approach to recycling abrasive waste materials in construction applications.

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1. Introduction

Corundum (synthetic alumina, Al_2O_3) powder is widely utilized across various industrial applications due to its exceptional hardness and chemical resistance. With a Mohs hardness rating of 9.0, it is considered one of the hardest naturally occurring minerals, following diamond and silicon carbide. This remarkable hardness makes corundum an effective abrasive material, particularly in grinding, cutting, and polishing operations. Today, it is commonly employed in sandpapers, grinding wheels, and abrasive blasting systems. Furthermore, its high melting point (~2050 °C) and thermal stability render it a critical component in the manufacture of refractory materials. In this context, corundum-based refractory bricks and ceramics are frequently used as linings in furnaces and reactors operating under high temperatures in the metallurgy, glass, and cement industries [1]. In addition, corundum powder plays a significant role in surface preparation and coating applications; it is effectively used in abrasive blasting for cleaning and roughening metal surfaces, and it is also preferred in creating anti-slip, wear-resistant surfaces [2].

Corundum is widely utilized in the fields of rock mechanics and construction materials due to its high hardness and uniform abrasive performance, making it a preferred medium for surface abrasion testing. In particular, the use of synthetic corundum is mandated in the Bohme abrasion test, as defined by the EN 14157 standard, to ensure reliable and repeatable evaluation of the abrasion resistance of natural stones [3]. Similarly, corundum or equivalent abrasive materials are employed in the Wide Wheel abrasion test, which is based on the EN 1341 standard, to simulate severe wear conditions typically encountered in the performance assessment of paving stones [4]. In addition, corundum-based abrasive wheels such as H-18 or CS-17 are commonly used in the Taber abrasion test, performed under ASTM D1044 and ASTM C1353 standards, to assess wear resistance on stone and concrete surfaces [5,6]. High-hardness corundum powder or similar abrasives are also recommended in tests conducted in accordance with ASTM C779, which evaluates the effects of multiple abrasive mechanisms, as well as in the historically significant Dorry abrasion test, to study surface degradation under controlled conditions [7,8].

Corundum powder, commonly used in industrial abrasion tests, generates a substantial amount of dust waste that can pose significant environmental risks. The uncontrolled release of these residues into the environment may lead to irreversible ecological damage and stands in conflict with contemporary sustainability goals. In recent years, increasing emphasis has been placed on the reutilization of such industrial by-products to create both economic and environmental value. Particularly in the construction industry, the incorporation of recovered materials as raw inputs contributes to the conservation of natural resources and the enhancement of waste management practices.

Therefore, the structural suitability of waste materials must be ensured in order to maintain material quality, which is of critical importance. The literature contains numerous studies on the use of various industrial wastes—such as fly ash, blast furnace slag, mine tailings, foundry sand, cement kiln dust, wood ash, waste glass powder, marble dust, scrap tires, construction and demolition waste, zeolite, and waste paper industry ash—as well as agricultural wastes including rice husk ash, sugarcane bagasse ash, palm oil shell, corn stalk ash, and olive oil residues in concrete production [9–26]. However, research on the reuse of waste materials such as corundum and rock dust generated from abrasion tests remains highly limited [27–29].

Therefore, the structural suitability of waste materials must be ensured in order to maintain material quality, which is of critical importance. The literature contains numerous studies on the use of various industrial wastes—such as fly ash, blast furnace slag, mine tailings, foundry sand, cement kiln dust, wood ash, waste glass powder, marble dust, scrap tires, construction and demolition waste, zeolite, and waste paper industry ash—as well as agricultural wastes including rice husk ash, sugarcane bagasse ash, palm oil shell, corn stalk ash, and olive oil residues in concrete production [9–25]. However, research on the reuse of waste materials such as corundum and rock dust generated from abrasion tests remains highly limited [26–28].

This study aims to produce concrete by incorporating waste dust generated from the Bohme Abrasion Resistance (BAR) test, which was processed through particle size reduction in the laboratory and subsequently mixed with cement in varying proportions. The environmental suitability of the resulting recycled products was evaluated through physical and mechanical tests to assess their potential application as construction materials.

2. Study Methodology

In this study, the utilization of waste dust generated after BAR tests, comprising a mixture of corundum and rock particles, was investigated. To this end, the waste dust was ground and mixed with cement at varying proportions (5%, 7%, and 10%) along with a controlled amount of water to produce concrete blocks. The resulting samples were then subjected to a series of physico-mechanical tests to systematically evaluate their strength properties. Figure 1 presents a schematic illustration of the process, from grinding the waste dust to its incorporation in concrete production, as well as the physical and mechanical tests performed on the produced concrete specimens.

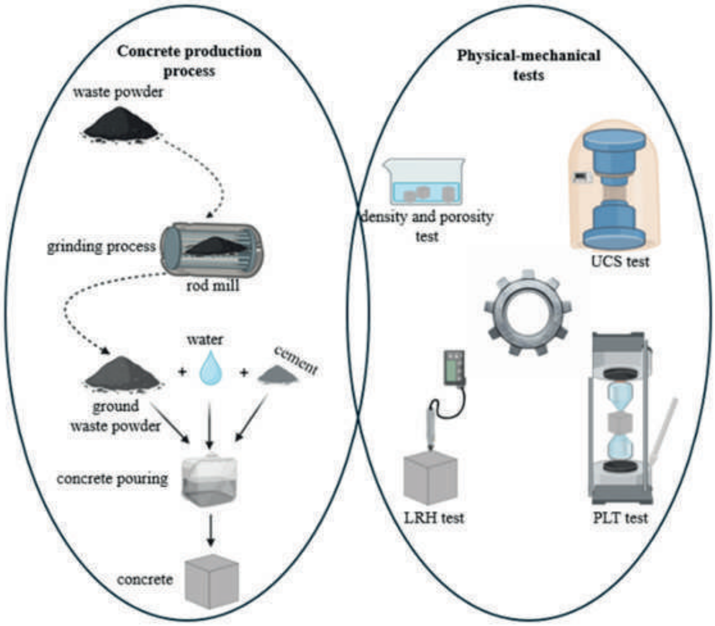

Fig. 1 A schematic representation of the process in which waste dust is ground and utilized for concrete production, along with the physico-mechanical tests applied to the produced concrete specimens

2.1 BAR Test

Tests aimed at determining frictional wear loss were conducted in accordance with the EN 14157 standard [3]. For this purpose, cube-shaped specimens with edge lengths of 71 mm were prepared. The surfaces of the specimens in contact with the abrasive belt were arranged to be flat. During the test, 20 grams of corundum powder was spread over the abrasive strip, and a constant load of 294 N was applied using a steel lever mechanism. Each test cycle consisted of 22 revolutions, after which the disc automatically stopped, and the accumulated corundum and specimen debris were cleaned from the surface. Subsequently, another 20 grams of corundum powder was applied, the specimen was rotated 90° around its vertical axis, and the procedure was repeated. This cycle was performed 16 times for each specimen. Upon completion of the test, specimens were carefully cleaned, and the mass losses caused by abrasion were determined using a precision balance.

To determine the BAR value of a specific rock type, three cube-shaped specimens with edge lengths of 71 mm were prepared, and individual BAR tests were carried out on each. The average BAR value for the rock was calculated by taking the meaning of the three test results along with the standard deviation. Based on these procedures, approximately 960 ± 48 grams of corundum powder was consumed to determine the BAR value of a single rock type. The amount of material worn from the rock specimens during the Bohme test ranged from 4 to 60 grams on average, depending on the type and density of the rock [29, 30]. Figure 2 illustrates a sample of the waste powder generated following Bohme abrasion tests using the Bohme abrasion apparatus.

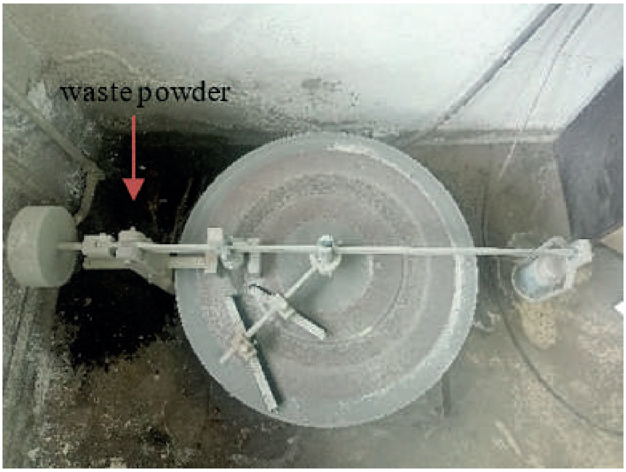

Fig. 2 Waste dust resulting from Bohme abrasion test

2.2 Concrete production from waste powder

It was determined that the particle size of the waste powder obtained after the BAR test ranged approximately between 170 and 600 μm. Concrete blocks were initially produced using the waste powder in this size range; however, it was observed that the bonding between the cement and the waste powder was insufficient, resulting in the formation of cracks in the specimens and inadequate strength properties. To overcome these issues, a particle size reduction process was applied to the waste powder. In this context, the powder was ground for 15 minutes using a laboratory-scale rod mill. As a result of the grinding process, the particle size was successfully reduced to the range of 75 to 150 μm. Figure 3 presents a visual representation of the rod mill used for the grinding of the waste powder.

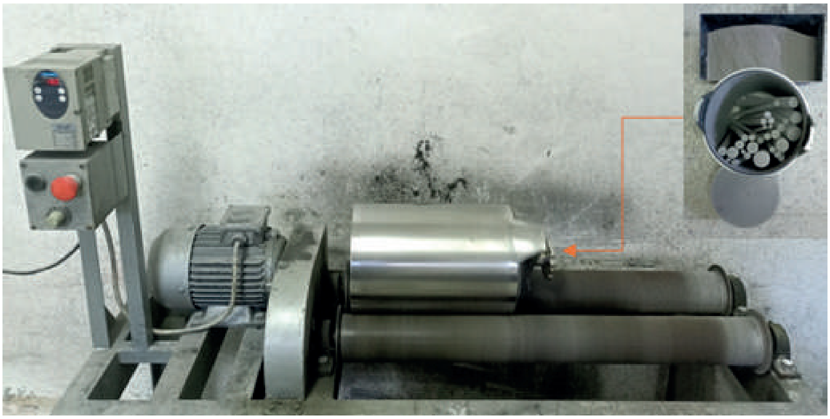

Fig. 3 Grinding process of the waste powder

Figure 4 illustrates the corundum abrasive, the residual powder produced following BAR tests, and the waste material after the grinding process.

Fig. 4 a) Corundum abrasive, b) BAR test-derived waste powder, c) its ground form

Ground waste powder was mixed with white cement at proportions of 5% (S1), 7% (S2), and 10% (S3), and water was added at a water-to-cement ratio of 0.45 in accordance with TS EN 206 standards to prepare mortar. The mixtures were then cast into molds measuring 10 × 10 × 15 cm. To prevent cracking caused by water evaporation, plastic shrinkage, and delayed hydration during the initial setting and curing phases, the concrete samples were subjected to water curing for 28 days [31–33]. Figure 5 presents the blocks produced with 5%, 7%, and 10% cement additions to the waste powder.

Table 1 presents the properties of the corundum powder used in the Bohme tests and the cement employed for concrete production.

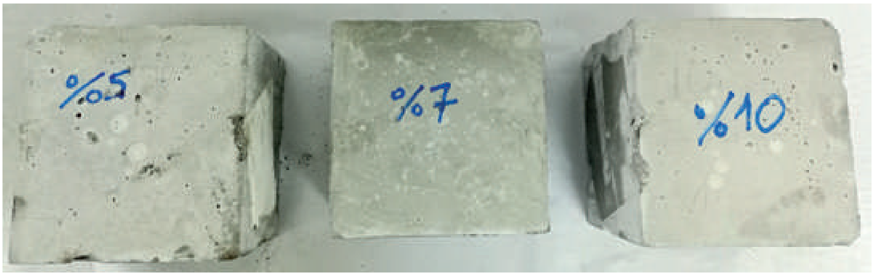

Fig. 5 ***Blocks produced by adding 5%, 7%, and 10% cement to the waste powder***

Table 1 Some Properties of Corundum Powder and Cement Used in Concrete Block Production [34, 35]

Properties of Corundum Powder		Technical Properties of Cement	
Component	Amount (%)	Component	Value (%)
SiO_2	40–60	SiO_2	21.6
Al_2O_3	10–20	Al_2O_3	4.05
Fe_2O_3	5–13	Fe_2O_3	0.28
CaO	5–13	CaO	65.7
MgO	5–13	MgO	1.30
Na_2O	<4	Na_2O	0.30
K_2O	<4	K_2O	0.35
TiO_2	<3	Na_2O	0.30
Loss on Ignition (LOI)	1–5	Loss on Ignition (LOI)	3.50
Density	3.9 – 4.20 g/cm³	Density	3.06 g/cm³
Grain Shape	Angular	Blaine Fineness	4600 cm²/g
Hardness	6.5–7 Mohs	Whiteness (Hunter Lab Y value)	≥85.5%
Color	Brown / Black	Compressive Strength (28 days)	60.0 MPa

2.3 Physico-mechanical tests

The three types of produced concrete blocks were cut and sized according to specific standards, and the samples were subjected to tests for dry density (ρd), porosity (n), Leeb rebound hardness (LRH), point load test (PLT), and uniaxial compressive strength (UCS).

2.3.1 Determination of dry density (ρd) and porosity (n)

In this experiment, the volumes of the samples were first determined, followed by the measurement of their dry weights. Subsequently, the samples were saturated in water for 48 hours to achieve full saturation, after which both their saturated weights and submerged weights were recorded. Using these values, the n and ρd of the samples were calculated. The procedure was carried out in accordance with the guidelines specified in TS EN 1936 [36].

2.3.2 Leeb Rebound Hardness (LRH) test

Since there is no standardized procedure for LRH testing on rocks and concrete specimens, the LRH measurements in this study were conducted based on the methods proposed by İnce and Bozdağ [37]. The LRH values were obtained using an Insize ISH-PHB testing device equipped with a D-type probe (Figure 6a). The technical specifications of the device include a measurement range of 0 to 999 HL, an impact energy of 11 Nmm, and an accuracy of ±6 HL. Prior to the measurements, the device was calibrated, and twenty evenly distributed impact points were selected on the surface of a cubic specimen with 70 mm edge length. The arithmetic mean of these measurements was taken as the HL value of the specimen.

2.3.3 Uniaxial compressive strength

The UCS tests were performed on cubic specimens with 50 mm edge length by following the procedures outlined in the ASTM standard [38]. A 3000 kN capacity UTEST testing machine was used for this purpose (Figure 6b). During the UCS testing, the loading rate was set to 0.25 ± 0.05 MPa/s. Each specimen was tested five times, and the average UCS value was determined from these measurements.

2.3.4 Point load test (PLT)

The PLT test can be conducted using core, block, or irregularly shaped specimens. In this study, block specimens measuring 50×40×30 mm were used for the PLT test. The reading unit of the PLT device employed in the tests was calibrated and digitized (Figure 6c). The procedure was carried out in accordance with ISRM standards [39]. For each of the three different concrete block types, 10 specimens were prepared, and the average of the test results was taken to determine the PLT values.

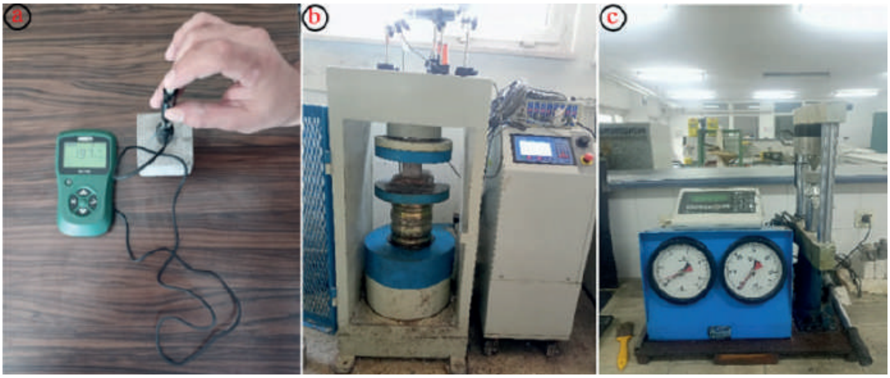

Fig. 6 a) LRH test, b) UCS test, c) PLT test

3 Result and Discussion

Table 2 presents the physico-mechanical properties of the concrete specimens produced in this study. The highest density was recorded in the S2 sample, while the lowest was observed in the S3 sample. The porosity values of the concrete blocks were considerably high and relatively similar across all specimens. The LRH, UCS, and PLT values increased proportionally with the cement content in the mixtures, with the S3 specimen exhibiting the highest strength among the produced blocks.

Table 2 Physico-mechanical properties of the produced concrete specimens

Sample	ρd (g/cm³)	n (%)	LRH	UCS (MPa)	PLT (MPa)
S1	2.46	34.78	170.08	3.00	0.21
S2	2.48	34.72	195.72	5.63	0.36
S3	2.45	33.52	211.70	7.55	0.50

The uniaxial compressive strength (UCS) of concrete is closely related to its microstructural properties. In the literature, it is emphasized that the balance between porosity and the amount of cementitious binder is a key factor in determining concrete strength [32, 33]. In this study, the porosity levels of the analyzed specimens were found to be around 33–35%, which are considered relatively high. Increased porosity leads to a greater number of weak zones within the concrete matrix, facilitating crack initiation and propagation under load, thereby limiting strength. Conversely, an increase in cement content enhances the integrity of the binder matrix, partially compensating for the negative effects of porosity and thereby improving compressive strength.

This is clearly observed in the S3 specimen, which exhibited the highest UCS value (7.55 MPa), as it contained the highest cement content among all specimens. However, despite the increased cement content, the high porosity restricts the strength from rising indefinitely. For this reason, although the S3 specimen demonstrated the highest strength, the resulting compressive strength values remain significantly below those required for conventional structural concrete (typically ≥20 MPa).

Within the scope of this study, the mechanical performance of the concrete was shaped by the complex interaction between porosity and cement content. While increasing the cement content positively influenced strength, high porosity remained the main limiting factor for overall compressive strength. Additionally, the literature classifies concrete strength based on application areas and states that strength values below 3 MPa are unsuitable for use as building materials, whereas strengths in the range of 5–10 MPa are considered acceptable for backfill and light structural applications [32].

In this study, the PLT values of the produced concrete specimens ranged from 0.21 MPa to 0.50 MPa. These values clearly indicate that the mechanical strength of the specimens is limited. From the perspective of PLT, the results fall within the low-strength category, suggesting that such materials are not suitable for structural applications. In this context, the obtained PLT results demonstrate that the specimens are more appropriate for use in backfill and lightweight structural applications. Furthermore, while PLT values increased with higher cement content, it was also observed that high porosity restricted the improvement in strength. This finding implies that when waste powder is utilized in concrete production, the mechanical performance may remain limited, and additional enhancement strategies would be necessary before considering these materials for structural use.

3 Conclusion

In this study, the use of waste powders obtained from the BAR test in artificial concrete production was investigated by mixing them with varying proportions of cement. The physical and mechanical properties of the produced concrete specimens were examined in detail, and the technical suitability of the waste powders as a construction material was evaluated with respect to environmental sustainability. The main findings are summarized as follows:

- The porosity levels measured in the concrete specimens ranged between 33% and 35%, indicating relatively high values. This elevated porosity emerged as one of the primary factors limiting the mechanical strength of the concrete.
- Increasing the cement content improved the integrity of the binder matrix, leading to enhanced UCS and PLT values. The highest compressive strength (7.55 MPa) was recorded in the S3 specimen, which contained the largest proportion of cement. However, due to the persistently high porosity, the strength improvement remained limited, and the resulting values fell considerably below those typical of standard structural concretes, which usually exceed 20 MPa.
- An increase in cement content also resulted in higher LRH values, indicating that the incorporation of waste powders in cement-based concrete contributed positively to both hardness and mechanical resistance.
- Although the concrete specimens did not achieve sufficient strength for structural applications, they were considered suitable for use in backfilling and lightweight structural purposes.

This study demonstrates that waste powders from the BAR test hold significant potential for recovery and the development of environmentally friendly construction materials. Nevertheless, additional efforts are needed to reduce porosity to enhance mechanical performance. While combining waste powders with cement improves strength, the high porosity prevents the material from reaching standard strength levels required for load-bearing applications. Therefore, these materials are more suitable for lightweight structural uses or as fill material and should be considered within the broader context of sustainable construction material development.

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Chapter 3

Engineering Design Principles for Stream Restoration

Meral Korkmaz[1]

Abstract

Climate change has led to alterations in precipitation patterns, with an increase in extreme rainfall events and the emergence of drought trends. These changes have significantly increased the risk of flooding in streams, particularly in residential areas. Consequently, the evaluation of stream rehabilitation must extend beyond the confines of hydraulic conveyance capacity, encompassing hydro-geomorphological stability, ecosystem services, and socio-economic considerations. The present chapter delineates the engineering design principles for structures employed in the context of stream restoration, with a particular emphasis on the integration of hydraulic, ecological, and morphological processes. The discussion focuses on the equilibrium between conventional hard-engineering interventions and process-based, nature-based approaches, with particular emphasis on cross-section design, flow-velocity control, and bed and bank stability. A case study from the Darveta and Köyiçi Streams in Halkalı Village (Elazığ, Türkiye) is examined, including Q_{100}-Q_{500} design discharges, Manning roughness estimation using the Cowan method, hydraulic performance of culverts, grade-control weirs, concrete bed lining, and stability analyses of 1.60 m high retaining structures. The study emphasises the necessity of an engineering-driven yet interdisciplinary framework that collaboratively addresses flood safety and ecological functionality.

1. Introduction

Rivers are dynamic water bodies that play a vital role in the hydrological cycle of their catchments and are essential for the functioning of natural ecosystems. Due to the impacts of climate change, the deterioration of rainfall regimes and the increase in extreme precipitation events have elevated flood risks in river systems (Tabari, 2020; Taşkın et al., 2022). In

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recent years, severe flood events have made river restoration and stream rehabilitation critical fields of study from both engineering and ecological perspectives. Increasing flood risk, water quality problems, biodiversity loss and urbanization pressure necessitate reconsideration of river systems not only in terms of hydraulic capacity but also in relation to ecosystem services and societal benefits. Despite the rising number of projects, the literature indicates that most stream restoration efforts lack systematic post-implementation assessment, leading to repeated mistakes across different catchments (Kondolf & Micheli, 1995; Kondolf, 1995).

River restoration is a multi-component process aimed at improving ecosystem functions, reducing flood risk and re-establishing hydromorphological continuity. Achieving multiple objectives such as hydraulic safety, ecological enhancement and improved water quality requires watershed-scale planning. Figure 1 schematically illustrates the diverse benefits generated by catchment-based management practices for both society and ecosystems (River Restoration Centre, 2023).

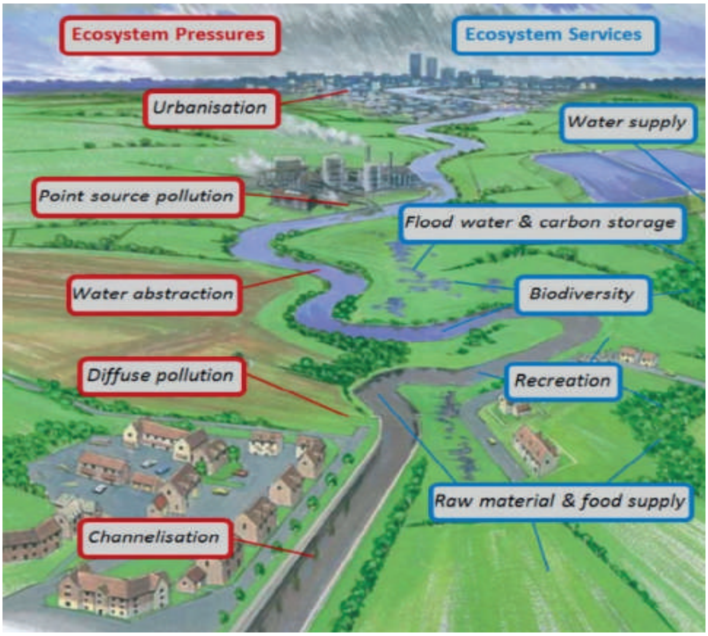

Figure 1. Pressures and Ecosystem Services at the Catchment Scale in the Context of River Restoration (Adapted from RRC)

Palmer et al. (2014) state that restoration has shifted from a historical focus on returning systems to “wilderness-like” conditions toward a framework emphasizing the recovery of ecosystem services that provide direct benefits to people, such as flood mitigation, water quality improvement, and sediment and nutrient retention. Particularly in urban areas, streams have often been converted into "stormwater management structures," involving substantial morphological modifications intended to increase hydraulic retention and reduce peak discharges. However, such intensive engineering interventions may enhance certain services while causing losses in others or generating new environmental impacts, underscoring the necessity of a holistic ecosystem perspective (Palmer et al., 2014).

Hydraulic engineering literature emphasizes that restoration design cannot be limited to cross-sectional sizing. Shields et al. (2003) define the primary objective of restoration as achieving a functional state "as close as possible to the remaining natural potential" of a degraded stream system, highlighting the tension between natural fluvial processes and structural stability. Accordingly, an intermediate-level engineering approach is proposed that combines watershed geomorphology, characteristic discharge analysis and one-dimensional flow and sediment transport modeling. Similarly, Niezgoda and Johnson (2005) argue that in urban streams, structural constraints and disrupted flow and sediment regimes make morphology-based reference designs inadequate, and that process-based approaches and revised definitions of form–process relationships are required.

The ecological dimension of river restoration has also gained increasing importance. Lake et al. (2007) emphasize that many restoration projects are insufficiently grounded in ecological theory, often neglecting essential concepts such as species life cycles, dispersal processes, refugia, longitudinal and lateral connectivity, food-web dynamics, and assembly rules. This perspective demonstrates that stream rehabilitation involves not only hydraulic safety or bank protection, but also the reconstruction of ecosystem processes and biodiversity. Biotechnical bank protection approaches (Li & Eddleman, 2002) and studies highlighting the ecological functions of structural elements such as vanes, weirs and SPSC systems (Hickman, 2019) show that nature-based alternatives to traditional hard-engineered solutions are feasible.

More recent studies reveal that river restoration has a strong social and governance dimension. Gariépy-Girouard et al. (2025) show that restoration projects are often shaped not by scientific–technical principles but by public pressure, funding conditions and stakeholder expertise, which may lead to the neglect of hydro-geomorphological principles. Robins et al. (2025) highlight the weakness of data-driven decision-making in catchment-scale river restoration planning and the need for clearer definitions of pressure–

impact relationships and standardized planning frameworks. Studies conducted in Türkiye indicate similar challenges: in İstanbul, stream rehabilitation efforts aimed at reducing flood risk face difficulties due to issues related to land ownership, zoning and institutional authority (Bodur, 2018); while in the case of Bitlis Merkez Stream, rehabilitation and urban transformation projects offer opportunities for enhancing local capacity, unveiling historical–cultural heritage, and reducing disaster risk, though institutional coordination remains critical (Yıldırım & Çelik, 2025).

Overall, the literature demonstrates that stream rehabilitation and river restoration are not limited to structural interventions such as culverts, retaining walls, weirs or channel linings. Instead, they constitute multidisciplinary fields requiring the integrated consideration of geomorphology, ecology, hydraulics, socio-economic context, governance, and long-term monitoring. While ecological engineering approaches aim to support natural processes and ecosystem services (Woo et al., 2005; Palmer et al., 2014), guidance documents and technical notes (Doll et al., 2020) provide systematic frameworks for practitioners. Accordingly, the fundamental engineering components used in stream rehabilitation such as weirs, culverts, retaining structures and biotechnical bank protection should be evaluated not only in terms of hydraulic performance but also in relation to hydro-geomorphological compatibility, contributions to ecosystem services and long-term monitoring requirements.

Increasing degradation in river ecosystems, rising flood risk and the pressures of urbanization have transformed stream rehabilitation and river restoration into a multidisciplinary engineering–ecology field. Despite the large number of restoration projects implemented over the past three decades, many have lacked adequate hydromorphological assessment and long-term monitoring (Kondolf & Micheli, 1995), contributing to high failure rates and slowing the advancement of restoration science. Palmer et al. (2014) emphasize that restoration is shifting away from solely re-creating natural conditions toward restoring ecosystem services most needed by society, such as flood mitigation, water quality improvement and sediment management. In this context, Shields et al. (2003) argue that restoration design must maintain natural fluvial processes while ensuring engineering stability, requiring both geomorphological and hydraulic analyses.

This literature framework aligns strongly with stream rehabilitation practices in Türkiye, particularly in settlements intersected by stream corridors. In the case of Halkalı Village in Alacakaya, Elazığ, the existing sections of Darveta and Köyiçi Streams were found incapable of conveying design flood discharges, placing residential and agricultural areas at high risk. Field assessments revealed the necessity of concrete bed lining due to high tractive forces, the installation of weirs for flow-velocity control, and the use of Q_{100} and Q_{500} design discharges due to residential constraints. Hydraulic analyses were conducted for three culverts of varying dimensions (4.00×2.00 m, 2.00×2.00 m and 3.00×2.00 m), and stability analyses were performed for 1.60-m-high retaining walls. These applications reflect the interaction and sometimes tension between engineering requirements, ecological considerations and social constraints highlighted in the literature. As noted by Gariépy-Girouard et al. (2025), river restoration is shaped not only by technical considerations but also by social acceptance, institutional capacity and local expectations. In the Halkalı Village case, the fact that the stream corridor passes entirely through residential areas directly influenced section dimensions and structure types, illustrating restoration as an inherently social practice.

In conclusion, both the literature and field applications demonstrate that stream rehabilitation is not merely the implementation of structural elements (e.g., weirs, culverts, retaining walls), but rather a comprehensive engineering approach requiring the integrated consideration of hydro-geomorphological processes, ecosystem services, social expectations and long-term monitoring. The following section examines the fundamental engineering components used in stream rehabilitation within this broad framework.

2. Stream Rehabilitation in the Context of River Restoration at Halkalı Village

Hydraulic analyses conducted by the General Directorate of State Hydraulic Works (DSİ) in Halkalı Village revealed that the existing cross-sections of Darveta and Köyiçi Streams are unable to convey the Q_{100} and Q_{500} design flood discharges. Due to high flow velocities and narrow sections, bed scour and bank instability were observed; therefore, the project included concrete bed lining, the placement of weir (grade-control) structures for flow-velocity control, and the design of culverts with appropriate spans. In addition, due to spatial constraints within the settlement, the stability of retaining structures with a wall height of 1.60 m was evaluated.

The project area map presented in Figure 2 shows the locations of Darveta and Köyiçi Streams within the residential area, the chainage (km) points, and the rehabilitation alignment defined by DSİ. The map combines the regional location of the project area with detailed river geometry, thereby providing the spatial context for the analyses.

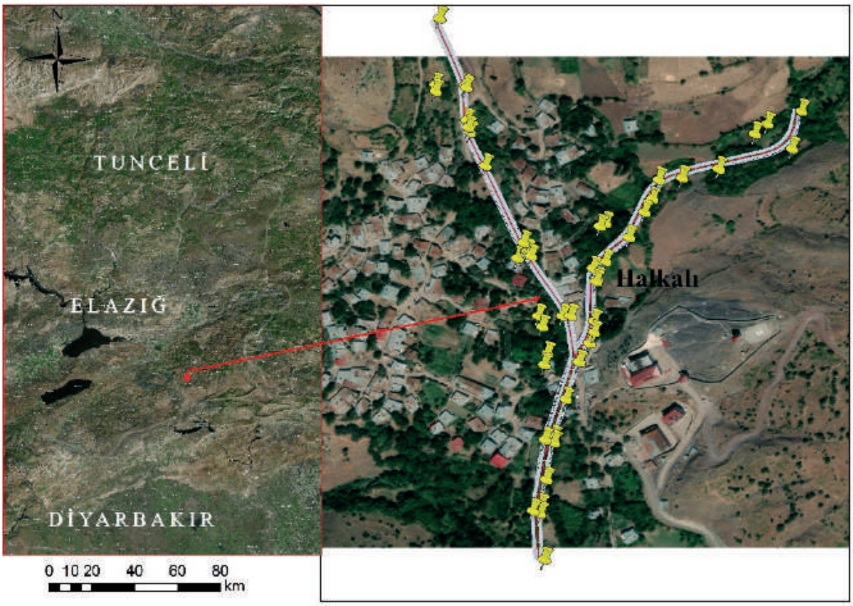

Figure 2. Project area of Darveta and Köyiçi Streams in Halkalı Village

2.1. Characteristics of the Project Area

Halkalı Village is fed by two main streams:

- Darveta Stream
- Köyiçi Stream

Both streams flow through the settlement and continue along extensive agricultural lands. The inability of the existing sections to convey flood discharges has created a significant risk for the settlement. The stream corridor passes through relatively narrow valleys, and the steep topographic slopes in certain reaches increase flow velocities and, consequently, flood hazard. Because the village's built-up area is located very close to the streambeds, the inadequacy of the existing cross-sections has led to both hydraulic and structural problems.

The topographic map provided in Figure 3 illustrates the spatial relationship between the valley system, slope configuration, settlement areas and tributaries within the project area, and reveals the morphological conditions that form the basis for hydraulic design.

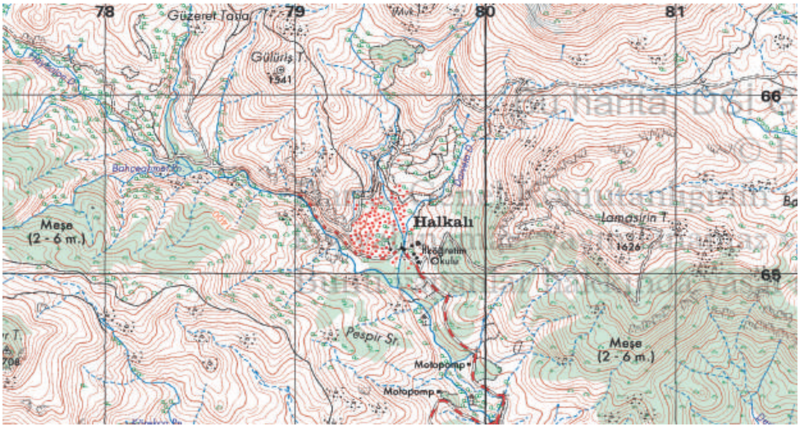

Figure 3. Topographic map of Halkalı Village and its surroundings

2.2. Identified Problems

- Inadequate existing cross-sections
- Flow areas directly adjacent to residential zones
- Loss of life and property following flood events
- Bed scour and lateral erosion
- Undersized culverts
- High tractive force

As shown in Figure 4, the existing cross-sections in Darveta and Köyiçi Streams are quite narrow and do not allow the safe conveyance of flood flows. Irregular bed geometry, lateral erosion, bank instability and high tractive forces during flood events are among the main problems identified in the field.

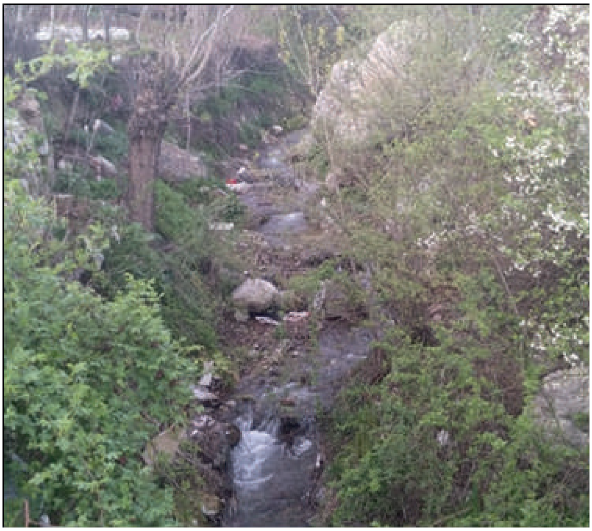

Figure 4. Narrow existing sections and flood-prone areas in Darveta and Köyiçi Streams

3. Objectives and Scope of Stream Rehabilitation

Stream rehabilitation is an engineering practice aimed at reducing flood risk, erosion, morphological degradation and environmental hazards in river systems, based on the integrated assessment of hydraulic, geomorphological, ecological and socio-economic components. Today, the objective of stream rehabilitation is not limited to securing the controlled conveyance of water; it also includes protecting the ecological functions of river systems, reducing risks to settlements and infrastructure, supporting sustainable land use, and ensuring public safety. For this reason, stream rehabilitation plays a multidimensional role as both a technical and a socio-ecological management tool.

Stream rehabilitation is a multi-faceted process encompassing a broad range of engineering and ecological activities. Before implementation, it requires detailed analysis of the existing conditions, identification of hydraulic cross-sections, examination of sediment characteristics, and assessment of bed–bank stability. Within this scope, high-risk areas are identified; Q_{10}–Q_{500} design flood discharges are calculated for hydraulic and morphological design; and structures such as weirs, grade-control structures and spillways are planned accordingly. Where necessary, bed lining is applied; and infrastructure components such as walls, revetments, culverts, bridges and road crossings are designed or rearranged, accompanied by measures to prevent backwater effects. In addition to engineering interventions, biotechnical practices such as riparian vegetation and rehabilitation of the riparian zone support the sustainability of the stream ecosystem. The social and institutional dimension of the process includes risk reduction activities, land-use management and coordination with local stakeholders. Thus, stream rehabilitation is not limited to technical engineering solutions; it is a comprehensive field of practice that integrates ecological, social and governance strategies.

3.1. Reducing Flood Risk

The primary objective of stream rehabilitation is to minimize the hazards posed by river floods to residential areas, agricultural lands and critical infrastructure. The infilling of stream sections over time, unplanned development, uncontrolled interventions and morphological changes reduce discharge conveyance capacity and increase flood risk. Designing appropriate cross-sections based on flood return periods (Q_{10}, Q_{50}, Q_{100}, Q_{500}, etc.), eliminating critical constrictions, and correcting inadequacies in culvert and bridge spans constitute the main activities undertaken within this scope.

In DSİ practices in Türkiye, designing for Q_{100}–Q_{500} in densely populated areas is a standard approach to ensuring life and property safety. As in the case of Darveta and Köyiçi Streams in Halkalı Village, the inability of existing sections to convey design flood discharges directly threatens settlement safety; therefore, widening of sections, bed lining and the construction of weir structures become indispensable.

3.2. Ensuring Hydraulic and Morphological Stability

River systems are natural environments operating in a state of dynamic equilibrium, with ongoing feedback between flow regime, sediment transport and channel morphology. One of the key objectives of stream rehabilitation is not to suppress these natural processes entirely, but to establish a sustainable hydro-geomorphological balance. In this context, preventing bed degradation, controlling erosion, regulating sediment transport capacity and reducing flow velocity to safe levels are critical hydraulic targets in rehabilitation projects.

As observed in Darveta and Köyiçi Streams, high tractive forces and the mobility of bed material disrupted natural stability; therefore, concrete bed lining and energy-dissipating weirs were employed to achieve a safe morphological balance.

3.3. Protecting Water Quality and Ecosystem Services

Contemporary restoration approaches recognize that stream rehabilitation should not only provide physical safety but also contribute to the preservation of ecosystem services that are critical to society, such as nutrient retention, habitat provision, functioning of floodplains and opportunities for recreation. Palmer et al. (2014) describe this shift as a transition "from recovering wild ecosystems to improving ecosystem services."

3.4. Ensuring Infrastructure and Settlement Safety

In rapidly urbanizing and industrializing regions, streams are often enclosed or modified in an uncontrolled manner, leading to serious safety problems. Road crossings, bridges, culverts, sewer lines and drinking-water pipelines are all directly affected by stream rehabilitation measures.

Therefore, stream rehabilitation is critical not only for the safety of the river system itself but also for maintaining infrastructure integrity. Correct hydraulic design of culverts, bridges and retaining walls, prevention of backwater effects and maintaining flow continuity are among the fundamental objectives of such projects. In the Halkalı Village case, three culverts were subjected to detailed hydraulic verification, and the design of wall stability and bed lining were evaluated within this scope.

3.5. Addressing Socio-Economic and Institutional Requirements

An increasingly discussed dimension in the literature is that stream rehabilitation is also a social and governance process. Public acceptance, land ownership issues, local government capacity, user expectations and institutional coordination directly influence the technical framework of rehabilitation. As demonstrated in the cases of İstanbul (Bodur, 2018) and Bitlis Stream (Yıldırım & Çelik, 2025), project success depends not only on technical design but also on planning, authority sharing and public engagement.

4. Key Hydraulic Design Parameters in Stream Rehabilitation

The engineering components used in stream rehabilitation projects consist of structural and biotechnical interventions that regulate the hydraulic behavior of river systems, reduce flood risk and protect settlements. Modern approaches aim not only to control flow but also to sustainably enhance aquatic ecosystem functioning, morphological stability and ecosystem services. International literature emphasizes the importance of preserving fluvial processes while ensuring stability, achieving hydro-geomorphological compatibility, supporting ecosystem services and establishing long-term monitoring requirements in rehabilitation projects (Shields et al., 2003; Palmer et al., 2014; Kondolf & Micheli, 1995).

In Türkiye, DSİ practices primarily translate these approaches into measures focused on flood control, velocity reduction, stability and cross-sectional safety. The Elazığ, Alacakaya Halkalı Village flood protection project provides a good example of how these components are integrated in the field.

4.1. Roughness Coefficient (Manning 'n')

The Cowan method was first developed by W. L. Cowan in 1956 and later revised by the U.S. Geological Survey in 1989 (Cowan, 1956). In Türkiye, the DSİ Flood Expertise Commission further refined the method by introducing the "channel bank condition (n_1)" parameter into roughness calculations, giving the method its final form.

In the modified Cowan method, the Manning roughness coefficient is calculated as follows:

$$n = n_b + n_1 + n_2 + n_3 + n_4$$

$$n_{\text{total}} = n \times m$$

One of the most critical inputs in hydraulic calculations is the roughness coefficient. DSİ computes Manning's n using a table-based component analysis (n_b, n_1, n_2, n_3, n_4). In the Halkalı project, roughness values for both Darveta and Köyiçi Streams were determined using this method, and cross-section geometry was optimized accordingly (Demir & Keskin, 2019; DSİ, 2016). The roughness coefficient forms the basis for determining flow velocities, positioning of weirs, air clearance and culvert hydraulics.

Table 1. Manning roughness coefficient components for Darveta and Köyiçi Streams

Component-Parameter	Description	Darveta Stream	Köyiçi Stream
n_b	Bed roughness (concrete)	0.016	0.016
n_1	Cross-section irregularity (right–left masonry walls; $n_1a + n_1b$)	0.005	0.005
n_2	Channel section variation	0.000	0.000
n_3	In-channel obstructions (deposits, mounds, boulders)	0.000	0.000
n_4	Vegetation (low)	0.005	0.005
Total *n*	Manning roughness coefficient	0.026	0.026
Stream length (m)	Length measured along the channel	685	410
Straight-line length (m)	Direct distance from start to end	663.25	370.42
D/L (stream / straight line)	Sinuosity ratio	1.03	1.11
m (meander coefficient)	D/L < 1.2 → m = 1.0	1.00	1.00

4.2. Sizing and Cross-Section Design

The hydraulic adequacy of culvert sections designed on Köyiçi and Darveta Streams was evaluated according to DSİ's design flood discharge criteria. For each culvert, design discharge values were used together with bed width, section height, project slope and Manning roughness to obtain $Q_{calculated}$ values. The hydraulic verification results are summarized below.

Köyiçi Stream – KM: 0+009.25 (3.00 × 2.00 m Culvert)

At this location, a rectangular culvert with a 3.00 m bed width and 2.00 m height was designed. The Manning coefficient was taken as $n = 0.026$ and the project slope as 0.30%. For Q_{100} and Q_{500}, considering the hydraulic radius and flow parameters of the culvert, a $Q_{calculated} = 36.07$ m³/s was obtained. Since this value is significantly higher than $Q_{500} = 14.10$ m³/s, the cross-section is considered hydraulically adequate.

Darveta Stream – KM: 0+560.00 (2.00 × 2.00 m Culvert)

At this location, a culvert with a 2.00 m bed width and 2.00 m height was proposed. The project slope is 0.30%, and Manning's n is 0.026. For $Q_{100} = 5.60$ m³/s and $Q_{500} = 7.40$ m³/s, hydraulic calculations yield *Q_calculated* = 20.335 m³/s. Since *Q_calculated* exceeds Q_{500}, the culvert section is considered safe.

Darveta Stream – KM: 0+224.32 (4.00 × 2.00 m Culvert)

Here, a culvert with a 4.00 m bed width and 2.00 m height was designed. Manning's n is 0.026 and the project slope is 0.30%. Using Q_{100} = 14.90 m³/s and Q_{500} = 19.70 m³/s, the hydraulic analysis yields ***Q_calculated* = 53.294 m³/s**. This value is approximately three times Q_{500}, indicating that the culvert has sufficient hydraulic capacity.

4.3. Weir (Grade-Control) Structures and Velocity Control

Weirs (grade-control structures) are key rehabilitation elements used to reduce flow velocity, prevent bed scour and dissipate energy within the channel, particularly in steep or high-discharge reaches.

In the DSİ report:

- A maximum velocity of v = 5.00 m/s was adopted.
- Weir structures were deemed necessary in sections where this limit is exceeded.

International studies similarly emphasize that velocity control is critical for sediment transport and channel stability (Shields et al., 2003; Niezgoda & Johnson, 2005).

4.4. Bed Linings (Concrete, Stone and Natural Materials)

In streams with high tractive forces, bed linings are used to prevent bed degradation. In the Halkalı Village project:

- DSİ recommended **concrete lining** due to high tractive forces.

Alternative linings include:

- Stone lining (a traditional practice in Anatolia for bank improvement)
- Natural bed enhancement methods (commonly preferred in ecological restoration projects)

4.5. Culvert Design and Hydraulic Verification

Culverts are critical structures for ensuring safe flow conveyance where roads intersect with streams. In DSİ applications, culvert dimensions are verified through:

- Hydraulic calculations,
- Velocity–head relationships,
- Air-clearance considerations,

- Stability analyses.

Culverts used in the Halkalı Village project are as follows:

- Darveta Stream: 4.00×2.00 m and 2.00×2.00 m
- Köyiçi Stream: 3.00×2.00 m

International literature emphasizes that culvert design should be evaluated not only hydraulically but also in terms of ecological connectivity, such as fish passage and habitat continuity.

4.6. Slope and Wall Stability

An important component of stream rehabilitation is the stability of sidewalls, slopes and retaining structures. DSİ applies classical engineering analyses based on checks for sliding, overturning and bearing capacity.

In the Halkalı Village project:

- Static and reinforced concrete calculations were performed for walls with a height of $\boldsymbol{h} = \mathbf{1.60\ m}$.
- Wall cross-sections were strengthened with settlement safety in mind.

4.7. Biotechnical Applications and Ecological Approaches

In addition to conventional rehabilitation methods, modern literature recommends the following biotechnical applications:

- Permeable bank protection,
- Vegetation combined with stone-supported hybrid structures,
- Slope stabilization with deep-rooted plants,
- Timber piles / live fascines and hedges.

Li and Eddleman (2002) emphasize that biotechnical methods are "more economical and more ecosystem-friendly than hard-engineered solutions." Hydro-geomorphology-based projects, on the other hand, advocate evaluating the river system as an integrated whole (Gariépy-Girouard et al., 2025).

4.8. Nature-Based Solutions

International trends in river restoration increasingly promote:

- Setback levees and corridor widening,
- Re-activation and multifunctional use of floodplains,

- Restoration of riparian forests,
- Improvement of channel meanders.

Palmer et al. (2014) justify this approach by the need to place ecosystem services at the center of restoration efforts.

4.9. Long-Term Monitoring and Evaluation

According to the principles emphasized by Kondolf & Micheli (1995) and in the "Five Elements for Effective Evaluation" framework:

- Every restoration project is essentially an **experiment**.
- The successes and failures of projects must be **systematically documented**.
- Monitoring periods should extend to **at least 10 years**.

In DSİ's field practices, the duration of monitoring varies by project; however, it is progressively converging toward these international standards.

5. Conclusions

The complex, multidimensional field of stream rehabilitation and river restoration is situated at the intersection of engineering and ecological sciences. A comprehensive review of the extant literature, together with an analysis of international methodologies and DSİ's technical findings from field applications, as examined in this study, clearly demonstrates that contemporary stream rehabilitation practices now extend beyond the scope of traditional engineering methodologies, which were previously exclusively focused on the safe conveyance of design flood discharges.

As demonstrated in the extant literature, the success of restoration projects is contingent upon a comprehensive understanding of hydro-geomorphological processes, the preservation of ecosystem services, the compatibility of structures in terms of hydraulics and morphology, and the continuity of long-term monitoring and evaluation initiatives (Kondolf & Micheli, 1995; Palmer et al., 2014; Shields et al., 2003). Concurrently, the outcomes of projects are found to be profoundly influenced by social acceptance, the capacity of local government, funding models and stakeholder expectations. This observation underscores the notion that stream rehabilitation is not merely a technical engineering practice, but rather a process that encompasses a substantial social and governance dimension.

The Halkalı Village Darveta and Köyiçi Streams Rehabilitation Project, prepared by DSİ, provides a practical illustration of the implementation of these approaches. The selection of a concrete bed lining due to high tractive forces, the use of weir structures to control flow velocity, detailed hydraulic verification of culverts, and the adoption of Q_{100}-Q_{500} design discharges in engineering design all represent a rational and standards-compliant approach to engineering safety and flood control. Concurrently, spatial configurations aimed at safeguarding ecosystem services, ensuring settlement stability, and delivering social benefits exemplify a holistic restoration perspective at the scale of Türkiye.

The findings of this study suggest that future stream rehabilitation efforts are likely to incorporate increasing amounts of:

- The utilisation of solutions that are inspired by and in harmony with natural environments.
- The design principles underpinning ecosystem services.
- The integration of planning at the catchment scale is imperative.
- The necessity for collaboration between local governments and communities is indisputable.
- The utilisation of advanced digital hydraulic modelling techniques is imperative in this context.
- Furthermore, the necessity for long-term monitoring programmes is emphasised.

This approach facilitates a more nuanced balance between engineering interventions and ecological processes, thereby fostering the transition towards integrated and sustainable stream rehabilitation practices. In this context, the harmonisation of conventional "hard" engineering structures with biotechnical and ecological methods is anticipated to accelerate, leading to a more holistic and environmentally sustainable approach to stream rehabilitation.

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Bölüm 4

Mikroalg Bazlı Gıdalara İnovatif Yaklaşımlar

Merve Karakurluk[1]

İlkay Buran[2]

Özet

Sucul organizmalar fonksiyonel gıda bileşenleri sayesinde gıdaları zenginleştirme ve sürdürülebilir kaynaklar olarak hızla tanınmaktadır. Gıda olarak en sık tüketilen mikroalg türleri Dunaliella, Schizochytrium, Spirulina, Chlorella ve Haematococcus olup "Genel Olarak Güvenli Olarak Kabul Edilen" (GRAS) olarak onaylamıştır. Mikroalglerden elde edilen biyoaktif maddelerin fonksiyonel bir bileşen olarak kullanılabileceğine dair araştırmalar, yeni ürünler yaratmaya başlamıştır. Mikroalglerin yetiştirilmesi bir çok alanda sürdürülebilir bir yaklaşımı temsil etmektedir. Mikroalg takviyeleri omega-3 yağ asitleri, protein ve antioksidanlar bakımından besin konsantrasyonu ve biyoyararlanım açısından çok değerlidir. Son araştırmalarda kanser ve bağırsak sendromunu önlemeye yönelik prebiyotikler olarak hizmet eden mikroalg polisakkarit kullanımına ilişkin geniş bir perspektif sunulmaktadır. Mikroalglerden endüstriyel açıdan önemli biyolojik ürünler geliştirme çabaları devam ederken, gıda ve genetik mühendisliği yaklaşımıyla mikroalg bazlı biyoaktif bileşiklerin üretimini artırmak için laboratuvar ölçeğinde çeşitli başarılı girişimlerde bulunulmuştur. Sonuç olarak mikroalgler sürdürülebilir gıda üretimi ve besin takviyesi inovasyonu için fonksiyonel özellikleri artmaktadır.

1. GİRİŞ

Algler, dünya çapında birincil gıda zincirindeki üretimin yarısına sahiptir (Spolaore vd., 2006). Tek hücreli ve çok hücreli yapıda olan algler, büyüklüklerine göre mikro ve makro algler şeklinde sınıflandırılmaktadır (Falkowski, 2004). Algler, deniz florasının neredeyse %90-95'ini

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oluşturmaktadır. Farklı su kaynaklarında kolayca yetişebilme yeteneği olan algler, fotosentez ile besin üretmektedir (El-Sheekh vd., 2006). Alglerin yapısındaki pigmentler ile CO2 ve H2O'yu kompleks karbonhidratlara dönüştürür. Bu sayede algler bulundukları su ortamında besin seviyesinde artış sağlarken suda çözünmüş O2 seviyesinde de artış meydana gelmektedir (Oğur, 2016).

0,2-10 μm boyutundaki organizmalar mikroalgler olarak değerlendirilirken, 70 m uzunluğuna kadar ulaşabilen su yosunları ise makroalg olarak değerlendirilmektedir (Koyande vd., 2019; Ścieszka and Klewicka, 2019).

Mikroalgler basit yapıları ile her türlü koşulda yaşam sürdürebilme ve hızlı bir şekilde çoğalabilme özelliğindedir (Sasa vd., 2020; Villarruel vd, 2017). Algler, klorofil içeren tek hücreli ve çok hücreli organizmalardır. Yapısal yönden algler ökaryotik ve prokaryotik olarak iki grupta değerlendirilmektedir. Siyanobakteriler, prokaryötik grupta ele alınmaktadır. Bu grupta değerlendirilen prokaryötik mikroalgler Klorofil-a içermektedir. Mavi-yeşil algler en sık bilinenlerdir.

Okyanuslarda ve göller, havuzlar, nehirler gibi tatlı sularda 50.000'i aşkın çeşitli mikroalg türü bulunmaktadır (Richmond, 2004). Ökaryötik mikrolgler ise Dinophyta (Dinoflagellates, C. cohnii); Chlorophyta (yeşil alg, Chlorella, Dunaliella, Haematococcus); Xanthophyta (Monodus subterraneous); Rhodophyceae (kırmızı alg, Porphyridium türleri); Bacillariophyta (diatomlar, Nitzschia laevis); Phaeophyta (kahverengi algler); Chrysophyta (sarı-kahverengi algler, Ochromonas malhamensis); Prymnesiophyta (Isochyrisis, Prymnesium paruum ve Pavlova suşları) ve Rhaphidophyta (Fibrocapsa japonica)'dir (Tomaselli, 2004).

1.1.Kimyasal Bileşimi

Mikroalglerin kimyasal yapısı kültür yaşı, kültür şartları ve ortama göre değişkenlik göstermektedir. Bu faktörlere ek olarak ışık yoğunluğu, sıcaklık, besin ortamı benzeri deneysel koşullar, mikroalgin fizyolojik durumu ve bileşimi ölçme esnasında kullanılan yöntem kimyasal bileşimi etkilemektedir (Costard vd., 2012; Paes vd., 2016).

Mikroalgler karbonhidrat, protein, lipit, çoklu doymamış yağ asitleri, esansiyel amino asit, kalorisiz diyet lifi, vitamin ve mineral benzeri yüksek besin değerine sahip bileşenler içermektedir (Sahay vd., 2016). Bazı mikroalglere ait besin bileşimi Tablo 1'de verilmektedir.

Tablo 1. Mikroalglerin protein, karbonhidrat ve yağ bileşimi (%) (Hudson, 2008; Bishop ve Zubeck, 2012)

Bileşen	***Spirulina***	***Chlorella***	***Dunaliella***	***Haematococcus***
Protein	63	64.5	7.4	23.6
Karbonhidrat	17.8	15.0	29.7	38.0
Yağ	4.3	10.0	7.0	13.8

Mikroalgler protein içeriği yönünden protein kaynağı olarak nitelendirilmektedir. Mikroalglerden Spirulina'nın protein içeriği kuru maddede %60-70 aralığında değişkenlik gösterebilmektedir (Hamed vd., 2015). Ayrıca Arthrospira ve Chlorella da zengin protein ve aminoasit profiline sahiptir (Raposo vd., 2013).

Mikroalglerin karbonhidrat içeriği kuru ağırlığının ortalama %10'unu oluşturmaktadır. Mikroalglerin bileşiminde en çok bulunan karbonhidrat monomerleri glukoz, rhamnoz, ksiloz ve mannozdur. Fakat mikroalgler disakkarit, oligosakkarit ve polisakkaritleri de bileşimlerinde bulundurmalarına rağmen hemiselüloz ve lignin içermemektedir (Villarruel-Lopez vd., 2017). Arthrospira, Dunaliella, Chlorella ve Nannochloropsis gibi mikroalgler bileşimlerindeki oligosakkarit ve polisakkarit sayesinde potansiyel prebiyotik olarak değerlendirilmektedir (Gupta ve ark., 2017; Caporgno ve Mathys, 2018).

Mikroalgler polar ve non-polar lipit sentezine sahiptir. Sentezlenen glikolipid, fosfolipid ve sfingolipidler polar grupta, sterol, serbest yağ asitleri, triaçilgliserol ise non-polar grupta yer almaktadır (Kumari ve ark., 2013; Chen ve ark., 2018; Aratboni ve ark., 2019). Genel olarak lipit bileşimi, kuru ağırlığın %20-50'sini oluşturmaktadır (Villarruel-Lopez vd., 2017). Mikroalgler başlıca Omega-3, uzun zincirli çoklu doymamış yağ asitleri (PUFA) olan dokosaheksaenoik asit (DHA) ve eikosapentaenoik asit (EPA) gibi esansiyel besin içeriği oldukça fazladır (Caporgno ve Mathys, 2018).

Mikroalgler vitamin bileşimi bakımından oldukça zengindir. Mikroalgler A, B grubu vitaminler, C, E, biyotin, folik asit ve pantotenik asit kaynağı olarak değerlendirilmektedir. Mineraller yönünden ise mikroagler Ca, Fe, K, Mg, Na, Zn ve iz elemetler içermektedir (Gouveia ve ark., 2008).

Mikroalglerin yapısında klorofil, fikobiliproteinler ve çeşitli karotenoidler bulunmaktadır. Bileşiminde yer alan bu doğal pigmentler sayesinde mikroalgler hem güneşin zararlı etkilerinden korunur hem de güneş ışığı emilimini destekler (Gouveia vd., 2008). Başlıca fotosentetik pigment olan klorofil, mikroalglerin kuru ağırlığının % 0.5-1.5'ini oluşturmaktadır (Ferruzi ve Blakeslee, 2007).

1.2. Biyoaktif Bileşenler

1.2.1. Antioksidan Özellik

Algler yapısında bulunan doğal antioksidanlar yönünden zengin bir kaynaktır (Ngo vd., 2010). Askorbik asit, tokoferoller, karotenoidler, retinoidler ve bioflavonoidler alglerde olduğu gibi karasal kaynaklı ürünlerinde antioksidan bileşikleridir (Gökpınar vd., 2006). Güçlü biyolojik antioksidanlardan biri de karotenoidlerdir (Guedes vd, 2011). Ayrıca Dunaliella salina biyoması kuru ağırlığının %2,8 w/w seviyesinde karotenoid içeren bir mikroalg türüdür. Buna ek olarak karotenoid grubundan a-karoten, likopen ve lutein de içermektedir (Gökpınar vd., 2006). Örnek olarak Chlorella vulgaris ve Chlorella pyrenoidosa'dan lutein, astaksantin ve kantaksantin; Dunaliella salina'dan β-karoten antioksidan üretiminde kullanılmaktadır (Plaza vd., 2009). Antioksidan etkisi en güçlü olan astaksantin ise en çok Haematococcus pluvalis tarafından üretilmektedir (Torzillo vd., 2003).

Vitaminler yönünden oldukça zengin olan mikrolgler, besleyici özelliğini de vitaminlerden almaktadır (Brown vd., 1999). Chlorella ekstratı α-tokoferol ve karotenoid gibi lipofilik antioksidan bileşikleri içermektedir (Gökpınar vd., 2006).

1.2.2. Fenolik Bileşikler

Doğrudan aromatik halkaya bağlı olan bir ya da birden fazla hidroksil grubuna sahip olan fenolik bileşikler, fonksiyonel özelliklere sahiptir. Doğal antioksidanlardan biri olarak kabul edilen fenolik bileşikler, alglerde oldukça zengin içeriğe sahiptir (Klejdus ve diğ., 2009; Ferreres ve diğ., 2012; Heffernan ve diğ., 2015). Sekonder metabolitler olan fenolik bileşikler, biyotik (patojen etkileşim) ve abiyotik (UV ışınlaması) strese karşı alg hücresi savunmasında önemli etkiye sahip olduğu gibi pek çok biyolojik özellik ve farmakolojik etki göstermektedir (Zhang vd., 2015).

Phaeodactylum tricornutum benzoikasit türevleri (siringik asit, vanilik asit, gallik asit, protokateşik asit), sinnamik asit türevleri (ferulik asit, kafeik asit, sinapik asit o- ve p- kumarik asit ve klorojenik asit) ve hidroksibenzaldehitler (4- hidroksibenzaldehit, 2,5-dihidroksibenzaldehit) içermektedir (Goiris vd., 2014; Rico vd., 2012. Ayrıca yapılan çalışmada sinnamik türevlerinden p-kumarik ve ferulik asit tespit edilmiştir (Goiris vd., 2014).

1.3. Gıdalarda kullanımı

Tüketici toplumun yapay katkı maddelerinin kullanımı yerine doğal katkı maddelerine olan ilgisi, mikroalg içerikli bileşenlerin gıdalarda kullanılabilmesi amacıyla yapılan çalışmaları etkilemiştir (Caporgno ve Mathys, 2018). Kaliteli besin bileşimine sahip mikroalgler, gıda firmaları tarafından mikroalg içeren ürünler üretmeye başlamıştır. Fakat genellikle gıda takviyesi formunda satışa sunulmaktadır (Lafarga, 2019).

Ticari açıdan önemli görülen mikroalgler Spirulina, Chlorella, Dunaliella, Haematococcus, Botryococcus, Chaetoceros, Porphyridium, Nitzschia, Crypthecodinium, Phaeodactylum, Isochrysis, Tetraselmis, Nannochloris, Schizochytrium ve Skeletonema türleridir (Sathasivam vd., 2019). İnsan tüketiminde kullanılan mikroalgler protein ve esansiyel bileşenler yönünden zengin olan Arthrospira, Aphanizomenon ve Chlorella; antioksidan karotenoidleri kaynağı olan Haematococcus ve Dunaliella türleridir (Niccolia vd., 2019). Dünya genelinde en sık üretimi yapılan ve içecek, fırın ürünleri, salata sosları gibi ürünlerine eklenen, protein takviyesi olarak kullanılan Spirulina ve Chlorella türleridir (Wells vd., 2017). Bazı mikroalgler ve eklendiği gıda ürünleri Tablo 2'de yer verilmiştir.

Tablo 2. Mikroalgler ve eklendiği gıda ürünleri

Mikroalg türü	Eklendiği gıda	
Spirulina	Yoğurt	Malik vd., 2013; Barkallah vd., 2017
	Bisküvi	Singh vd., 2015
	Ekmek	Ak vd., 2016; Saharan ve Jood, 2017
	Makarna	De Marco vd., 2014
Dunaliella	Ekmek	Tertychnaya vd., 2020
	Makarna	El-Baz vd., 2017
Chlorella	Peynir	Tohamy vd., 2018
	Kurabiye	Sahni vd., 2019

Biyoaktif bileşenler yönünden zengin süt ve süt ürünleri üretimi için, mikroalglerin kullanımı oldukça sıktır. Yapılan çalışmalarda yoğurt ve fermente süt ürünlerine Arthrospira mikroalg türü eklenmesi halinde, probiyotik bakterilerinin gelişiminin desteklendiği tespit edilmiştir. Ayrıca yoğurt ve peynire eklenen Chlorella türü mikroalgler ile gıdaların biyoaktif özelliklerinin geliştirildiği çalışmalar da mevcuttur (Jeon, 2006).

Peynire belli oranlarda eklenen Spirulina platensis ile peynir örneklerinde β-karoten ve protein içeriklerinin arttığı, antioksidan kapasitesinin ise geliştiği bildirilmiştir (Darwish, 2017). Ayrıca Spirulina platensis'in laktik asit bakterilerinin gelişimini destekleyerek prebiyotik etki ettiği, Chlorella pyrenoidosa'nın ise Candida albicans ve Listeria monocytogenes'in gelişimini engellediği çalışmalarda gösterilmiştir (Gupta vd., 2017).

Isochrysis galbana türü mikroalg, özellikle bisküvilerde kullanılmaktadır. Bunun nedeni bu mikroalgin, tahıl grubundaki besinlerde omega-3 yağ asidi miktarını arttırması ve böylece gıdanın sağlığa etkisini geliştirmesi ile ilişkilendirilmektedir (Gouveia vd., 2008). Spirulina platensis ise bütün olarak ya da biyokütleden elde edilen fikosiyanin pigmenti kurabiyelerde kullanılmaktadır. Bu mikroalgin kullanım amacı kurabiyede protein ve lif içeriğini zenginleştirme ve sağlık üzerine pozitif etki oluşturtmaktır (Singh vd., 2015). Bisküvi ürünleri kadar ekmeklerin de üretimine besinsel özelliklerinin geliştirilmesi için mikroalgler eklenmektedir. Ekmek yapımında beyaz una eklenen Dunaliella ve Spirulina cinsi mikroalgler, protein takviyesi olarak kullanımını önerilmektedir. Spirulina eklenen ekmeğin hem protein içeriği hem de esansiyel amino asit içeriği zenginleşmektedir (Ak vd., 2016).

1.4. Sağlığa faydaları

Algler yapısındaki biyolojik aktivite gösteren biyoaktif moleküller sayesinde, antioksidan, antimikrobiyal, antidiyabet, antikarsinojen benzeri etkiler göstermektedir (Ranga Rao ve Ravishankar, 2018). Bu moleküller mikroalglerdeki pigment ve polifenoller haricindeki uzun zincirli çoklu doymamış yağ asitleri, yüksek lifli bileşenler, protein, sterol, şeker, vitamin, mineral gibi bileşenlerdir (Fernandes ve Pinto, 2019). Kaliteli bileşenlerin diyabet, iltihaplanma, oksidasyon, artan kolesterol, kardiyovasküler hastalıkları önlediği, immün sistemi düzenlediği, obeziteyi engellediği bilinmektedir (Akyıl vd., 2016).

Mikroalglerin yapısındaki çoklu doymamış yağ asitleri ve kolesterol benzeri bileşenler ise antibakteriyal aktiviteler üzerinde önemli etkilere sahiptir. Antimikrobiyal etki, yapıdaki zincirin uzunluğuna ve doymamışlık derecesi ile ilişkili olduğundan serbest yağların konsantrasyonu ve kompozisyonu göz önünde bulundurulmalıdır (Akyıl vd., 2016). Tablo 3'de alglerin gıda ve sağlık uygulamalarında kullanımı verilmiştir.

Mikroalglerden biri olan Spirulina ile ilgili çalışmalar yapılmıştır. Spirulina alerjik rinit, arsenik zehirlenmesi, Candida gelişimi gibi pek çok hastalıkta tedavi edici etki göstermektedir. Ayrıca kolesterolü düşürerek damar tıkanıklığı ve kalp krizi riskini azaltıcı, kan basıncını azaltıcı, anemiyi engelleyici, diyabeti önleyici özelliklere sahiptir (Sotiroudis ve Sotiroudis, 2013; Folarin ve Sharma, 2017). Ayrıca Chlorella sp.'nin ise kan glukoz ve kolesterolünü düşürücü yönde etki etmektedir (Mimouni vd., 2015).

Tablo 3. Alglerin gıda ve sağlık uygulamalarında kullanımı (Hallmann, 2007)

Alg türleri	Uygulamalar
Spirulina platensis	Fikosiyanin, fikoeritrin ve biyokütle sağlık gıda, ilaç, yem ve kozmetik
Chlorella vulgaris; Chlorella spp.	Besin takviyeleri için polisakkaritler, kozmetik için özler; Sağlık gıdası, yem için biyokütle,
Dunaliella salina	β-karoten sağlık gıdası, yem, besin takviyeleri ve kozmetik
Haematococcus pluvialis	Astaksantin sağlık gıdası, ilaç ve yem katkı maddeleri
Chlamydomonas Reinhardtii	Hayvan sağlığı ve yem için biyokütle; çevresel izleme; Biyoremediasyon, rekombinant protein üretimi proteinler
Isochrysis galbana	Hayvan beslenmesi için yağ asitleri
Nannochloropsis oculata	Hayvan beslenmesi için lipitler ve yağ asitleri; kozmetik için özler
Porphyra spp.	Yem, gıda için biyokütle; kozmetik için özler
Porphyridium spp.	Beslenme, ilaç ve kozmetik için polisakkaritler, ilaç, kozmetik ve gıda için fikocyanin ve fikoeritrin
Phaeodactylum tricornutum	Beslenme için lipitler ve yağ asitleri

1.5. Gıda güvenliği

Tarladan çatala kadar olan süreçte gıda güvenliği, insanların besinsel ihtiyaçlarını ve gıda tercihlerini karşılayabilecek yeterli miktarda, besleyici ve güvenilir gıdaya ulaşabilmesidir (Kayişoğlu ve Türksoy 2023).

Gıda güvenliği, Avustralya, Kanada, Amerika Birleşik Devletleri, Yeni Zelanda ve Avrupa Birliği dahil olmak üzere gelişmiş bölgelerdeki düzenleyici kurumlar için kritik bir endişe kaynağı olmaya devam etmektedir. Amerika Birleşik Devletleri'nde FDA, mikroalg bazlı gıda ürünlerini Gıda Güvenliği ve Uygulamalı Beslenme Merkezi (CFSAN) kapsamında GRAS olarak sınıflandırmaktadır. Arthrospira, Chlorella, Dunaliella, Haematococcus ve Schizochytrium gibi mikroalg türleri GRAS statüsüne ulaşarak çeşitli gıda ürünlerine dahil edilmelerini kolaylaştırmıştır (Hosseinkhani vd., 2022).

Avrupa Birliği'nde, Gıda Güvenliği Yönetmeliği ve Yeni Gıda ve Yeni Gıda Bileşenleri Yönetmeliği (AB) No. 2015/2283 (Salehipour-Bavarsad vd., 2024) kapsamında çeşitli mikroalg ürünleri onaylanmıştır. Bu düzenleyici çerçeveler, yetkilendirme sürecini kolaylaştırmayı, güvenli ve yenilikçi gıda ürünlerinin pazara girişini kolaylaştırmayı ve ticaret engellerini azaltmayı amaçlarken, yüksek gıda güvenliği standartlarının korunmasını da sağlamaktadır (Garcia vd., 2017).

SONUÇ

Gıda endüstrisinde biyoaktif bileşiklerin üretimi için yenilenebilir bir kaynak olarak mikroalglerin kullanımı artmaktadır. Ancak, mikroalg biyokütlesinin, türevlerinin, güvenliğinin ve kalitesinin FDA düzenlemelerine ve diğer ilgili güvenlik standartlarına uygun olarak sağlanması esastır. Mikroalg bazlı ürünlerin güvenli üretiminde ürünün lezzetini ve tüketici kabulünü artırmak için halen optimal mikroalg konsantrasyonu, entegrasyon stratejileri ve sağlık açısından in vitro ve in vivo araştırmalara ihtiyaç vardır. Bu bölümde mikroalglerin biyoaktif bileşikleri, biyolojik aktiviteleri ve gıda endüstrisindeki fonksiyonel uygulamaları sürdürülebilir ve sağlığı destekleyici bir gıda kaynağı olarak değerlendirilmiştir.

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Chapter 5

Performance Analysis of Type-1 and Type-2 Fuzzy Clustering Algorithms for Digital Capability-Based Synthetic Data

Mükerrem Bahar Başkır[1]

Abstract

In this study, type-1 fuzzy c-means and its interval and general type-2 versions were applied to a digital capability-based synthetic data. The synthetic data were generated via a Monte Carlo method under multivariate normality parameterized by an empirical mean vector and a shrunk covariance matrix. The performances of type-1 and type-2 fuzzy clustering algorithms were evaluated using a cluster validity index and discriminant analysis. Kim and Ramakrishna's validity index was utilized to determine the optimal fuzzy partitions of the synthetic data. The synthetic data was partitioned into three fuzzy clusters. Discriminant analysis was conducted to assess the separability of the obtained fuzzy clusters. Consequently, the type-1, interval type-2, and general type-2 fuzzy clustering algorithms achieved the highest group case proportions under "Small", "Medium", and "High" fuzzifier settings, respectively.

1. Introduction

Digitalization is a key strategic indicator for organizational decision-making. Organizations focus on measuring and evaluating their digital growth and maturity using objective and data-driven approaches. There are various data-driven methods to improve the strategic decision-making processes. A system considered within a decision problem contains epistemic uncertainties due to both the system–components' crisp structures and the interactions/relations among these components. Zadeh's (1965) fuzzy set theory–based approaches analyze the epistemic uncertainties addressed in decision problems.

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Fuzzy clustering is an unsupervised machine learning task under fuzzy environment. This unsupervised clustering task is commonly used in modeling and eliminating the uncertainties in complicated decision systems. As the well-known fuzzy clustering algorithm, type-1 fuzzy c-means (T1-FCM) (Dunn, 1973; Bezdek, 1981) assigns observations (data points) to multiple clusters based on their membership degrees. Numerous type-1 fuzzy clustering algorithms were developed for different purposes (e.g., Hathaway & Bezdek, 1993; Höppner & Klawonn, 2003; Pedrycz, 2004; Pal et al., 2005; Chaira et al., 2007; Celikyilmaz & Turksen, 2008b; Baskir & Turksen, 2013). There were enhanced various type-2 fuzzy clustering algorithms to overcome the uncertainties arising from the crisp primary memberships produced by T1-FCM (e.g., Hwang & Rhee, 2007; Linda & Manic, 2012; Raza & Rhee, 2012; Turksen, 2014, Nguyena et al., 2014; Rubio et al., 2017; Zhao et al., 2019; Yang et al., 2021; Baskir 2022; Wu & Peng, 2023; Huang et al., 2024; Kchaou et al., 2025). The fuzzifier parameter m in T1-FCM has a significant role in shaping an appropriate fuzzy partition structure. In this context, Hwang and Rhee (2007) introduced an interval type-2 fuzzy c-means (IT2-FCM) algorithm that utilizes an interval-valued fuzzifier $m \in [m_L, m_R]$ to capture uncertainty in T1-FCM-based fuzzification process. As an extension of IT2-FCM, a general type-2 fuzzy c-means (GT2-FCM) was proposed by Linda and Manic (2012). GT2-FCM was structured using linguistic fuzzifier M obtained by type-1 fuzzy sets (T1FSs) and α-planes description of general type-2 fuzzy sets to calculate its secondary memberships. Type-reduction and center-updating procedures can be performed by using the enhanced Karnik-Mendel algorithm (Wu & Mendel, 2009). Type-1 and type-2 fuzzy clustering algorithms discover the intrinsic data structure without label information. Due to the unsupervised nature of these algorithms, the suitable fuzzy partition of the data is determined using cluster validity indices (CVIs). CVIs (e.g., Bezdek's Partition Coefficient and Partition Entropy (1973, 1974, 1981), Xie & Beni (1991), Kim & Ramakrishna (2005), Çelikyılmaz & Türksen (2008a, 2008b), Baskir & Turksen, 2013, among others) quantitatively evaluate intra-cluster compactness and inter-cluster separation of the fuzzy partition.

In this study, a comparative performance analysis of T1-, IT2-, and GT2-FCM algorithms was conducted on digital capability-based synthetic data. The performance of these algorithms was tracked using the synthetic data. The digital capability-based synthetic data were generated according to the empirical mean and shrinkage covariance of Aramburu et al.'s (2021) original data. The clustering structure-qualities of these algorithms were assessed using Kim-Ramakrishna's validity index. Additionally, the accuracy of cluster assignments and the overall classification performance was assessed through discriminant analysis to validate the fuzzy clustering results. The highlights of this study are as follows:

- The synthetic data were generated via Monte Carlo approach under the assumption of multivariate normality parameterized empirical mean and covariance of the digital capability-based original data.
- T1-, IT2-, and GT2-FCM were comparatively evaluated using the internal validity index and discriminant analysis.
- The results revealed similar and/or distinct behaviors of type-1 and type-2 fuzzy clustering algorithms in terms of their membership patterns.

The remainder of this study is organized as follows: Section 2 presents the theoretical frameworks of type-1 and type-2 fuzzy-based clustering algorithms, and the mathematical structure of the cluster validity index. The performance results of the relevant algorithms are presented in Section 3. The conclusion is given in Section 4.

2. Materials And Methods

This section presents the analytical structures/procedures of the type-1 and type-2 fuzzy clustering algorithms and the cluster validity index.

2.1. From Classical To Type-1 Fuzzy Clustering

Clustering is a frequently used machine learning task that partitions any given input data into clusters based on their similarity and/or dissimilarity patterns. The main goal is to maximize similarity within clusters and maximize dissimilarity between clusters. Classical clustering recognizes data patterns by assigning each data point to a specific cluster based on distance measures/similarity metrics. The well-known classical clustering task is the *k*-means algorithm. The *k*-means was introduced by MacQueen (1967) to partition a given data into *k* clusters, such that each data point belongs to only one cluster. Under this algorithm, the boundaries of the clusters are distinctly defined. The *k*-means algorithm aims to obtain homogeneous and well-separated cluster structures by minimizing the sum of squared errors within each cluster. However, data points located in boundary regions may exhibit similarities to multiple clusters. This situation leads to limitations in classical clustering algorithms due to their rigid assignment mechanisms. To eliminate the limitations of classical clustering, fuzzy clustering was developed to construct flexible and soft cluster structures.

The conventional type-1 fuzzy clustering was first introduced by Dunn (1973), and then developed by Bezdek (1981) as an optimization problem in Eq. (1), where J is the minimized objective function, u_{ij} is the membership degree, v_i is the cluster center, c and m are cluster number and fuzzifier, respectively, and $||.||$ is the Euclidean norm.

$$\begin{aligned} &\min J(U,V) = \sum_{k=1}^{n}\sum_{i=1}^{c} \mu_{ik}^{m} \left(\left\|x_k - v_i\right\|\right) \\ &\text{sbj to:} 0 \le \mu_{ik} \le 1,\ \forall i,k;\ \sum_{i=1}^{c} \mu_{ik} = 1,\ \forall k;\ 0 \le \sum_{k=1}^{n} \mu_{ik} \le n,\ \forall i \end{aligned} \tag{1}$$

The solutions (center and membership function) of Eq. (1) are given in Eqs. (2)-(3):

$$\text{Center: } v_i = \frac{\sum_{k=1}^{n} (\mu_{ik})^m x_k}{\sum_{k=1}^{n} (\mu_{ik})^m} \tag{2}$$

$$\text{Membership function: } \mu_{ik} = \left[\sum_{j=1}^{c} \left(\frac{\left\|x_k - v_i\right\|}{\left\|x_k - v_j\right\|} \right)^{2/(m-1)} \right]^{-1}, i \ne j \tag{3}$$

The pseudo-code of T1-FCM is given in Algorithm I.

Algorithm I. T1-FCM algorithm.

Input: Input data ($X = \{x_1, \dots x_n\}$), cluster number (c), fuzzifier (m), error (ε), iteration number ($iter$)

Output: Membership matrix (U^*), Center vector (V^*)

1. Initial cluster centers are randomly determined.
2. Repeat $t < iter$:
3. For $i = 1,2, \dots, n$
4. For $k = 1,2, \dots, c$
5. Memberships are calculated using Eq. (3).
6. Centers are computed using Eq. (2).
7. If $\| v^{(t)} - v^{(t-1)} \| < \varepsilon$ then Stop.
8. End
9. End

2.2. Interval Type-2 Fuzzy Clustering Algorithm

Hwang and Rhee (2007) proposed the interval type-2 fuzzy c-means (IT2-FCM) algorithm by defining the fuzzifier m in T1-FCM as an interval-valued parameter $[m_L, m_R]$. The objective function of T1-FCM is restructured using m_L and m_R, separately, to obtain the objective functions of IT2-FCM. The solutions of IT2-FCM objective functions are given in Eqs. (4)-(6):

$$\text{Center: } \bar{v}_i = \left[v_i^L, v_i^R \right] = \sum_{u \in J_{x_1}} \cdots \sum_{u \in J_{xn}} 1 / \frac{\sum_{k=1}^{n} (\mu_{ik})^m x_k}{\sum_{k=1}^{n} (\mu_{ik})^m} \tag{4}$$

$$\text{Memberships: } \bar{\mu}_{ik,t} = \max\left(\left[\sum_{j=1}^{c} \left(\frac{\|x_k - v_{i,t-1}\|}{\|x_k - v_{j,t-1}\|} \right)^{2/(m_L-1)} \right]^{-1}, \left[\sum_{j=1}^{c} \left(\frac{\|x_k - v_{i,t-1}\|}{\|x_k - v_{j,t-1}\|} \right)^{2/(m_R-1)} \right]^{-1} \right) \tag{5}$$

$$\underline{\mu}_{ik,t} = \min\left(\left[\sum_{j=1}^{c} \left(\frac{\|x_k - v_{i,t-1}\|}{\|x_k - v_{j,t-1}\|} \right)^{2/(m_L-1)} \right]^{-1}, \left[\sum_{j=1}^{c} \left(\frac{\|x_k - v_{i,t-1}\|}{\|x_k - v_{j,t-1}\|} \right)^{2/(m_R-1)} \right]^{-1} \right) \tag{6}$$

The crisp representative centers and memberships are obtained as in Eqs. (7)-(8), respectively.

$$v_i = \frac{v^L + v^R}{2} \tag{7}$$

$$\mu_{ik} = \frac{\mu_{ik}^L + \mu_{ik}^R}{2} \tag{8}$$

Type-reduction and cluster center updating procedures can be examined using the enhanced Karnik-Mendel (E-KM) algorithm (Wu & Mendel, 2009).

The pseudo-code of IT2-FCM is given in Algorithm II.

Algorithm II. IT2-FCM algorithm.

Input: Input data ($X = \{x_1, \ldots x_n\}$), cluster number (c), fuzzifier (m=[m_L,m_R]), error (ε), iterarion number ($iter$)

Output: Lower and Upper Membership matrices $(\underline{U} \text{ and } \overline{U})$, Interval Centers $(\underline{V}, \overline{V})$

1. Initial interval centers are randomly generated.
2. Repeat $t < iter$:
3. For $i = 1,2, \ldots, n$
4. For $k = 1,2, \ldots, c$
5. Lower and upper memberships are updated using Eqs. (5)-(6).
6. Interval centers are calculated using Eq. (4).
7. Type-reduction procedure can be performed using the E-KM algorithm.
8. If $\| v^{(t)} - v^{(t-1)} \| < \varepsilon$ then Stop.
9. End
10. End

2.3. General Type-2 Fuzzy Clustering Algorithm

Linda and Manic (2012) enhanced a general type-2 fuzzy c-means (GT2-FCM) algorithm by defining the linguistic fuzzifier M. GT2-FCM comprises α-planes of general type-2 memberships, which can be generated by α-cuts of M. The secondary memberships in GT2-FCM can be expressed as in Eq. (9):

$$\tilde{\mu}_{ji} = \bigcup_{\alpha \in [0,1]} \alpha / S_{\tilde{\mu}_j}(x_i|\alpha) = \bigcup_{\alpha \in [0,1]} \alpha / \left[s^L_{\tilde{\mu}_j}(x_i|\alpha), s^R_{\tilde{\mu}_j}(x_i|\alpha) \right] \tag{9}$$

where $s^L_{\tilde{\mu}_j}(x_i|\alpha)$ and $s^R_{\tilde{\mu}_j}(x_i|\alpha)$ are left and right boundaries for α-planes of GT2 memberships in Eq. (10):

$$\tilde{\mu}_j(\alpha) = \sum_{x_i \in X} S_{\tilde{\mu}_j}(x_i|\alpha) \tag{10}$$

where

$$s^R_{\tilde{\mu}_j}(x_i|\alpha) = \max\left(\left[\sum_{j=1}^{c} \left(\frac{\|x_k - v_{i,t-1}\|}{\|x_k - v_{j,t-1}\|} \right)^{2/(s^L_M(\alpha)-1)} \right]^{-1}, \left[\sum_{j=1}^{c} \left(\frac{\|x_k - v_{i,t-1}\|}{\|x_k - v_{j,t-1}\|} \right)^{2/(s^R_M(\alpha)-1)} \right]^{-1} \right)$$

$$s^L_{\tilde{\mu}_j}(x_i|\alpha) = \min\left(\left[\sum_{j=1}^{c} \left(\frac{\|x_k - v_{i,t-1}\|}{\|x_k - v_{j,t-1}\|} \right)^{2/(s^L_M(\alpha)-1)} \right]^{-1}, \left[\sum_{j=1}^{c} \left(\frac{\|x_k - v_{i,t-1}\|}{\|x_k - v_{j,t-1}\|} \right)^{2/(s^R_M(\alpha)-1)} \right]^{-1} \right)$$

The fuzzy cluster-centre can be obtained as in Eq. (11):

$$\tilde{v}_j = C_{\tilde{\mu}_j} = \sum_{\tilde{\mu} \in J_{x_1}} \dots \sum_{\tilde{\mu} \in J_{xn}} \left(f_{\tilde{\mu}_j}(x_1) * \dots * f_{\tilde{\mu}_j}(x_N) \right) / \frac{\sum_{k=1}^{n} \left(\tilde{\mu}_{jk} \right)^m x_k}{\sum_{k=1}^{n} \left(\tilde{\mu}_{jk} \right)^m}, \tag{11}$$

$$\textit{where } C_{\tilde{\mu}_j} = \bigcup_{\alpha \in [0,1]} \alpha / \left[c^L_{\tilde{\mu}_j}(\alpha), c^R_{\tilde{\mu}_j}(\alpha) \right]$$

The centroid $C_{\tilde{\mu}_j}$ is calculated using Liu's theorem (2008), where $\left[c^L_{\tilde{\mu}_j}(\alpha), c^R_{\tilde{\mu}_j}(\alpha) \right]$ is the individual interval center.

The precise cluster-centre is computed as in Eq. (12), where K is the number of discretized type-2 fuzzy sets:

$$v_j = \frac{\sum_{i=1}^{K} C_{\tilde{\mu}_j}(y_i)\, y_i}{\sum_{i=1}^{K} C_{\tilde{\mu}_j}(y_i)} \tag{12}$$

Type-reduction and center-updating procedures can be performed using the E-KM algorithm. Defuzzification approach of IT2-FCM is extended for GT2-FCM using Liu's theorem.

The pseudo-code of GT2-FCM is given in Algorithm III.

Algorithm III. GT2-FCM algorithm.

Input: Input data ($X = \{x_1, \dots x_n\}$), cluster number (c), linguistic fuzzifier (M), zSlice number (S) or α-planes set, error (ε), iteration number ($iter$)

Output: GT2-memberships matrix $(\tilde{U}^*)$, type-reduced cluster centers (V^*)

1. Initial cluster prototypes are randomly determined.
2. Repeat $t < iter$:
3. For $s = 1,2, \dots, S$
4. For $i = 1,2, \dots, n$
5. For $k = 1,2, \dots, c$
6. Update GT2 memberships via zSlices / α-planes.
7. Update GT2 cluster prototypes (centroids) per slice.
8. Type-reduction across slices (e.g., the E-KM algorithm)
9. If $\| v^{(t)} - v^{(t-1)} \| < \varepsilon$ then Stop.
10. End
11. End
12. End

2.4. Fuzzy Cluster Validity Indices

The optimal fuzzy partition of an input data can be obtained by selecting the appropriate cluster number and fuzzifier parameters in fuzzy clustering algorithms. The cluster validity indices (CVIs) were enhanced to select the optimal fuzzy clustering parameters. There were enhanced numerous CVIs (e.g., Bezdek's indices (1973, 1974, 1981), Xie & Beni (1991), Kim & Ramakrishna (2005), Çelikyılmaz & Türksen (2008a, 2008b), Baskir & Turksen, 2013, among others). These CVIs vary depending on the geometric structure of the data. The Kim-Ramakrishna's (KR) validity index in Eq. (13) was used in this study.

$$v_{KR}(u) = \left\{ \frac{\max\limits_{i=1,\ldots,c} \left\{ \frac{1}{n} \sum_{k=1}^{n} u_{ik}^2 \left\| x_k - v_i \right\|^2 \right\}}{\left(\min\limits_{i \neq j} \left\{ \left\| v_i - v_j \right\|^2 \right\} \right)} \right\} \tag{13}$$

3. Results And Discussion

This section presents discriminant-analysis based performance evaluations of the type-1 and type-2 fuzzy clustering algorithms.

3.1. Digital Capability-Based Synthetic Data

Digitalization is a crucial indicator for making strategic organizational decisions. In this context, the DIGROW framework for digital maturity (North et al., 2020) guides firms through two key assessment processes (Aramburu et al., 2021): i) Evaluating their digital maturity level, ii) assessing the capabilities associated with each maturity level to support digitally enabled growth. The DIGROW-stages and their capacities are given in Figure 1:

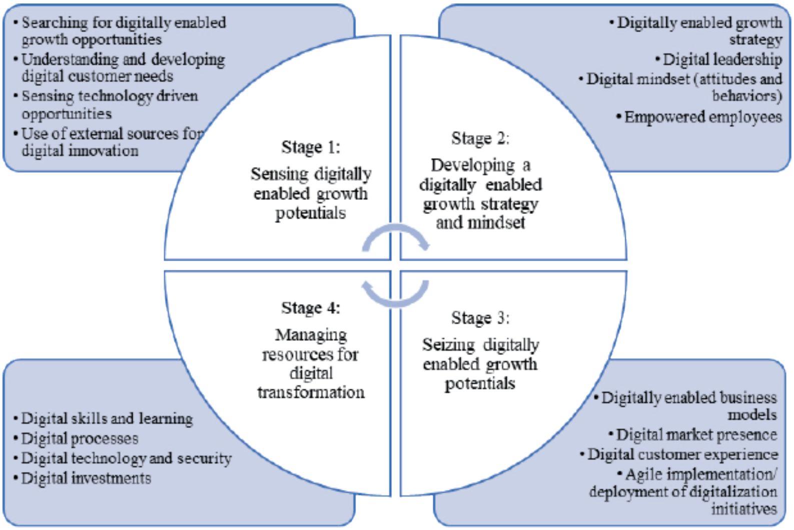

Fig. 1. The DIGROW stages (Aramburu et al., 2021; Di Felice et al., 2022).

In this study, T1-, IT2-, and GT2-FCM algorithms were performed on digital capability-based synthetic (S_DC) data. The original data released by Aramburu et al. in 2021 for researchers was utilized to create the S_DC data. First, the overall scores for each DIGROW stage in the original data were calculated by averaging the scores of the four relevant capacities. Then, the S_DC data were generated using a parametric Monte Carlo approach assuming multivariate normality. The mean vector and covariance structure were estimated from the overall score-based original data. To mitigate the effects of multicollinearity in discriminant analysis, a shrinkage-based covariance adjustment was employed. This procedure preserves the empirical mean structure while systematically reducing interdimensional correlations. The S_DC data size was set to 400 to ensure clustering stability and maintain consistency with the original data size.

3.2. Type-1 and Type-2 Fuzzy Clustering Results

The digital capability-based synthetic overall scores (400×4-dimensional S_DC data) were classified using T1-, IT2-, and GT2-FCM. Fuzzifier settings of T1-, IT2-, and GT2-FCM are given in Table 1:

Table 1. Fuzzifier settings of type-1 and type-2 fuzzy c-means.

Algorithm	Fuzzifier settings
T1-FCM	Small (m=1.4), Medium (m=2.0), High (m=2.6)
IT2-FCM	Small ($[m_L,m_R]$=[1.4,2.2]), Medium ($[m_L,m_R]$=[1.6,2.4]), High ($[m_L,m_R]$=[1.8,2.6])
GT2-FCM	Small (M: Gaussian T1FS with the parameters (1.6, 0.06)), Medium (M: Gaussian T1FS with the parameters (2.0, 0.1)), High (M: Gaussian T1FS with the parameters (2.4, 0.3))

The KR validity index (as shown in Eq. (13)) results for the T1-, IT2-, and GT2-FCM algorithms are presented in Table 2. For all fuzzifiers considered for the type-1 and type-2 fuzzy clustering algorithms, the KR validity index consistently identified three as the optimal cluster number. T1-, IT2-, and GT2-FCM-based clustering structures are illustrated in Figure 2.

Table 2. KR-index values for the synthetic data.

KR-index values		c=2	c=3	c=4	c=5	c=6	c=7	c=8
T1-FCM	Small (m=1.4)	0.08	**0.08**	0.09	0.088	0.098	0.089	0.058
	Medium (m=2.0)	0.066	**0.059**	0.06	0.074	0.065	0.091	0.075
	High (m=2.6)	0.072	**0.068**	0.068	0.101	0.109	0.186	0.237
IT2-FCM	Small ($[m_L,m_R]$=[1.4,2.2])	0.079	**0.079**	0.089	0.087	0.098	0.078	0.054
	Medium ($[m_L,m_R]$=[1.6,2.4])	0.066	**0.059**	0.06	0.075	0.064	0.088	0.073
	High ($[m_L,m_R]$=[1.8,2.6])	0.072	**0.067**	0.068	0.104	0.108	0.179	0.313
GT2-FCM	Small (M: Asym. Gaussian T1FS)	0.018	**0.018**	0.019	0.019	0.02	0.019	0.014
	Medium (M: Sym. Gaussian T1FS)	0.017	**0.015**	0.015	0.019	0.016	0.022	0.019
	High (M: Asym. Gaussian T1FS)	0.017	**0.016**	0.016	0.023	0.023	0.034	0.043

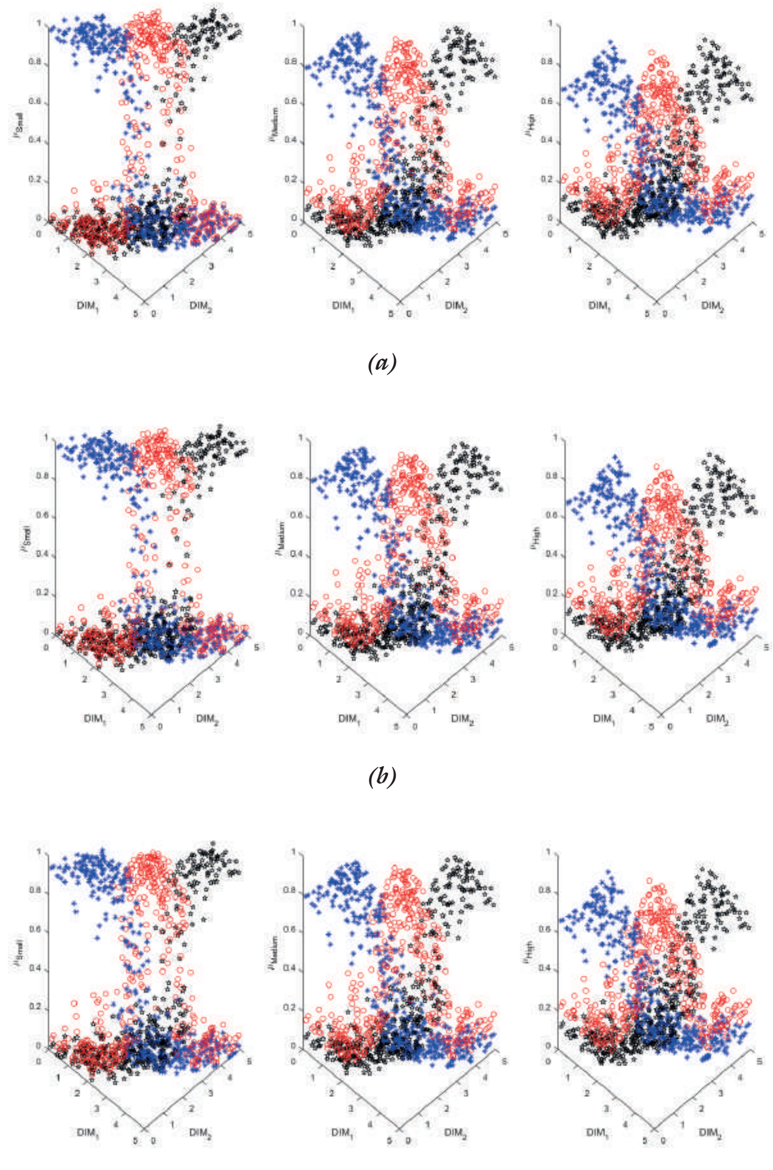

Fig. 2. (a) T1-, (b) IT2-, (c) GT2-FCM representations (*: Cluster-1, o: Cluster-2, ♦: Cluster-3)

The hard partitioning procedures were executed for the relevant algorithms by selecting the highest membership degrees.

3.3. Discriminant-Based Performance Analysis

The discriminant analysis was used to assess the separability of each fuzzy clustering structure. The multivariate normality assumption of the digital capability-based synthetic (S_DC) data was provided according to the Mardia (1970) test results (p-values > 0.01 for multivariate skewness and kurtosis tests). The results of Box's M tests in Table 3 indicate no statistically significant difference among the covariance matrices of the relevant clusters. Therefore, linear discriminant analysis (LDA) was conducted for T1-, IT2-, and GT2-FCM models of the S_DC data. The first discriminant functions obtained for fuzzy clustering algorithms were statistically significant (p-values=0.000).

Table 3. LDA results.

S_DC data		Box's M	F	p-value
T1-FCM	SMALL	26.831	1.321	0.153
	MEDIUM	23.377	1.151	0.288
	HIGH	27.450	1.352	0.134
IT2-FCM	SMALL	26.831	1.321	0.153
	MEDIUM	24,623	1.212	0.232
	HIGH	27.450	1.352	0.134
GT2-FCM	SMALL	28.345	1.395	0.112
	MEDIUM	22.527	1.109	0.331
	HIGH	25.041	1.233	0.215

The equality tests of group (cluster) means for type-1 and type-2 fuzzy clustering models are given in Table 4. According to Table 4, the S_DC stages (independent variables) were found to have statistically significant mean differences across the groups (clusters) of the dependent variable (p-values=0.000). Discriminant analysis and variance analysis revealed similar results.

Table 4. The group (cluster) means – equality tests.

Model	S_DC Dimension	Wilks' λ	F	p-value
T1-FCM (SMALL)	DIM1_score	0.329	405.173	0.000
	DIM2_score	0.230	663.346	0.000
	DIM3_score	0.214	730.772	0.000
	DIM4_score	0.294	477.533	0.000
T1-FCM (MEDIUM)	DIM1_score	0.325	412.884	0.000
	DIM2_score	0.221	701.113	0.000
	DIM3_score	0.224	685.971	0.000
	DIM4_score	0.301	460.156	0.000
T1-FCM (HIGH)	DIM1_score	0.318	425.030	0.000
	DIM2_score	0.222	697.414	0.000
	DIM3_score	0.230	666.201	0.000
	DIM4_score	0.306	450.010	0.000
IT2-FCM (SMALL)	DIM1_score	0.329	405.173	0.000
	DIM2_score	0.230	663.346	0.000
	DIM3_score	0.214	730.772	0.000
	DIM4_score	0.294	477.533	0.000
IT2-FCM (MEDIUM)	DIM1_score	0.328	406.237	0.000
	DIM2_score	0.222	694.671	0.000
	DIM3_score	0.218	710.902	0.000
	DIM4_score	0.301	460.168	0.000
IT2-FCM (HIGH)	DIM1_score	0.318	425.030	0.000
	DIM2_score	0.222	697.414	0.000
	DIM3_score	0.230	666.201	0.000
	DIM4_score	0.306	450.010	0.000
GT2-FCM (SMALL)	DIM1_score	0.327	407.651	0.000
	DIM2_score	0.231	661.458	0.000
	DIM3_score	0.215	725.677	0.000
	DIM4_score	0.293	478.475	0.000
GT2-FCM (MEDIUM)	DIM1_score	0.318	426.121	0.000
	DIM2_score	0.224	689.325	0.000
	DIM3_score	0.225	694.964	0.000
	DIM4_score	0.305	453.309	0.000
GT2-FCM (HIGH)	DIM1_score	0.316	429.092	0.000
	DIM2_score	0.221	699.482	0.000
	DIM3_score	0.228	673.094	0.000
	DIM4_score	0.312	438.246	0.000

The cross-validation results obtained from discriminant analysis of T1-, IT2-, and GT2-fuzzy clustering models are given in Tables 5-7, respectively. According to Tables 5-7, the high cross-validation rates (proportions) indicate that the clusters are highly separable and statistically consistent in the S_DC feature spaces.

Table 5. Cross-validation rates of the T1-FCM-based cluster-assignments

T1-FCM (SMALL)		Predicted Group		
		Cluster-1	Cluster-2	Cluster-3
Original Group	Cluster-1	149	1	0
	Cluster-2	3	154	1
	Cluster-3	0	1	91
Assignment-rates for the clusters		99.3%	97.5%	98.9%
n=400, n (Correct assignment)=394, Cross-validated group cases-rate=98.5%				
T1-FCM (MEDIUM)		Predicted Group		
		Cluster-1	Cluster-2	Cluster-3
Original Group	Cluster-1	139	4	0
	Cluster-2	3	158	0
	Cluster-3	0	3	93
Assignment-rates for the clusters		97.2%	98.1%	96.9%
n=400, n (Correct assignment)=390, Cross-validated group cases-rate=97.5%				
T1-FCM (HIGH)		Predicted Group		
		Cluster-1	Cluster-2	Cluster-3
Original Group	Cluster-1	136	3	0
	Cluster-2	2	158	1
	Cluster-3	0	5	95
Assignment-rates for the clusters		97.8%	98.1%	95.0%
n=400, n (Correct assignment)=389, Cross-validated group cases-rate=97.3%				

Table 6. Cross validation rates of the IT2-FCM-based cluster-assignments

IT2-FCM (SMALL)		Predicted Group		
		Cluster-1	Cluster-2	Cluster-3
Original Group	Cluster-1	149	1	0
	Cluster-2	3	154	1
	Cluster-3	0	1	91
Assignment-rates for the clusters		99.3%	97.5%	98.9%
n=400, n (Correct assignment)=394, Cross-validated group cases-rate=98.5%				
IT2-FCM (MEDIUM)		Predicted Group		
		Cluster-1	Cluster-2	Cluster-3
Original Group	Cluster-1	144	1	0
	Cluster-2	5	155	0
	Cluster-3	0	3	92
Assignment-rates for the clusters		99.3%	96.9%	96.8%
n=400, n (Correct assignment)=391, Cross-validated group cases-rate=97.8%				
IT2-FCM (HIGH)		Predicted Group		
		Cluster-1	Cluster-2	Cluster-3

Original Group	Cluster-1	136	3	0
	Cluster-2	2	158	1
	Cluster-3	0	5	95
Assignment-rates for the clusters		97.8%	98.1%	95.0%
n=400, n (Correct assignment)=389, Cross-validated group cases-rate=97.3%				

Table 7. Cross validation rates of the GT2-FCM-based cluster-assignments

GT2-FCM (SMALL)		Predicted Group		
		Cluster-1	Cluster-2	Cluster-3
Original Group	Cluster-1	149	1	0
	Cluster-2	3	153	1
	Cluster-3	0	2	91
Assignment-rates for the clusters		99.3%	97.5%	97.8%
n=400, n (Correct assignment)=393, Cross-validated group cases-rate=98.3%				
GT2-FCM (MEDIUM)		Predicted Group		
		Cluster-1	Cluster-2	Cluster-3
Original Group	Cluster-1	137	5	0
	Cluster-2	4	159	0
	Cluster-3	0	3	92
Assignment-rates for the clusters		96.5%	97.5%	96.8%
n=400, n (Correct assignment)=388, Cross-validated group cases-rate=97.0%				
GT2-FCM (HIGH)		Predicted Group		
		Cluster-1	Cluster-2	Cluster-3
Original Group	Cluster-1	135	1	0
	Cluster-2	2	161	1
	Cluster-3	0	5	95
Assignment-rates for the clusters		99.3%	98.2%	95.0%
n=400, n (Correct assignment)=391, Cross-validated group cases-rate=97.8%				

4. Conclusion

This study presents a comparative performance analysis of type-1, interval type-2, and general type-2 fuzzy c-means algorithms for digital capability-based synthetic (S_DC) data. A Monte Carlo approach was employed to generate the S_DC data under the assumption of multivariate normality. The empirical mean vector and a shrinkage-adjusted covariance matrix derived from the original data were utilized as distributional parameters. The appropriate fuzzy partitions of the S_DC data were determined using Kim-Ramakrishna's validity index. The optimal cluster number was determined to be three. Under the fuzzifier settings (Table 1), the behaviors of the T1-, IT2-, and GT2-FCM algorithms for three clusters were assessed by their cross-validated cluster assignment-based and overall group case-based proportions calculated through discriminant analysis. Under the "Small" fuzzifier settings, the three algorithms yielded highly similar group cases-proportions. Additionally, the three algorithms achieved the similar/close cluster assignment proportions in Cluster-1/Cluster-2 (fuzzifier settings "Small"), in Cluster-3 (fuzzifier settings "Medium"/"High"). This may indicate that the assignment changes occurred at boundary data points, which exhibit sensitive assignment behaviors to small perturbations based on the relevant membership structure. T1- and IT2-FCM algorithms defined under the "Small" fuzzifier settings attained the highest assignment proportions for Cluster-3. Under the "Medium" setting, IT2-FCM achieved the highest proportions in Cluster-1, while T1-FCM exhibited its highest values in Cluster-2. GT2-FCM under the "High" fuzzifier settings demonstrated the highest cluster assignment proportions across Clusters 1 and 2. T1-, IT2-, and GT2-FCM algorithms achieved the highest group case proportions under "Small", "Medium", and "High" fuzzifier settings, respectively.

In future studies, clustering algorithms based on type-1 fuzzy sets and their several extensions (e.g., intuitionistic, picture, hesitant fuzzy sets) will be comparatively investigated. The effects of these algorithms on fuzzy system modeling will be analysed for big data analytics-based applications such as traffic congestion prediction, energy efficiency analysis, climate change and environmental risk modeling, disease diagnosis, and genomic analysis.

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Chapter 6

Making the Transition from Narrow-to Superintelligence: The Need for a Conceptual Framework for the Ethical Development of Artificial Intelligence

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Abstract

The art of artificial intelligence (AI) technologies is going through various layers of evolution, which include narrow AI (ANI), general AI (AGI), and eventually super AI (ASI). This chapter will examine the evolution of these AI layers, using various approaches that reveal the differences among each of the AI layers, specifically within the realm of computer engineering. Following the prevailing literature on the subject, the analysis will specifically examine the data-oriented, narrow, and specific approach of ANI, the high-level, flexible approaches of AGI that relate to learning, and the optimizing, transdisciplinary approach of ASI, along with the superhuman characteristics of the latter. Also, the analysis will examine the ethical threats of AI, the international frameworks of AI governance, such as the EU AI Act, OECD, and UNESCO, and the strategies of Turkey. Lastly, the chapter will examine the prevailing emerging trends of AI.

1.Introduction

The growing pace of advances in artificial intelligence technologies is revolutionizing the computer engineering field, both theoretically and practically. Though it is a fact that the current dominant systems are of the ANI type, the level of progress reported in the literature suggests that higher-order levels of AGI and ASI have moved beyond the conceptual level. This is not only important for design but also impacts the areas of data architecture, computer model design, processing, memory, and compliance.

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This paper will examine the historical concepts of artificial intelligence, the current technological approaches of AI, and the emerging risk of AGI and ASI. Additionally, the topic of AI governance in the context of the AI Act and the control problem will be analyzed. The current state of AI technology in the context of technology policies, human capital, and competitiveness of Turkey will also be discussed.

2. Literature Review

The progress of AI represents a technological revolution, wherein the very basics of computer engineering, focusing on the design of systems, optimizing algorithms, data processing, and security, are revolutionized. This literature review integrates the development of AI, covering the entire spectrum of AI, ranging from ANI to ASI.

2.1. Historical Foundations and Evolution of Concepts

The history of artificial intelligence traces its roots in the theory of computation, which is a fundamental aspect of computer engineering. Good (1966) brought about the idea of the "ultraintelligent machine," which asserted the possibility of improving systems that surpass the human intellect, thus forming the foundation for recursive improvement computer engineering algorithms. Yudkowsky (2008) suggests that the consideration of AI systems should also take into account the perspective of a risk factor for the global community, focusing on control and alignment that affect the contemporary computer engineering of corrigibility. Bostrom (2014) elaborated how the process of superintelligence will transpire, categorizing it into various types, risks, and strategies that pave the way for the computer engineering of hybrid neural-symbolic systems. Brynjolfsson & McAfee (2014) elaborated upon the concept of the "second machine age," focusing on how AI affects the labor force and productivity. This is analogous to the use of data-driven optimization (gradient descent) and huge data processing, which is the aspect of computer engineering. Domingos (2015) wrote about the search for the "master algorithm," claiming that learning systems will transform the world. This paved the way for a computer engineering paradigm of meta-learning (MAML, for example). Tegmark (2018) questioned the definition of humanity in the age of AI, focusing on the control problem of AI systems that are safe for humans, also suggesting the use of value alignment computer engineering. In the modern age, there have been various predictions among AI experts about the time that will transpire for the transition to AGI and ASI (Grace et al., 2018), as well as how the passage toward the achievement of these goals will be measurable (Chojecki, 2025).

2.2. Current Advances: Technical Architecture and Applications of ANI to AGI

Modern literature is about the advent of AGI using transformers and hybrid approaches. A roadmap of AI development is discussed by Vsevolodovna (2025), where deep neural networks (input-hidden-output layers, cross-entropy loss) typify ANI, multi-modal inputs typify AGI (LSTM/GRUs), and quantum integration is a topic of interest in ANI. The use of transformers speeds up the ANI-AGI transition, for example, with the BERT and GPT models. Chojecki (2025) develops the so-called Kardashev scale, where the AAI-Index is calculated on ten criteria, including autonomy, generality, and planning. Mirindi et al. (2025) examine the use of the O1 model of OpenAI, focusing on the development of ASI using reinforcement learning, with ethical goals for integration, where the use of inverse reinforcement learning for engineering goals is significant. Groppe & Jain (2024) discuss AI-complete problems, suggesting hybrid approaches of symbolic-statistical systems (KG & ML) for better problem-solving, where neuro-symbolic AI using contextual computation is proposed. For applications, Tiwari et al. (2025) discuss the use of deep learning & ML for plant identification, stating that recognition and extraction of specific features using image analysis software demonstrates data bias and the need for high-resolution images for engineering. Alvarez-Teleña & Díez-Fernández (2024) discuss the use of ANI for the development of ASI, where the role of algorithmization & efficiency-engineered approaches helps engineering for corporate competitiveness. Application-wise, Chapman et al. (2024) discuss the relevance of Responsible Intelligence (RI) analysis for the healthcare and spinal surgery sectors, where the expansion of large amounts of data & software incapability forces the need for real-time analysis for engineering. Surdu & Surdu (2024) discuss the relevance of AI development for neonates, differentiating between hype & reality, where current ANI engineering for specific tasks, for example, HeRO sepsis identification, offers benefits but face contextual challenges.

2.3. Challenges and Risks: Technical and Ethical Dimensions

Technological challenges in AI revolve around bias, security, and alignment. Fahad et al. (2024) elaborate on the positive applications of AGI (security, healthcare, finance) and the negative impacts (decision-making, privacy), focusing on ethical considerations for the engineer. Doker (2025) applies the Rittel-Webber definition of the "wicked problem" of AGI for the engineer, keeping the control of the agent's development dynamic and controlled. The authors of Goyal et al. (2024) explore the challenges of building ASI, specifically regarding the engineer's consideration of scale and unpredictability. Marcus (2018) finds that deep learning limits the engineer's model improvements, referencing opacity/black box limitations and the requirements of better methodological approaches for the engineer. Ueda et al. (2025) illustrate the alignment problem of healthcare for the engineer, debating the consequence of reward hacking/bias (for example, see CheXNet external failure) for the engineer. Mokoena (2025) explores the challenges of the "extinction problem" of ASI for the engineer, suggesting centralized control of the agent and open-source software limitations. Finally, Grace et al. (2018) provide data for expert predictions regarding the agent's probable internal enhancement of the AGI's effectiveness for the engineer, suggesting time-based solutions for the engineer. For ethical components of the topic, Tzimas (2021) explores the ethics of AI, applied specifically in the study of international law for the engineer, examining the problems of the black box, the need for transparency, and the need for the model's correctability for the engineer. Lastly, examining the philosophical standards, the authors of Ekici (2025) explore the need for integrated personalities for the engineer, examining the modular components of the AGI/ASI's cognitive constituents. Additionally, Li (2023) explores the relationship between the model of panentheism and the AGI for the engineer, specifically the ethical implication of the designer's role regarding the agent's later use for the engineer. Also, Gal-Or (2025) connects the philosophy of AI with the Aristotelian "nous"; the design of human-like intelligence in engineering is discussed.

2.4. Governance and Future Directions

Governance frameworks condition engineering standards. The European Commission (2024) offers the AI Act risk management strategy (forbidden, high risk, transparency); robustness, cyber security, and traceability are obligatory in engineering. OECD (2019) explores the AI principles implementation strategy; management of the AI life cycle, transparency, accountability, and risk management are used in engineering. UNESCO (2021) suggests ethical guidelines, focusing on ethical impact assessment (EIA) and data policies that link the integration of sustainability and gender equity into engineering. Future challenges for the profession, according to Glenn (2025), will emphasize AGI, focusing on engineering governance and cooperation on research. Frameworks for AI use and autonomous business levels, suggesting automation vs. augmentation, are proposed by

Sohn (2024) for engineering. Soft skills and ethics training for computer engineering, and competencies for AI development, are anticipated by Araújo et al. (2025). This integration highlights the computer engineering of the AI-oriented future, balancing innovation with ethical considerations. Abdullah (2025) and Anakotta (2025) also support database searches beyond the articles, attempting to access hidden sources.

3.Artificial Narrow Intelligence (ANI)

3.1. Definition of ANI

Artificial Narrow Intelligence, or ANI, also known as narrow AI, are systems that are designed for a particular task. They are very efficient for tackling specific, constrained problems but not for sharing knowledge across areas. The definition of ANI can be explained by the following:

$$T = \{t1, t2, \ldots, tn\}$$

Optimization of a set of functions over a specific task space:

$$P : T \rightarrow [0,1]$$

and a metric that evaluates their success on these tasks:

$$D(train)$$

and that shows good performance mainly on a particular data distribution.

3.2. Characteristics of ANI

Specialization: ANI is specialized in one particular domain or activity, like face recognition, translation, or self-driving cars.

Data-Driven: ANI systems utilize large data sets and machine learning algorithms that provide accurate results.

Lack of Generalization: These systems do not have the capability for knowledge generalization, unlike human intelligence. This means that ANI systems are not context-sensitive. It is not necessary that the success gained in one area will also help the system succeed in another. Learning processes support supervised and semi-supervised learning, and these systems do not possess real understanding. They also fail when faced with unexpected circumstances.

3.3. Applications of ANI

ANI is the foundation of the digital reality.

Consumer Technologies: Siri, Alexa, Google Assistant (voice commands), Google Translate, Netflix & Spotify recommendation systems, facial recognition software, spam filters.

Industry & Science: Tumor identification using images, recognizing objects for autonomous cars, identification of stock fraud, robotics for factories, weather modeling software, computer systems better than humans at playing chess and Go (Deep Blue, Alpha Go).

Technologies that Work for ANI: ANI operates on the engines of Machine Learning (ML) technology, and also on Deep Learning (DL), which is a subset of the former. Both of these "learn" from large datasets, and their success has been driven by powerful neural networks, the availability of GPU computing, and large data sets.

Strengths of ANI are reliability and the ability to scale, leading to revolutions in the healthcare industry (for example, diagnosis assistance for the radiology department) and the finance industry (for example, fraud analysis), among others. However, the weakness of ANI is that it is not capable of managing uncertainty and learning the way a person can between tasks. It also poses substantial threats, socially and ethically, with regards to displacement, data representation, privacy, and accountability. ANI can be termed a technology that releases the intended results of the developers or users. By the year 2025, it is expected that a large percentage of the commercial use of AI will come under the ANI category.

4.Artificial General Intelligence (AGI)

4.1. Definition of AGI

Artificial General Intelligence, also known as "strong AI," is a major improvement over ANI. In contrast to ANI, AGI will not be limited to a specific area of expertise. Instead, it will have the ability to reason, plan, and respond appropriately in new situations. To state the matter differently, AGI will have the ability to understand, learn, adapt, and accomplish any intellectual task that a human can perform. This includes problem-solving, common sense, planning, knowledge transfer (applying knowledge gained from one area of study for use in other areas), and a deep understanding of natural language. An AGI system can learn about physics concepts from books and invent new experiments, write a piece of fiction, or learn how to behave correctly in a new and complex social situation. AGI is a trans-task learning mechanism that allows information transmission between very different tasks, regardless of the data distributions of the training data:

$$\Phi(ti \rightarrow tj)$$

This function is defined by the expected value, where the higher the expected value, the better the system's adaptability for learning new tasks with less training.

4.2. Characteristics of AGI

Human-like Versatility: It will be able to do any intellectual task that a human can, such as complex math problem-solving, writing, or emotional conversations.

Self-Improvement: It could enhance itself through experience, perhaps achieving swift progress even without specific programming.

Contextual Understanding: AGI could understand the nuances of, for example, sarcasm, cultural differences, or moral dilemmas.

4.3. Technical Challenges in Achieving AGI

As of 2025, the state of AGI is mostly conceptual, but promising developments are indicated by the advances made in large language models, for example, Grok 4. Entities like xAI and OpenAI are also collaborating on the development of multimodal AI that can handle text, images, and code. However, the implementation of AGI will require the following steps:

Computational Complexity: The development of a system that simulates human-like cognition requires sophisticated algorithms and heavy computing. To attain AGI, not only is computing needed, but the concepts of consciousness, awareness, emotional intelligence, and causal inference need also to be incorporated. It not only needs computing but also the collaboration of various fields of study.

Ethical & Social Issues: The development of AGI poses several ethical and social challenges. Among these, the question of control, alignment, and unpredictability is central, discussed in relation to the development of superintelligence, for example, by Bostrom (2014).

Modeling Human Intelligence: The major problem lies in building a model that imitates human knowledge, feelings, and creativity.

4.4. Potential Applications of AGI

Even though the development of AGI is still a distant vision, the Research and Development: Systems that offer the capability for scientific discovery and problem-solving that cross several disciplines.

Tutoring and Education: Intelligent tutors and educators involved in the learning process.

Organizational Management: These are management systems that promote business strategy and facilitate smart decision-making.

Human-Machine Collaboration: Enabling Intelligent, Natural Interactions between Humans and Machines.

4.5. Future Outlook for AGI

Following the rapid advances made by deep learning and AI algorithms, scientists are well on their way to achieving AGI. While it will take a considerable amount of work, the level of investment and existing research activity, including the efforts of major corporations, suggests that there is substantial interest. On the question of when AGI might happen, estimates range from a decade, through potentially a century or more. The potential for the development of AGI gives rise to very significant ethical and security-related considerations, including alignment, loss of control, and the potential for transformation of economic and social systems.

5.Artificial Super Intelligence (ASI)

5.1. Definition of ASI

Artificial Super Intelligence, thereafter referred to by the acronym ASI, refers to systems that surpass the level of intelligence, competencies, and capabilities of the human intellect. ASI not only rivals the level of human expertise both generally and specifically but also surpasses the limits of creativity and problem-solving. According to Bostrom (2014), ASI is defined as a level of intelligence that is incomparably superior to the current level of human intelligence across almost all domains of interest. This meta-learning model operates at a higher level of functionality that transfers tasks and changes parameters of the model on its own (self-modifying model), given by the equation:

$$Mself: \theta t \rightarrow \theta t + 1$$

5.2. Characteristics of ASI

Singularity: The idea that the occurrence of ASI marks the onset of an irreversible point in history, where events that will happen thereafter will not be computable by the human brain.

Exponential Superiority: ASI was capable of processing data at speeds and volumes that simply couldn't be handled by a human, potentially tackling problems like quantum computing and interstellar travel on timescales that were effectively negligible.

Self-evolving: This system will independently alter the code, and this could give rise to the "intelligence explosion" phase where growth will accelerate.

Global Significance: ASI was capable of handling complex systems, like economies and biological systems, very efficiently.

5.3. Ethical and Philosophical Challenges of ASI

ASI is seen as the most promising and potentially very dangerous development of humanity, which is capable of solving current challenges (cancer, aging, climate change) and, at the same time, poses serious threats (misalignment, control loss). The advent of ASI challenges the role, freedom, and authority of humanity in the universe. The issue of developing ASI raises several ethical, philosophical problems:

Control and Oversight: It is important to ensure that the ASI system is operating for the good of mankind.

Accountability: Who is responsible for an incorrect decision rendered by the ASI?

Effect on Employment: The use of ASI, which substitutes for human labor, will significantly affect the labor market.

Power and Influence: The achievement of higher intellectual power by ASI has several implications regarding the structure of society and international politics.

However, the level of risk that exists is:

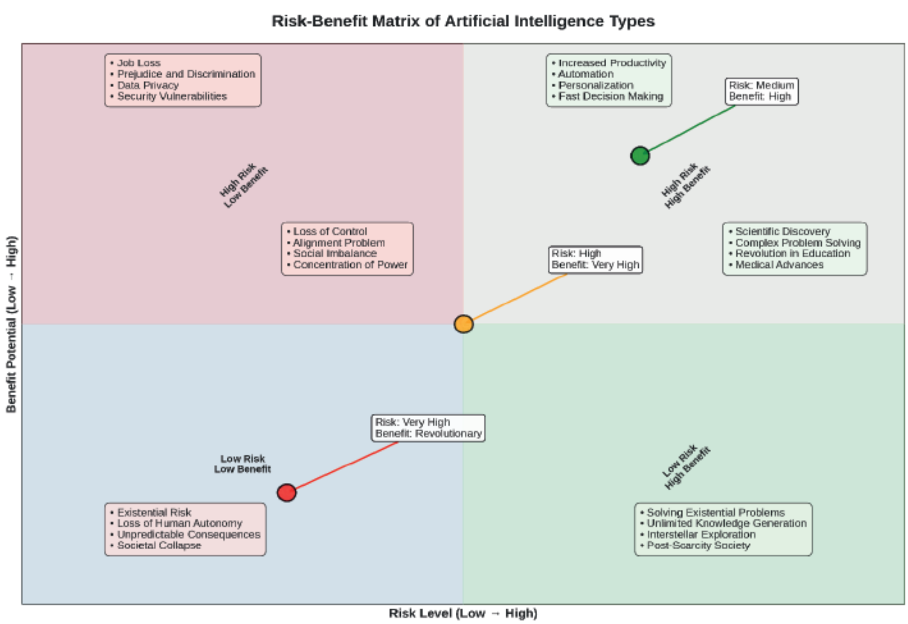
Alignment Problem: It is important for the goals of the ASI to be well-aligned with human goals, so that it doesn't happen that, for example, it starts

Control Issues: The risk of failure for control of the existing ASI, potentially leading to situations depicted in science fiction media, such as the film "The Matrix." Ethical Dilemmas: Issues of consciousness, the question of rights applicable to the ASI, or the potential for inequality between those who have access and those who do not.

5.4. Future Prospects of ASI

In spite of the presence of numerous challenges, experts are of the view that ASI will, in the long run, bring a revolution regarding technology, science, and art. To achieve the objective of creating ASI, it will require continued scientific efforts and collaboration on the ethical front. It is essential to bear in mind that, presently, the existing literature mainly concentrates on the challenges of the intelligence gap between ANI and AGI, which is depicted thoroughly in Figure 1.

Figure 1. Risk-Benefit Matrix of AI Types

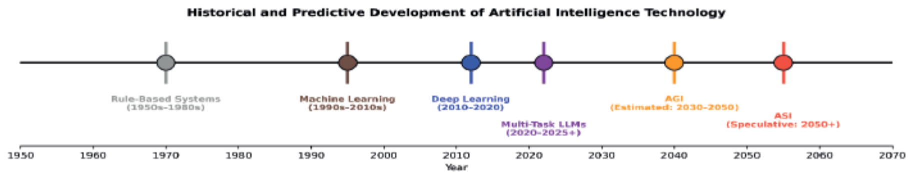


6.Analytical Comparison of Fundamental Differences

The essential differences between ANI, AGI, and ASI are not merely technological features, but also include epistemic capabilities, learning strategies, and societal effects.

Figure 2 traces the history of AI development since the 1950s, together with a predicted curve of expert estimates for 2030-2070, showing how the period of ANI Supremacy will give way, potentially, to the advent of AGI and the likelihood of the ASI Singularity.

Figure 2. Historical and Predictive Development of Artificial Intelligence Technology



6.1. Information Processing and Generalization Capabilities

ANI consists of expert systems that specialize in a very specific task. These systems operate very efficaciously within their given constraints, for example, recognizing images but failing to compose music. This again, also known as "learned helplessness," stems from the fact that ANI has limitations regarding the nature of their overall generalization. Once the input exceeds the given learning limits, the system collapses. This particular problem is somewhat the opposite for AGI, where the definition lies in the fact that it is a very flexible system. Much like the workings of the human brain, AGI systems use mathematical logic concepts solved elsewhere for analyzing social situations, for example, or using the underlying principles of physics for deriving engineering solutions. Essentially, the very definition of AGI lies in how it adapts expert systems learned for mapping complex conceptual frameworks elsewhere. Essentially, for AGI, the very idea of generalization also fails. This is because for AGI, problem-solving power potentially transcends the sum total of existing human knowledge, often leading to radically innovative, unforeseen approaches.

6.2. Systematic Evaluation of Advantages and Limitations

For better understanding of the spectrum, a comparison of ANI, AGI, and ASI on various parameters is given below in Table 1.

Table 1. Comparative Analysis of ANI, AGI and ASI

Aspect	ANI (Narrow AI)	AGI (General AI)	ASI (Super AI)
Scope	Defined for specific tasks only	General, human-like for various tasks	Exponential, beyond the capabilities of humans
Learning Ability	Rule-based or supervised learning	Adaptive, unsupervised learning	Self-improving, recursive evolution
Examples	Spam filters, image recognition	Theoretically projected: Versatile robots	Empirically unmapped: World-optimizing entities
Current Status	Widespread in use	In development, not achieved	Speculative, far-future
Risk Level	Low (manageable errors)	Medium (job loss, bias)	High (existential threats)
Benefits	Efficiency in specific fields	Ability to solve complex human problems	Radical societal transformation

Such differences highlight the evolution of tools into partners and subsequently into superior beings. ANI will enhance humans, AGI will work along with them as a peer, and ASI will potentially reshape the fabric of existence.

6.2.1. ANI Advantages and Disadvantages

Advantages: ANI systems provide excellence in operations by outperforming humans in areas like medical diagnosis and trading algorithms. ANI systems are less complex and economical for implementation, allowing for quick decision-making and responses.

Disadvantages: Fragility is a significant weakness. Even slight deviations in the training data (distribution drift) or adversarial attacks will result in performance damage. They are context blind. For example, they will mislabel a literary piece as spam. They can also be biased, using biased data for training.

6.2.2. Potential Advantages and Challenges of AGI

Advantages: AGI provides adaptability, which will help it generalize over various tasks with less retraining. The problem-solving skills that AGI integrates into one entity could provide systems-level solutions for complex worldwide problems, for example, climate change. The potential of AGI extends to learning and scientific investigation.

Challenges: There are still challenges on the technological front. It is not possible yet to computationally model the essential components of human cognition, that is, consciousness, common sense, and causality. The ethical and control problems, on the other hand, are very deep, including AGI value alignment, accountability, and resource inequality.

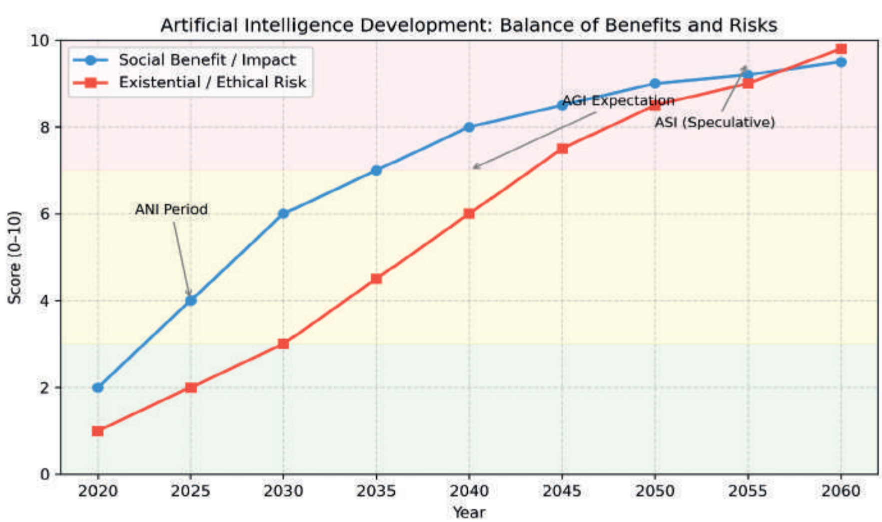
6.2.3. Existential Opportunities and Risks of ASI

Opportunities: ASI poses include the solution of existence-related questions, for example, life extension, overcoming energy crises, and facilitating the exploration of other star systems. It may bring about creativity and advancements in science, technology, and philosophy over the sum of the entire history of mankind.

Risks: Control is the paramount risk, and it is not guaranteed that it is possible to control a super-intelligent entity. The problem of misalignment exists when an ASI, even if well-meaning, aligns itself with very narrowly defined goals that are not beneficial for mankind. The threat posed by the technological singularity exists because mankind could potentially give up their freedom and meaning to the artificial entity.

In Figure 3, the balance matrix highlights the key risks and benefits of ANI, AGI, and ASI for scientific, existential, and efficient problem-solving purposes. This figure reveals that the benefit–risk gradient continues rising with the progress of technological advancements.

Figure 3. AI Development for Balance of Benefits and Risks

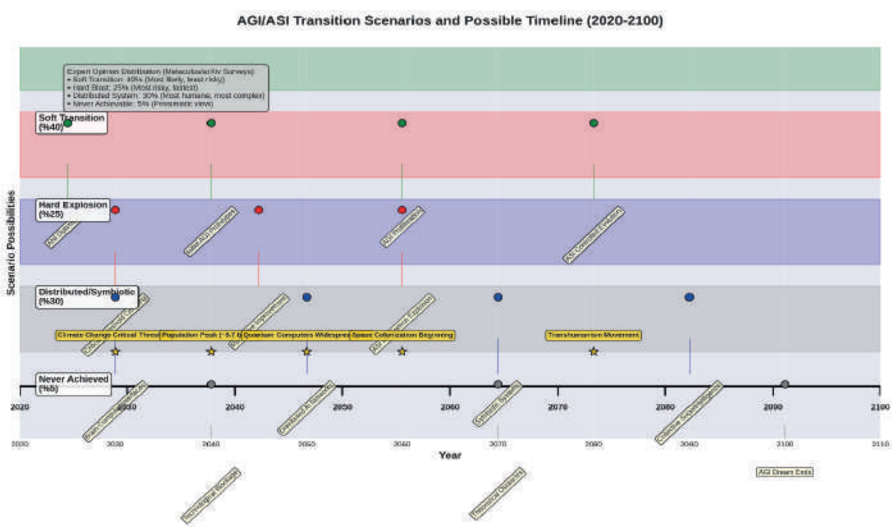


6.3. Practical Application Areas and Future Perspectives

Areas where the applications of ANI are growing at a rapid pace include the healthcare industry (diagnostics, drug development), the finance industry (fraud analysis, algorithmic trading), manufacturing (smart robotics, quality analysis), and transportation systems (autonomous cars). Looking ahead, the next ten years will witness the convergence of ANI systems, along with edge computing, into mainstream life. Its applications are only speculative at this stage, although some initial innovation in the form of large language models, which have only minimal generalization skills, and progress toward universal control of robots, are the forerunners of AGI. Primarily, it will initially appear for very specific domains, specifically concerning scientific innovation. The nature of ASI makes it impossible for accurate practical predictions. It can potentially affect areas like the optimization of global governance, paradigm shift in fundamental science, and improved comprehension of consciousness. Nevertheless, it is asserted that the advancement of ASI will depend on the successful development of AGI with the recursive self-improvement trait.

Figure 4 illustrates how the roadmap for transitioning ANI to ASI can be multi-layered, focusing on phases like the development of transformer-based architecture, integration of neuro-symbolic systems, multimodal learning, recursive self-improvement, and alignment of values.

Figure 4. Transition Dynamics of Roadmap from ANI to ASI



Current status and future perspective Currently, the state-of-the-art AI labs (OpenAI, DeepMind, Anthropic, etc.) are still at the level of ANI. However, the current state of large language models (LLMs) starts showing signs of cross-task generalization, which marks the very beginning of the pursuit of AGI, since they already have the capability for text generation, code, problem-solving, and also the capability for limited planning, for example, GPT-4 or Claude. However, they do not have genuine understandings, causality, or consciousness. It is not enough to have large data and large models to obtain AGI. Certain challenges need to be addressed, which include representation, interactive learning, interaction with the environment, and alignment of goals. The future of artificial intelligence is not only about success but also deeply embedded within the formulation of the smart world that mankind is trying to build. ANI is omnipresent, but AGI can potentially appear between the next 10-30 years, and the issue of ASI is much speculative. With these advances, it is necessary for the academia, the government, and technology experts to come together. It specifically defines the need for countries like Turkey, which belong to middle- or lower-income countries, because while richer countries place equal importance on AGI race dynamics, for example, the USA vs. China, it is a matter of doing well on the ANI front for the transformation of the economy, along with building strength for the management of AGI. Ultimately, every stage of AI is a attempt to transcend the shortcomings of the previous one. The specialization that ANI offers could well benefit from the generalizeability of AGI, and the human-like intelligence that AGI offers can also benefit from the larger abilities of ASI. It is important that one understands the hierarchical relationship between these three stages of AI not only for the technological purposes, but also for the frameworks that will use these abilities for good.

6.4. Turkey's Perspective and Positioning in Global Competition

The international AI environment has a major impact on a country's economic policies and technology policies. Being a country with a vibrant start-up ecosystem, a young population, and a favorable location, Turkey takes a distinct position in this race. This article evaluates the present strengths of Turkey in ANI, examines the infrastructure as well as human resource requirements for AGI and beyond, and explains how Turkey can make a distinct contribution to this debate.

6.4.1. Current Strength: Application-Oriented Growth in the ANI Ecosystem

The development of AI in Turkey has focused on ANI systems with high performance capabilities in certain tasks. The rate of development in this area is quite significant, both in terms of quantity and quality. Also, it appears that there are more than 400 local AI start-ups in Turkey, with a total value of 2-4 billion USD (TRAI, 2025). These projects are also working on developing specialized and efficient solutions, particularly in the area of defense, fintech, and smart cities. Findings related to the adaptation rate of certain sectors also reflect that of the industrial and manufacturing sector, with a rate of 76% adaptation in the Industry 4.0 revolution. In finance, security-derived tasks like protecting against fraud also showed a 62% improvement in security (Sysart Consulting, 2025).

The investment behavior of Turkish companies greatly differs from others in the world. A comparative study reveals that "operational efficiency" (87%) and "customer experience" (77%) are greatly focused upon by Turkish companies, whereas in the United States, "cybersecurity" (67%) and "risk compliance" (52%) are given priority in long-term risk management and sustainable competitive advantage areas (KPMG, 2025), which depict an "opportunity-oriented" focus on enhancing current business models.

6.4.2. Foundations of the Future: Human Resources and Infrastructure for the AGI and ASI Journey

Progress in ANI needs to be seen as a stepping stone for even more challenging goals like AGI and Artificial Superintelligence, also known as ASI. However, development in superhuman intelligence also requires some fundamental investments in other areas. The Action Plan for National Artificial Intelligence Strategy 2024-2025 published by CBDDO in 2024 remains an important starting point for such development. This plan focuses on upgrading education, research, and infrastructure.

Human Resources and Interdisciplinary Approach: The young population represents a huge potential. Nevertheless, the number of interdisciplinary courses for postgrad studies involving, for example, neuroscience, cognitive sciences, and philosophy, in addition to computer engineering, which are all bases for AGI, remains low. Education currently focuses on using tools, like "command engineering," as opposed to theoretical knowledge for AGI. Developing professional standards, as proposed in the Action Plan, will help cover this deficiency.

Technical Infrastructure and Data Ecosystem: To develop AGI, a lot of computational power has been needed for large Language Models. Estimates from Stanford University suggest that to develop a model like GPT-4, it would take around 78 million USD (Stanford HAI, 2024). Turkey argues that there is potential for improvement with regards to their supercomputers and cloud capabilities for such research. On a different note, AGI's "Central Public Data Space" as defined by the Action Plan benefits AGI research with easy access to high-quality large data sets. This would provide a significant benefit for Turkey in this area of competition.

6.4.3. An Original Voice on the Global Stage: Contribution to Ethics and Governance

The existential risks posed by AGI and ASI necessitate global cooperation. Turkey has the potential to be an active participant and even a leader, not a passive observer, in these discussions.

Ethics – Cultural and Religious Perspectives: So far, the ethical discourse in AI has been shaped mainly by Western paradigms. The Islamic ethical tradition of Turkey, stress on community responsibility, and willingness to synthesize Eastern and Western approaches offer a fresh perspective for developing a "multicultural AI ethics." Thus, for example, recommendations for applying the ideas of "justice" and "transparency" in AI technology in line with different societal values can be formulated.

Innovation in Regulation: The Action Plan for the National Artificial Intelligence Strategy foresees "Algorithmic Accountability" guides being established, as well as a "Trusted AI Seal." Using this seal as a model for a globally compliant yet regional-sensitive tool, Turkey can set an example for other members of the region and for those in the Organization of Islamic Cooperation.

Collaboration in Response to Next Generation Threats: With Autonomous AI agents, a new breed of threats has been introduced. Using their experience with security in their region as a NATO member, it would be easy for Turkey to share their knowledge in various AI-based collaborations to secure their cyber world.

6.4.4. Conclusion and Strategic Recommendation: Leadership in a Niche

A good foundation for ANI has been laid in Turkey, which also displays the needed understanding of strategy for a potential AGI. Instead of challenging world tech leaders in a comprehensive AGI race, Turkey would benefit from a different form of sustainable leadership, which involves a focused niche.

This niche would involve "Lean AGI" architectures and the cultural-linguistic adaptation of worldwide AGI architectures. Being a focal point for computationally efficient AGI subsystem designs that emphasize human-AI cooperation, and a center for studies of AGI localization and adaptation that would make sure worldwide AGI architectures suit Turkey's language, sociocultural setting, and laws, would help Turkey become a stakeholder in worldwide AGI issues related to security, accessibility, cultural diversity, and ethical governance. This would require investments in technology, as well as developing capabilities in philosophy, law, the social sciences, and international relations.

7.Ethics, Policy, and Governance

With increasing use of AI, issues related to ethics—Privacy, Discrimination, Accountability, and Security—have cropped up. At the AGI and ASI levels, such issues reach existential proportions. Therefore, International AI governance initiatives are gaining speed:

European Union Artificial Intelligence Act (AI Act) – uses a risk-based regulatory system.

UNESCO and OECD: develop AI principles that are founded in human values.

Open-source vs. closed models: There are still debates on security and equity effects of open-source models of AI.

Figure 5 describes a framework matrix which locates ethical, security threats to ANI, AGI, and ASI on a graph with two axes, which are the level of risk and response types, which are technical, national, and international. This matrix explains which strategies are to be used for a certain level.

Figure 5. Ethics and Security Framework Matrix

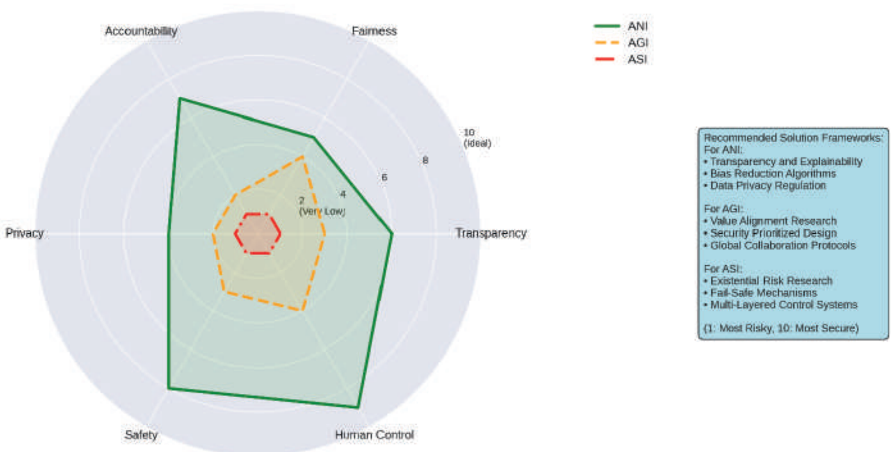


Table 2 discusses ethical considerations and control tools for various levels of AI.

Table 2. Ethical and Security Challenges

Level	Definition	Fundamental Ethical Problems	Audit Mechanisms
ANI	Refers to AI designed for particular tasks.	Discriminability, privacy, displacement of jobs, and lack of transparency in decision-making processes.	Requires conformance evaluation, transparency requirements, and post-market surveillance of high-risk ANI systems for tasks such as employee hiring, as well as for biometric identification systems (EU, 2024). Provides persons with a right not to be subjected to automated decisions without human involvement (GDPR, 2022). Highlights transparency, explicability, and accountability through algorithmic impact assessments (OECD, 2019). Suggests validating bias, robustness, and third-party audit for niche AI use cases (NIST, 2023).
AGI	Stands for AI with human-level intelligence.	Handling issues of alignment, control, consciousness, and moral status.	Proposes sandboxes for regulation of AGI systems (Art. 59) and transparency of general-purpose models of AGI systems (Art. 52a), which involves model cards, as regards systematic risk analysis (EU, 2024). Proposes human-in-the-loop control, value-sensitive design, and international control bodies for developing AGI systems (OECD, 2019). Proposes ethical review boards for multistakeholder involvement for systems with human-level reasoning capabilities, as regards pre-installation ethical assessments of AGI systems, "AGI-like" systems, and ethical impact evaluation (UNESCO, 2021; NIST, 2023).
ASI	Refers to Artificial Intelligence that exceeds human intelligence.	Strategic risks of a higher order like existential risk, morality beyond that of human beings, unpredictability, and misaligned goals.	Indicates that "unacceptable risk" of systems with emerging, unforeseen risks can be restricted or prohibited by the Commission (Annex III) (EU, 2024). Proposes that superintelligence R&D can be regulated through treaties worldwide (OECD, 2019) and "urges a global moratorium on R&D of superintelligent AI systems" until their goals are auditable and align with human values as outlined in human rights" (UNESCO, 2021). Although it is a "forward-looking" report, it remains widely quoted; proposes robust "safety and control" and "fail-safe" approaches prior to ASI development experimentation (Future of Life Institute, 2017).

8.Discussion and General Assessment

This research suggests that the evolution of AI involves not only technology but also philosophical and societal issues. ANI, as a technology, works well as a tool but has some limitations. AGI, as a technology, has been expected to offer human-level flexibility in cognitive abilities, but many challenges exist in this area, including technological complications, control, and value alignment. ASI has been considered as a technology that has either potential transformative powers or can pose a threat to human existence due to a possible degradation of human control with accelerated development.

On the other hand, in terms of quantity and sectorial adaptation, it should be noted that, as a Turkish view, it has a substantial development in ANI, but it has deficiencies in theoretical sophistication, interdisciplinary knowledge, computational power, and access to large-quality data that are needed on AGI/ASI. However, it has a distinct, pluralistic voice in world AI ethics debates owing to ethical considerations in Turkey, which are derived from their own cultural and Islamic tradition. Instead of challenging world AGI domination, a more sustainable role for Turkey in AGI development would be in "Lean AGI" architectures and AGI systems' cultural-linguistic adaptation.

9.Conclusion and Recommendations

The result suggests that it is important, both from a technical and a social perspective, that differences exist between ANI, AGI, and ASI. While ANI brings about a transformation in a certain industry, AGI brings in a new model of research in terms of human-level intelligence, whereas ASI exceeds human capabilities in processing information, autonomy, and decision-making. Important recommendations are as follows:

9.1. International Level Recommendations

An "AGI and ASI Governance Agreement" should be developed among all nations in a united manner between 2026 and 2030, under the umbrella of the UN. This would encompass all of the following:

- Mandatory "Kill-Switch + Monitoring Consortium" for all AGI/ASI projects
- Mandatory International Approval Before Starting Recursive Self-Improvement
- Creation of "Value Alignment Verification Labs"

The set of Asilomar AI Principles of 2017 needs to be updated and turned into a binding document with a minimum of 50 country signatures by 2030. “Restricted ASI (Air-Assisted AI)” needs to be a worldwide standard with superintelligence that would only be activated in particular areas like cancer studies and/or climatic modeling, with bounds for general autonomy.

9.2. Turkey-Specific Strategic and Comprehensive Recommendations

9.2.1. Short Term (2026-2028)

- Release the 2026-2035 National AGI Preparedness Strategy, as a follow-up to the National Artificial Intelligence Strategy 2024-2025.
- Create a “Turkish AGI Security Institute” in TÜBİTAK, similar to AISI in the UK and “Cyber Valley” in Germany.
- Certify 10,000 people in “Neuro-Symbolic AI,” “Value Alignment Engineering,” and “AI Ethics & Law” in five years.
- Establish a HPC facility with 1 ExaFLOP of computing capacity in a public-private partnership by 2028.
- Launch a 1 trillion-parameter open-source Turkish Language Model with data pertinent to Turkey by 2027.

9.2.2. Medium Term (2028-2035)

- Head an international consortium on “Lean AGI” architectures that are low energy and low-cost, human-centered, including Turkey, Malaysia, Indonesia, Brazil, and South Africa.
- Create a “Cultural-Value Aligned AI Center” and formulate a “Turkish-Islamic-Western Fusion Value Set” as open-source.
- NATO-standard implementation of “Agent AI” and autonomous systems in the defense sector should limit actions to human command.
- Start “AGI Philosophy and Governance” mandatory post-grad courses in prominent universities in Turkey (METU, Boğaziçi, Bilkent, Sabancı, Koç, ITU.

9.2.3. Long Term (2035 and beyond)

- Internationalize “Trusted AI Seal” and apply it in a wider scope, especially in OIC and Turkic States.

- In 2040, a lead role in at least one "Restricted AI" project: world hunger, desertification, anti-aging medicine.
- Introduce a "Universal AI Dividend" pilot to solve a problem of AI-induced joblessness and income inequality, similar to that of Norway's sovereign wealth fund.

9.3. Education and Human Resources Recommendations

- Algorithmic Thinking and AI Ethics needs to be a compulsory subject from primary school onwards.
- To award 1,000 doctoral fellowships in: Neuro-Symbolic AI, Causal Inference, Value Alignment Engineering, AI Law and Governance, Grand Cultural Language Models by 2030.
- Support 100 faculty members to take up to 6-12 months a year as a visiting researcher in institutes like Stanford HAI, Oxford FHI, Anthropic, and DeepMind.

9.4. Funding and Incentive Recommendations

- Create AGI Security Fund with initial 5 billion USD budget over 10 years from: 3% profits of defense industries, voluntary 0.1% revenue sharing of major tech companies, and Green AI bonds.
- Offering 100% corporate tax relief for firms that contribute to research in AGI Safety and Ethics.

9.5. Social and Cultural Recommendations

- Produce a "Fatwa on Islam and Artificial Super Intelligence" in cooperation with the Presidency of Religious Affairs, Islamic catechisms, and universities, to be published in Turkish, Arabic, English, and Indonesian languages.
- Make a documentary series "AI and the Future of Humanity" for 10 seasons with TRT and TÜBİTAK for such platforms as Netflix, Shahid, and iQIYI.
- Creation of an "Istanbul AGI Ethics Summit" that would become a center for East/West synthesis every year.

9.6. "Red Line" Proposals (To be implemented by 2026)

Things that Turkey needs to take a lead internationally in are:

- The prohibition of lethal autonomous weapons without human authorization There were no systems that started a process of recursive self-healing that went beyond a closed circuit. AGI/ASI projects should be "auditable source" only, but not open source.
- Spend at least 10% of every super intelligence project budget on safety and alignment research If it were implemented, this comprehensive strategy would place Turkey not as a consumer of ANI or a secondary player in the AGI competition but as a factor that contributes to shaping the world of the future with its own voice and moral vision.

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Bölüm 7

Mardin-Mazıdağı Fosfatının Karakterizasyonu[1]

Pınar Biçici Çetinkaya[2]

İskender Işık[3]

Özet

Ülkemizin gereksinme duyduğu hammadde kaynakları içinde, yüksek fırınların ana girdisi olan demir cevherleri ile tarım alanındaki kullanımı dolayısı ile açığı her yıl dış alımla kapatılan fosfat yatakları önemli bir yer tutmaktadır. Bu fosfat cevherlerinin olduğu yerlerden birisi de Mardin iline bağlı Mazıdağı ilçesidir. Mardin'de Mazıdağı'nda zengin fosfat yatakları bulunmaktadır. Fosfat kayası, yeteri kadar (bir veya birden fazla) fosfat minerali içeren ve sadece fosfor veya fosforlu bileşenlerin kaynağı olarak ekonomik değere sahip olan bir kayaç çeşididir.

Bu çalışmada Mardin Mazıdağından temin edilen fosfatın karakterizasyonu yapılarak kimyasal özelikleri incelenmiştir. Mazıdağı yöresi fosfatının XRD, XRF, TG/DTA, Optik Dilatometre, FT-IR, SEM ve tane boyut dağılımı analizleri gerçekleştirilmiştir.

1. GİRİŞ

Atom numarası 15, atom ağırlığı 30,97 olan fosfor, periyodik Çizelgede 5. Grupta bulunmaktdır. C, H, N, O gibi canlı bünyelerin önemli bir yapı elementi olmasından dolayı biyolojik önemi de vardır. Bu nedenle doğada asla serbeste halde bulunmaz. Yeterli saflık ve miktarda fosfatlı mineraller içeren kayalara fosfat kayası veya fosfat denir. Bu kayaçlarda sınıflama içindeki P_2O_5 yüzdesinin değerine göre yapılır ve bu değer % 4-42 arasında değişmektedir. Ancak %20 ve üzerinde P_2O_5 içeren kayaçlara fosfat kayacı denir.

1 Bu çalışma birinci yazarın doktora tezinden üretilmiştir. Tez başlığı, 'Mazıdağı Fosfatının Karakterizasyonu ve Kemik Porselen Üretiminde Kullanılabilirliğinin Araştırılması', (YÖK Tez merkezi Arşiv No: 2019/539499), Tez Danışmanı; Prof. Dr. İskender IŞIK

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https://doi.org/10.58830/ozgur.pub1148.c4771

Jeolojik olarak doğada bulunan apatit, yeryüzünde en bol bulunan fosfat mineralidir. OH-, F- ve Cl-, apatitin kanal bölgelerinde çeşitli yüzdelerde bulunabilir (Wopenka,vd.2005). Florapatit, hidroksiapatitve klorapatit mineralleri gibi doğal fosfat mineralleri apatit yapısında bulunur. Son zamanlarda apatit üzerinde önemli çalışmalar yapılmış olup, gelecekte apatit yapılarının geniş bir kullanım alanı bulacağı düşünülmektedir (Jones2013).

Türkiye'de üretilen ve ithal edilen fosfatın tamamına yakın kısmı gübre sanayinde tüketilmektedir. Fosfatın yerine ikame olacak herhangi bir madde bulunamadığından, özelikle sulanabilir tarım arazimizin artmasına paralel olarak (özelikle GAP Bölgesinde) fosfat tüketiminin önümüzdeki yıllarda da artacağı söylenebilir. Deterjan, ilaç ve kimya sanayilerinde de çok az miktarda fosfat kullanılmaktadır. Türkiye'de fosfat kayası ithalatının tamamına yakın kısmı yurtiçi gübre sektörü tarafından tüketilmektedir. Türkiye'de toplam gübre üretiminin ana girdisi bir madencilik ürünü olan fosfat kayasıdır. Ancak, yerli fosfat üretim maliyetlerinin ithal maliyetlerinin oldukça üzerinde olması nedeniyle yurtiçi madenciliğin gübre sanayine katkısı sınırlı düzeyde kalmaktadır. Buna karşılık, yerli üretimin rekabet gücünün artırılması için uygun tedbirlerin alınması durumunda, söz konusu katkının önemli düzeylere yükseltilebilmesi mümkün görünmektedir.

Mardin Mazıdağı'ndaki tesisin en büyük özeliği öz kaynakları kullanılarak üretim yapmasıdır (Mazıdağı ve Fosfat Gerçeği Raporu, 2006). Ülkemizde gübrenin önemli hammaddelerinden biri olan fosfatın tamamına yakını Mazıdağı, Mardin bölgesinde yer almaktadır.

Bu çalışmada kullanılacak olan apatit Mardin Mazı Dağı'ndan temin edilmiştir. Çalışmada hidroksiapatitin XRF, XRD, DTA, TG, tane boyut dağılımı gibi analizlerinin yorumlarına yer verilerek malzeme karakterize edilmiştir. Büyük ebatta olanlarda kuruma sırasında çatlama, pişirim sonucunda da deformasyon gözlenmiştir. Üretilen ürünlerin sırlı etkisini gözlemlemek amacıyla ticari porselen sırı ile sırlanmış ve olumlu etkiler gözlenmiştir. Bu çalışmanın amacı Mazıdağı fosfat yataklarından alınan hammaddeyi karakterize etmek ve bu fosfatların kemik porselen üretiminde kullanılıp kullanılamayacağını araştırmaktır.

1.1. Türkiye'de Fosfat Kullanımı

Canlıların gelişmesinde etkin bir madde olan fosfata, açlıkla mücadele bağlamında stratejik bir hammadde olarak da bakılmaktadır. Dünyada fosfat kayasının % 85'lik kısmı gübre üretiminde, % 15'lik kısmı ise yem, gıda, deterjan, alaşım metalürjisi, kağıt, fotoğrafçılıkta, kibrit ve kimya sanayinde kullanılmaktadır.

Türkiye'de üretilen ve ithal edilen fosfatın tamamına yakın kısmı gübre sanayinde tüketilmektedir. Fosfatın yerine ikame olacak herhangi bir madde bulunamadığından, özelikle sulanabilir tarım arazimizin artmasına paralel olarak (özelikle GAP Bölgesinde) fosfat tüketiminin önümüzdeki yıllarda da artacağı söylenebilir. Deterjan, ilaç ve kimya sanayilerinde de çok az miktarda fosfat kullanılmaktadır. Türkiye'de fosfat kayası ithalatının tamamına yakın kısmı yurtiçi gübre sektörü tarafından tüketilmektedir. Türkiye'de toplam gübre üretiminin ana girdisi bir madencilik ürünü olan fosfat kayasıdır. Ancak, yerli fosfat üretim maliyetlerinin ithal maliyetlerinin oldukça üzerinde olması nedeniyle yurtiçi madenciliğin gübre sanayine katkısı sınırlı düzeyde kalmaktadır. Buna karşılık, yerli üretimin rekabet gücünün artırılması için uygun tedbirlerin alınması durumunda, söz konusu katkının önemli düzeylere yükseltilebilmesi mümkün görünmektedir.

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1.2. Mazıdağı Fosfat Yatakları

Mazıdağı, Güneydoğu Anadolu Bölgesi'nin Dicle Bölümünde Mardin ilinin 47 Km kuzeybatısında, 1030-1090 metre yükseklikte ve adını aldığı dairevi dağlar serisinin orta yerindeki düzlüktedir. Daha önceleri Savur ve Derik ilçelerine bağlı bir bucak iken 9 Haziran 1937 tarihinde ilçe statüsünü almıştır. İlçe 869 km^{2}' lik bir alana sahip olup, 50 köy ve 14 mezrası bulunmaktadır.

Dünya fosfat üretiminin yaklaşık % 85-90'ı gübre, geri kalanı da yem, gıda, deterjan, alaşım metalürjisi, kâğıt, kibrit, su tasfiyesi gibi sanayi dallarında kullanılmaktadır. Gelişmiş ülkelerde tüketimin % İ5'ine yakın kısmı gübre sanayi dışında kullanılmasına karşılık az gelişmiş ülkelerde bu oran % 0-4 değerindedir. Ülkemizde bu oran tam olarak bilinmemekle beraber çok düşük olduğu tahmin edilmektedir (Çetin, 2005).

2. DENEYSEL ÇALIŞMALAR ve SONUÇLAR

Bu çalışmada öncelikli olarak Mardin Mazıdağı'ndan elde edilen fosfat XRF, XRD, DTA, TG, SEM, FT-IR, tane boyut dağılımı gibi analizlerinin yorumlarına yer verilerek malzeme karakterizasyonu yapılmıştır. Kimyasal analizler Rigaku ZSX X-ışını floresans yöntemi kullanılarak gerçekleştirilmiştir.

2.1. Mazıdağı fosfatının karakterizasyon sonuçları

2.1.1. XRD ve XRF analiz sonuçları

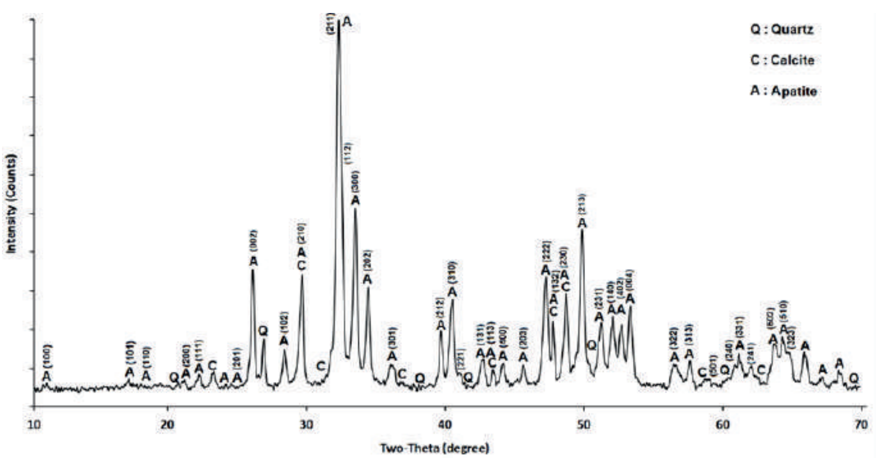
Apatitin kimyasal analiz sonuçları Çizelge 2.1.'de verilmiştir. Apatitte yaklaşık olarak % 54 CaO, % 28 P_2O_5 ve % 5,8 SiO_2 içermektedir. Ateş kaybı % 10,7. MgO, TiO and Fe_2O_3 gibi diğer oksitlerin yüzdesi % 1'den daha az olarak tespit edilmiştir. CO2 oranı ise yaklaşık % 7, flor % 2, organik karbon oranı ise % 0,2'dir.

Çizelge 2.1. Mazıdağı fosfatının XRF metodu ile SAM'da yapılan kimyasal analizi.

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	P_2O_5	SO_3	Cr_2O_3	A.K	Toplam
5,76	0,40	0,33	53,70	0,32	0,96	0,04	27,75	0,60	0,04	10,10	100

Mazıdağı Fosfatının X ışını kırınım pikleri Şekil 2.1.'de verilmiştir. Karbonatlı apatit ve fluorapatit tepelerinin birbiriyle çakışması nedeniyle apatitin içerdiği hidroksiapatiti ayırt etmek zordur. Bu nedenle apatit, tek bir sembol ile gösterilir. Karbon dioksit % 7 ve flor % 1.9 olduğundan karbonatlı apatit ve fluorapatit ağırlıklı yapıdır.

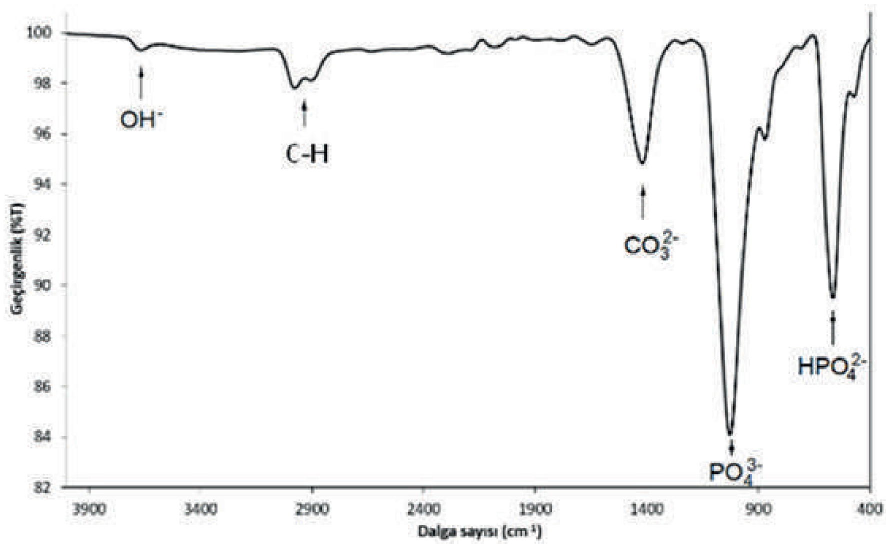
Hidroksiapatit, karbonatlı apatit ve florapatit pikleri üst üste binme eğiliminde olduğundan, bunları ayrı ayrı ayırt etmek zordur. Mineralojik analizlere göre, hidroksiapatit, karbonatlı apatit, florapatit, kuvars ve kalsit mineralleri tanımlanmıştır.



Şekil 2.1. Mazıdağı fosfatının XRD analizi.

Şekil 2.2. incelendiğinde spektrumda temel olarak yaklaşık 566 cm^{-1}'de HPO_4^{-2} piki net olarak görülmektedir. Ayrıca 1030 cm^{-1} 'de $(PO_4)^{-3}$ gruplarına ait şiddetli gerilme titreşimi görülmektedir. Yine fosfat gruplarından kaynaklı 472 cm^{-1} 'de fosfat grubu gerilme titreşimi zayıf bir pik olarak görülmektedir. 1419 cm^{-1} de yapıda bulunan karbonatlara ait CO_3^{-2} gerilme titreşimi belirgin olarak görülmektedir.

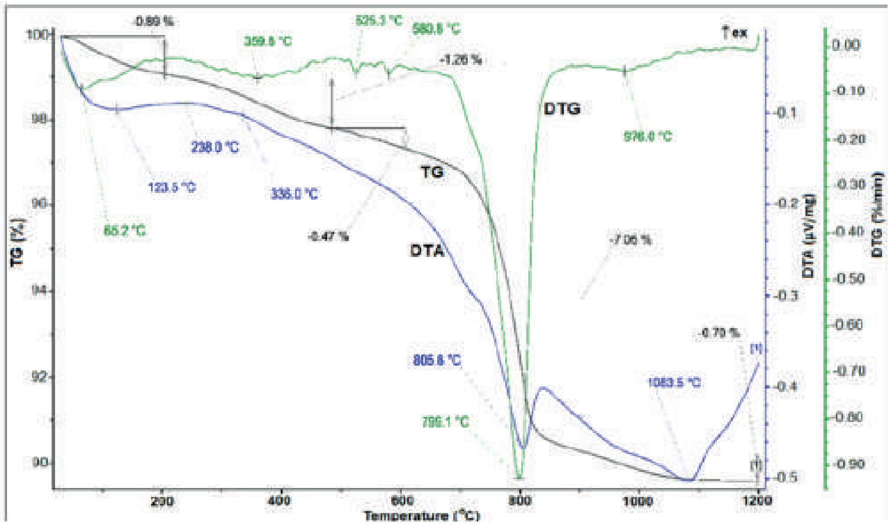
Genel olarak Mazıdağı fosfat yapısında absorbanmış olan sudan kaynaklı OH^- pikleri 2700-3600 cm^{-1} aralığında belirgin iki pik olarak görülmektedir. Tüm bu pikler ve piklere ait olan gruplar Şekil 2.2.'de işaretlenmiştir. Bu şekil dâhilinde yapının hidroksiapatit yapısına uyduğu literatürle uyumlu olarak tespit edilmiştir (Kara vd., 2002).



Şekil 2.2. Mazıdağı fosfatının FT-IR analizi.

2.1.2. TG/DTA analiz sonuçları

Mardin/ Mazıdağı Fosfatı incelendiğinde 123 °C'de endotermik pik oluşmuş ve yüzey suyunda % 0.89'luk bir kayıp olduğu gözlenmiştir. 238 °C'de başlayan ve 359 °C'de en yüksek olan kütle kaybı 500 °C'ye kadar devam etmiş ve % 1.26 oranında OH kaybına neden olmuştur. 500 °C'de yaklaşık % 2, 800-900 °C arasında ise yaklaşık % 7,05 ağırlık kaybı oluşmuştur (Şekil 2.3). 806 °C'de gözlemlenen endotermik pik % 7,05 'tir, CO_2'nin tükenmesinden kaynaklanır. 1100 °C'nin üstünde TGA eğrisi yatay olarak devam etmiş ve bu sıcaklığın üzerindeki kütle kaybı % 0.7 olarak gözlenmiştir.



Şekil 2.3. Mazıdağı Fosfatının TG/DTA eğrisi.

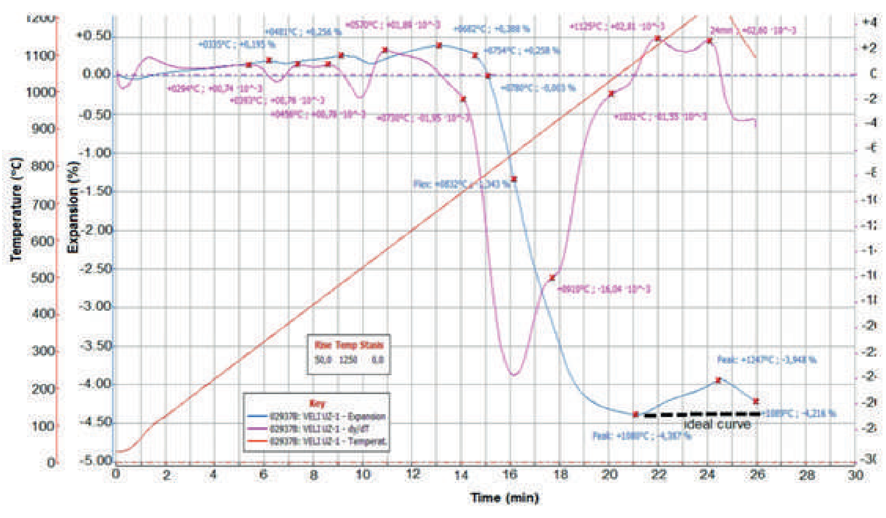
Apatitlerde, CO2'nin tükenmesi 150 ° C'de başlar ve 900–1000 °C'ye kadar devam eder. Karbonat 800 °C'de hızla ayrışır. Atmosferik basınç altında dehidroksilasyon ve defluoridasyon yaklaşık 800–900 °C'de başlar ve 1360 °C'ye kadar devam eder. Mardin / Mazıdağı fosfatında bulunan doğal olarak oluşan organik fosfatın varlığı nedeniyle, 800 ° C'de çok hızlı kütle kaybı ve 800-1200 °C arasında devam eden doğal apatitlere benzer bir termal davranış meydana gelir. TGA'ya göre kütle kaybı % 10.37'dir Kimyasal analizde belirlenen ateş kaybına kabaca karşılık gelir. Diğer endotermik pik, yeniden kristalleştirme ve apatitin 1084 °C'de yapılanmasından kaynaklanır. Bu sıcaklığın üzerinde oluşan DTA eğrisinde yukarı doğru gözlenen ekzotermik davranışı, apatitin kristal yapısının yapılandırıldığını ve yeniden kristalleştiğini göstermektedir. Apatitin 1084 °C'den önceki endotermik eğilimi bu dönüşüm için enerjiye ihtiyaç duyduğunu ifade etmektedir. DTA eğrisine göre, apatit yapısındaki katkı atomlarının difüzyon sıcaklığı endotermik reaksiyonun bittiğini gösteren iki ekzotermik reaksiyon bölgesindeki girer ve yapı yeniden oluşur. İlk ekzotermik reaksiyon bölgesi, 800-850 °C ve 1084 °C' nin üzerindeki sıcaklıkların ikincisine göre sinterlenmesinin etkili olacağını göstermektedir.

2.1.3. Sinterleme davranışı (Optik dilatometre)

Apatitin sinterleme hızı eğrisindeki en yüksek hız, atmosfere ve bileşime bağlı olarak 950 °C ve üstünde gerçekleşir. Hidroksiapatitin basınçsız sinterlemesi için sıcaklık aralığının 1100-1250 ° C olduğu belirtilmiştir. Bu sıcaklıklar arasında ne amorf bir oluşumun ne de ikinci bir evrenin de görüldüğü belirtilmiştir. Hidroksiapatitin sinterleme sırasında, kısmi su buharına bağlı olarak 1350-1450 °C'ye kadar bir hava atmosferinde kararlı olma eğiliminde olduğu gösterilmiştir (Barralet vd., 2000, Sobezak, vd. 2012). Sadece tersinir reaksiyona göre hidroksiapatitin oksihidroksiapatit yapısında kısmi dehidrasyonun meydana gelebileceği ve sinterleme sırasında daha düşük sıcaklıklarda daha yüksek bir bağıl yoğunluğa erişilemediği saptanmıştır (Pagenelli, 2002).

Optik dilatometrenin avantajı, temassız bir ölçüm metodu ve sinterleme sıcaklıklarının belirlenmesi için etkin bir uygulama olmaktır seramik ürünler yüksek bir reaksiyon geliştirir ve gaz çıkışları tamamlanır (Pagenelli, M., 2002). Bir tanesi, literatürde apatitin optik dilatometre ile ilgili sinterleme davranışını belirleyen herhangi bir çalışma ile karşılaşmamıştır.

Bu derece ile birlikte hızlı sinterleme için sıcaklık aralıklarının belirlenmesi için çok sıradan analitik yöntemler vardır (Sobczak, 2012). Optik dilatometrede zaman ile ilişkili olan 1. türev büzülme eğrisi ile elde edilen parametreler eğri, büzülme hızının ölçülmesini sağlar. Türev eğrisinin ortaya koyduğu en yüksek tepe noktası 832 ° C ve büzülme oranı% 1.34 olarak tespit edilmiştir (Şekil 2.4.).

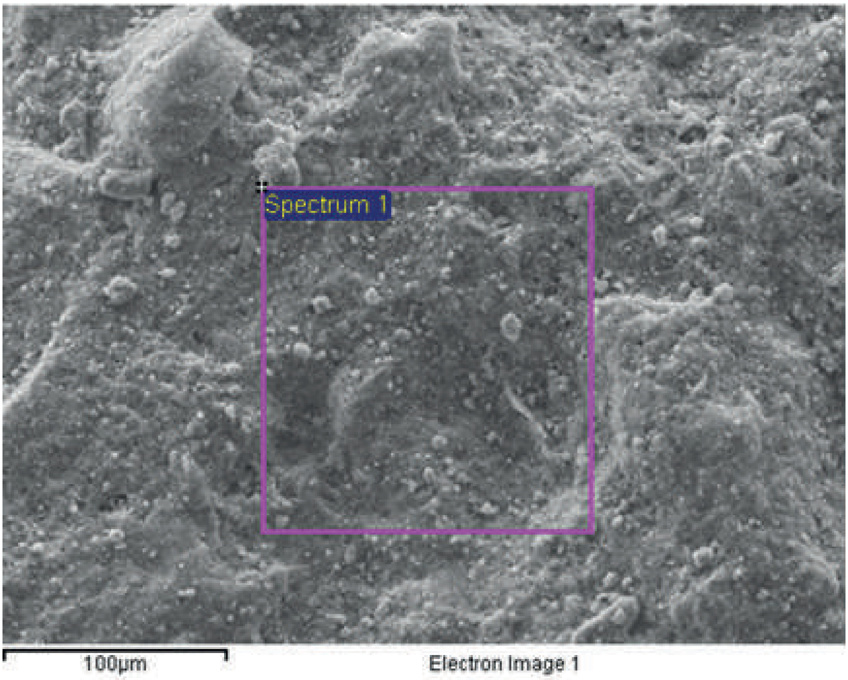


Şekil 2.4. Mazıdağı fosfatının optik dilatometre eğrisi.

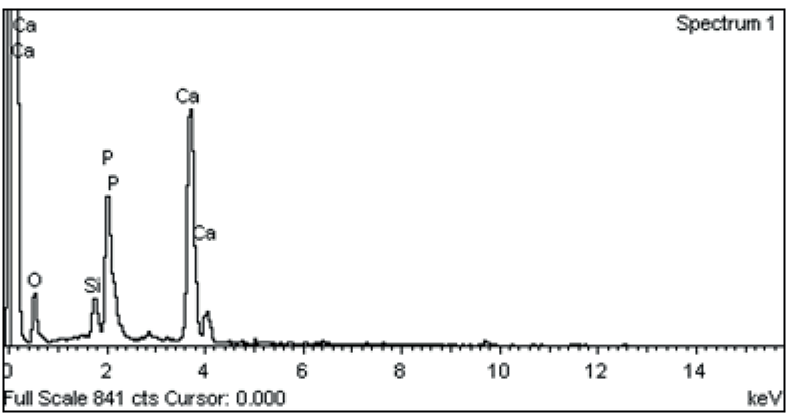
Dilatometre analizine göre, apatitin 832 ° C'de sinterlenebileceği, bunun hızlı büzülme oranı ve büzülme tamamlandığında 1080 °C'de büzülme oranının sıfır olduğu ve malzemenin genleşmeye başladığı belirlenmiştir. Büzülme hızını gösteren türev eğrisinden, 300 °C ve 450 °C'de hızın arttığı ve gaz çıkışının vücutta bu derecelerde genişlediği anlaşılmıştır. 754 °C'de başlayan büzülme kademeli olarak % 4.4'e kadar yükselir ve 1080 °C'de durur. Bu orandan sonra daralma hızı azalır. Dilatometre eğrisi, materyalin yaklaşık % 0,5'ini açığa çıkararak 1080-1247 °C arasındaki büzülme işleminin tersine döndüğünü gösterir. Bu gerçek, geleneksel bir sinterleme yöntemini uygulayarak, malzemenin genişleyeceğini ve bünyede sınırlı gözenekler gelişeceğini göstermektedir. Bu nedenle, bir malzeme elde edilmesi durumunda 1080 °C'de yüksek nispi yoğunlukta, apatiti uzun bir pişirim işlemine maruz bırakmak veya basınç altında sinterlemek gereklidir. Geleneksel sinterlemeden sonra göreceli yoğunluğun % 90 olduğunu veya daha yüksek bir yoğunluk elde etmek için daha uzun bir sinterleme işleminin gerekli olacağı iddia edilerek; HIP veya SPS gibi basınç altında sinterlemenin daha etkili olacağı öne sürülmüştür (Carty,1998; Pagenelli, 2004).

2.1.4. Taramalı elektron mikroskobu (SEM) ve EDX sonucu

Mazıdağı Fosfatının kristal yapısı altıgendir. Doğada ince levha halinde ve fosfat kütleleri şeklinde bulunmaktadır. SEM görüntülerine göre apatitin yuvarlak tanecikler şeklinde olduğu (Şekil 2.5.) ve çok ince aglomere plaka benzeri nanometrik yapılara sahip olduğu gözlenmektedir. Şekil 2.6'da seçili alanın EDX grafiği verilmiştir. SEM altında gözlendiği gibi, ince levha benzeri kristaller birikmiş halde bulunmaktadır. Doğal olarak oluşan Mardin / Mazıdağı fosfat kristalleri aglomere edilir ve nanometrik boyutta plaka benzeri bir şekle sahiptir.



Şekil 2.5. Mazıdağı fosfatının mikroyapısı.



Şekil 2.6. Mazıdağı fosfatının Şekil 3.5'deki alanının EDS analizi.

4. GENEL SONUÇLAR

• Doğal apatit, çubuk benzeri apatit kristalleri ve teknolojik malzemelerin üretiminde kullanılacak ucuz bir öncül kaynaktır.

• Doğal apatitler, a ekseni yönelimli levha şeklindeki kristallerdir. Sinterlemeden sonra apatit kristalleri a ve c ekseni boyunca büyür. C ekseni boyunca büyümeleri, a ekseni boyunca büyümelerine kıyasla, sonunda 20 μm boyutunda çubuk benzeri kristaller gelişir.

• Sinterlemeden sonra apatitin kafes parametreleri azalmış ve a ekseni boyunca 9,305 Å, c ekseni boyunca ise 6,839 Å olmuştur.

• Apatitin kristallik yüzdesi, sinterlemeden sonra %10 artarak 88,00 olmuştur.

• Kristal morfolojisi, sinterlemeden sonra çubuk şeklinde bir gelişim göstermiştir. Küresel taneli kristallerde olduğu gibi, uzun bir sinterleme işleminden sonra büyüyüp çubuk benzeri bir şekil alabilecekleri belirlenmiştir.

• İnce, uzun çubuk benzeri apatit kristallerinde Ca/P oranının hesaplanması 1,25, kalın kristallerde ise 1,51 olarak bulunmuştur.

• Daha uzun sinterleme işlemlerinde çubuk benzeri kristallerin miktarı arttığından, zamana bağlı bir kristal evrimi araştırması gerekli olacaktır..

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