

CURRENT TREND AND STUDIES IN AGRICULTURE, FOREST AND WATER ISSUES



All Sciences Academy

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Editor

Prof. Dr. NİGAR YARPUZ BOZDOĞAN





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CONTENT

1. Chapter	5
Mechanization Applications and Recent Developments in Cumin (<i>Cuminum cyminum</i> L.) Cultivation	
<i>Cevat FİLİKÇİ, Tamer MARAKOĞLU</i>	
2. Chapter	18
Blue Bioeconomy and Algae: Fundamentals and Emerging Trends	
<i>Seher DİRİCAN</i>	
3. Chapter	36
An Open-Source QGIS Plugin for Thiessen (Voronoi) Polygon-Based Areal Weighting of Irrigation Station Data	
<i>Selçuk ALBUT</i>	

Mechanization Applications and Recent Developments in Cumin (*Cuminum cyminum* L.) Cultivation

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ABSTRACT

Cuminum cyminum L., commonly known as cumin, is a spice crop of considerable economic value for Türkiye, India, Iran and a number of other producing countries; despite this importance, its cultivation continues to lag behind most field crops in terms of mechanization. Because the plant is short-statured, has a fragile stem, ripens unevenly and sheds its seed readily, harvesting and threshing have traditionally relied on manual or only partially mechanized methods, with consequences that include elevated labour costs, delayed harvest operations, and reduced yield and essential-oil quality. This chapter surveys recent literature on mechanizing cumin production along the entire value chain, beginning with seedbed preparation and ending with post-harvest handling. Three strands of ongoing research receive particular emphasis: first, the physical and mechanical characteristics of the seed and taproot that inform the engineering of cutting, uprooting, threshing and drying machinery; second, precision-seeding technologies — notably conveyor-belt and fluted-roller metering systems — adapted for small-seeded spices including cumin, coriander, sage and black cumin; and third, efforts to build purpose-designed cumin harvesters, several of them tested within the cotton-cumin intercropping systems of China's Xinjiang region. Drying and cleaning methods that safeguard essential-oil content after harvest are likewise considered. The chapter closes by assessing where cumin mechanization currently stands in Türkiye and by proposing ways to adapt this expanding international knowledge base to domestic growing conditions, with the broader goals of easing labour dependence, cutting harvest losses and safeguarding product quality.

Keywords – Cumin; Cuminum cyminum; Agricultural mechanization; Precision seeding; Harvest mechanization; Postharvest processing

1. INTRODUCTION

Belonging to the family Apiaceae, cumin (*Cuminum cyminum* L.) is a one-year plant grown for its aromatic seed, which serves as a spice. Its uses span the food sector, pharmaceuticals and dye manufacturing, and it ranks among the export goods of importance not only for Türkiye but also for India, Iran, Syria and China (Kan et al., 2007). Globally, output is dominated by two Indian states, Rajasthan and Gujarat, which jointly hold close to 80% of the crop's total sown area (Lal et al., 2014). Domestic cultivation in Türkiye is largely confined to Central Anatolia, with Afyon, Ankara, Eskişehir and Konya foremost among the growing provinces.

Compared with most other field crops, cumin cultivation has advanced little in terms of mechanized operations. Because the crop stands only 35-50 cm tall, carries a thin, easily damaged stem, ripens unevenly across the field,

and drops its seed readily once mature, growers still depend largely on hand labour or partially mechanized techniques for harvesting and threshing (Lal et al., 2014; Malhotra and Vashishtha, 2010; Alam, 2007). The practical consequences are higher labour expenditure, harvest operations that fall behind schedule, and eventual losses in both quantity and quality of the crop (Kumar et al., 2024). A harvest that is delayed, together with lengthy exposure to sun during drying, is particularly damaging: it depletes the seed's essential-oil fraction and thereby diminishes market quality (Lal et al., 2014).

Over the past several years, published work targeting this constraint has grown substantially. A key driver has been the spread of cotton-cumin intercropping across Xinjiang, China, which has generated pressing demand for mechanizing the entire cultivation sequence and, in turn, spurred efforts toward purpose-built cumin harvesters (Tai et al., 2025a; Man et al., 2025). In a wide-ranging review, Tai et al. (2025a) organized the obstacles facing cumin-harvest mechanization around five themes: the crop's biological characteristics together with its intercropping arrangement; grain losses and stem damage associated with stripper-type headers; how the interaction between roots and soil governs uprooting force; the methods used for uprooting, conveying, row separation and plant singulation; and, finally, threshing and cleaning technology. The same team went on to characterize the friction generated between the cumin taproot and the surrounding soil, applying both mechanical modelling and the discrete element method (DEM); their static friction coefficient of roughly 0.766 was proposed as a useful parameter for engineers designing uprooting-type headers (Tai et al., 2025b). In a parallel effort, Man et al. (2025) built a harvester intended for the cotton-cumin system that, when operated with a 32.6 mm stubble height, a 28 r/min reel speed and a 3.26 km/h forward speed, delivered an 89.54% harvest rate alongside a 7.33% damage rate.

Regarding the mechanics of cutting, Kumar et al. (2024) built a test rig to measure, under dynamic conditions, the force and power needed to sever cumin stalks; their results showed cutting force falling as cutter-bar speed rose, but climbing again as forward speed increased. As for the force needed to release the seed from the stalk, Pathak et al. (2017) reported a mean value of 0.408 ± 0.146 N, data intended to inform a prototype threshing unit. Since the seed's own mechanical strength is likewise essential to machine design, Saiedirad et al. (2008) studied how moisture content, seed size, loading rate and orientation influence the force and energy needed to fracture cumin seed, finding that rupture force fell while rupture energy climbed as moisture content increased. Building on this, the same team later applied artificial

neural networks (ANN) to model these relationships, allowing the seed's mechanical behaviour to be predicted across a range of moisture levels (Saiedirad et al., 2010). For their part, Singh and Goswami (1998; 2000) described both the compressive mechanical response and the thermal characteristics — specific heat, thermal conductivity and thermal diffusivity — of cumin seed as functions of moisture, information regarded as indispensable for designing conveying, aeration, drying, storage and milling machinery.

Turning to sowing, conveyor-belt metering units have emerged as a favoured solution for the precision seeding of small-seeded spices such as cumin, coriander, sage and black cumin. Turkusay and Yazgi (2024) used a conveyor-belt unit — initially built as a micro-granule applicator — to improve the in-row distribution uniformity of sage seed, and the same team later repeated this approach for coriander, modelling how forward speed, seed rate and seed-falling angle shape in-row uniformity (Turkusay and Yazgi, 2025). By 2026 the method had been applied to black cumin (*Nigella sativa*) as well, with mathematical models confirming, under laboratory conditions, that the conveyor-belt unit is a workable option for precision-seeding small spice seeds (Turkusay and Yazgi, 2026). Working along similar lines, Değirmencioğlu and Özdemir (2020) modelled how efficiently a fluted-roller metering unit fills with nine different seed types, coriander among them, while Varol and Değirmencioğlu (2022) assessed coriander-seeding performance with an alternative metering mechanism. Across these studies, a consistent message emerges: because small, irregularly shaped spice seeds behave differently from cereal grain, metering units must be engineered around each seed's own physical characteristics — size, surface texture and flow behaviour.

Turning to operations after harvest, drying stands out as decisive for seed quality, given that excessive heat or an overly long drying period drives off part of the essential oil, cuminaldehyde in particular. Ultrasound-assisted air-drying units built to address this problem can cut drying time, lower energy use by roughly 40%, and help retain the product's colour. At the same time, agronomic research carried out within the Xinjiang intercropping system has demonstrated that the density at which cumin is planted meaningfully alters the soil's moisture and temperature regime and, with it, the overall output of the cotton-cumin system (Zhang et al., 2025). Collectively, these results point to a broader conclusion: mechanizing cumin production cannot be reduced to harvester design alone but must instead be treated as a connected chain

running from seed physics through seeding precision and planting arrangement to post-harvest handling.

The remainder of this chapter first outlines, briefly, the economic and botanical background to cumin farming, before turning to the mechanization systems used at each stage of production — from seedbed preparation through to post-harvest processing — and to the recent developments reported for each, viewed together as an integrated whole.

2. ECONOMIC IMPORTANCE OF CUMIN

Valued chiefly for its distinctive aroma, cumin serves as an ingredient in *sucuk* (a traditional Turkish fermented sausage) and finds further application in pharmaceutical and dye manufacturing. Türkiye ships cumin abroad on a regular basis, with the United States as well as European, Middle Eastern, Arab and Gulf markets among the destinations. India supplies close to 70% of the world's cumin (Lal et al., 2014), and alongside Türkiye, Iran and Syria are counted among the other leading producers.

3. BOTANICAL AND ECOLOGICAL CHARACTERISTICS OF CUMIN

Individual cumin seeds measure 4-5 mm in length, are light brown, and are notably small and light. The plant itself reaches 35-40 cm, branching on slender stems and bearing small leaves somewhat like those of the lentil. Cultivation in Türkiye centres on Central Anatolia — Afyon, Ankara, Eskişehir and Konya foremost among the growing areas — where an early spring sowing date suits the region's hot summers and cold winters.

Winter cold poses little threat to cumin, and the crop adapts to a broad range of soil types, although it performs best on deep, humus-rich, stony ground with sufficient lime. It withstands extended dry spells but fares poorly in exposed, windy sites or on heavy sand or clay. A pH between 7 and 8 is ideal. Where sowing takes place in autumn, favourable growing conditions typically mean 300-400 mm of annual rainfall falling mostly in spring, relative humidity near 60-65%, and average temperatures of 10-15 °C.

Fertilizer should always accompany sowing. Nitrogen matters more to the crop than phosphorus, although both are required. About 10 kg per decare of an 18-46 DAP-type or comparable compound fertilizer is typically applied at sowing, with a further 10-15 kg per decare of nitrogen fertilizer top-dressed after emergence to boost yield.

4. MECHANIZATION APPLICATIONS IN CUMIN PRODUCTION

4.1. Mechanization of Land (Seedbed) Preparation

Across Central Anatolia, cumin is customarily grown after a cereal crop within the rotation. Once the stubble has been cleared, ploughing with a mouldboard plough to 18-20 cm is advised once the autumn rains have fallen. Come early spring (15 February to 15 March), a duckfoot cultivator is used to eliminate weeds emerging early, after which a further pass with a harrow levels the seedbed. Because germination success and the later performance of the drill both hinge on it, the seedbed needs to be fine-textured, well prepared and capable of holding moisture.

4.2. Sowing Mechanization and Precision-Sowing Technologies

Row sowing with a grain drill remains the conventional method for cumin, though broadcasting is still practised on smaller holdings. A common ratio is roughly 10 kg of fertilizer combined with 1 kg of seed per decare, loaded together into the drill's seed box; sowing depth is kept to 2-3 cm at most, since seed placed any deeper generally fails to emerge.

Given how small cumin seed is — roughly 4-6 mm long and 1-2 mm wide — together with its irregular shape and poor flow characteristics, the metering units built into ordinary cereal drills, whether fluted-roller or cell-wheel types, often struggle to dose and distribute it evenly along the row. This has prompted the development, in recent years, of metering units purpose-built for small spice seeds. Değirmencioğlu and Özdemir (2020), for example, modelled the volumetric fill efficiency of a fluted-roller unit across nine seed types, coriander included, and found that each seed type produced its own distinct efficiency response. A related line of research by Turkusay and Yazgi (2024; 2025; 2026) tested a conveyor-belt metering unit — first conceived as a device for applying micro-granular fertilizer or pesticide — for its suitability in precision-sowing sage, coriander and black cumin. Using a Central Composite Design (CCD), these studies related operating variables such as forward speed, seed rate (kg/ha) and the angle at which seed falls to two performance measures, the variation factor (Vf) and the goodness criterion (λ), before fitting polynomial models to pinpoint optimum settings. In the case of black cumin, the optimum was found near a forward speed of 1.67-1.68 m/s, a seed rate of 14.7-20.4 kg/ha and a seed-falling angle of 25.9-31.5° (Turkusay and Yazgi, 2026). Because cumin seed is of comparable size, these results can reasonably guide the precision sowing of cumin and other similarly sized spice seeds.

Mechanization of Crop Maintenance and Weed Control

Roughly 30-40 days pass between sowing and emergence in cumin. Slow early growth and weak competitiveness against weeds make weed pressure a serious agronomic challenge for the crop. Once top-dressing has been applied, growers usually address weeds between 1 and 15 May, either by hand-pulling or through suitable herbicide treatments; applying herbicide once flowering has begun, however, is known to cut yield sharply. Pre-sowing or pre-emergence herbicides aimed at broadleaf weeds, combined with mechanical hoeing, help lessen the need for hand-weeding. Any broomrape (*Orobanche* spp.) that appears should be pulled up and disposed of.

4.3. Harvest Mechanization

Of all the operations in cumin production, harvesting is both the most decisive and the least mechanized. Because the plant is short (20-50 cm), the stem thin and fragile, and the seed prone to shattering, conventional cereal combines cannot be used without modification (Kumar et al., 2024; Tai et al., 2025a). Traditionally, harvesting relies on sickle-type hand tools, and a labourer can hand-pull no more than roughly half to one decare in a working day — a pace that makes harvesting an expensive undertaking in both time and labour.

a) Cutting: Using a rig that reproduced dynamic field conditions, Kumar et al. (2024) measured the force and power needed to cut cumin stalks. Cutting force, they found, declined as cutter-bar speed rose but climbed as forward speed increased, with blade type, cutter-bar speed and forward speed all exerting statistically significant influence. Among the three blades tested, the most efficient used 18-30% less power than its counterparts — figures that feed directly into the design of lighter, lower-power cutting units suited to cumin.

b) Uprooting: Given cumin's shallow taproot, uprooting the whole plant, rather than cutting it, is favoured by some harvesting strategies. Tai et al. (2025b) modelled the friction between the taproot and the surrounding soil during uprooting, combining mechanical analysis with the discrete element method (DEM) and measuring taproot properties such as moisture content (80.91%), Poisson's ratio (0.40), elastic modulus (15.95 MPa), shear modulus (5.70 MPa) and bending strength. They arrived at a static friction coefficient of about 0.766, and their model predicted uprooting force to within 0.4-5% error — figures of clear relevance to the power and geometric design of uprooting-type headers.

c) Building complete harvesters: Motivated by the demand for full mechanization in Xinjiang's cotton-cumin system, Man et al. (2025) designed a harvester built around its header unit, refining the design through orthogonal experiments and multi-objective regression modelling. Field testing, conducted at a 32.6 mm stubble height, 28 r/min reel speed and 3.26 km/h forward speed, produced an 88.2% harvest rate and 5.6% damage rate, figures that departed from the model's predictions by only 1.34% and 1.73%, respectively. Tai et al. (2025a) note in their review that existing cereal harvesters are ill-suited to cumin's fragile build, and that although stripper-type headers appear promising for limiting grain loss and stem damage, cumin-specific adaptation is still needed.

The timing of harvest is equally consequential for successful mechanization. Cumin usually flowers in June and becomes ready for harvest between late June and early July, once its seed colour shifts from green to a dull brown. Kan et al. (2007) tracked the essential-oil composition of cumin fruit gathered at various harvest dates and found that oil yield and composition were both best when seed was harvested at full maturity, after the colour had darkened — a result suggesting that mechanical harvesters should be timed to coincide with such agronomic cues as colour and moisture content, rather than a fixed calendar date.

4.4. Mechanization of Threshing, Cleaning and Post-Harvest Processing

Traditionally, cumin is threshed either by beating the harvested bundles with sticks or by dragging a threshing sledge across them — a slow, physically demanding task. As an alternative, a combine harvester, its beater and fan adjusted accordingly, can be driven over bundles laid out in the field, effectively merging harvesting and threshing into a single pass. Mechanical threshers are also an option where production is large-scale (Lal et al., 2014). In developing a prototype threshing unit, Pathak et al. (2017) measured the force needed to detach seed from stalk at 0.408 ± 0.146 N and found no meaningful link between seed size and this force — findings that support tuning threshing-unit settings such as cylinder speed and concave clearance to keep seed damage to a minimum.

Cleaning after threshing generally relies on air aspiration combined with screening to separate seed from stalk fragments and dust; multipurpose threshing-and-cleaning machines fitted with vibrating screens and fans — suited to spice seeds such as cumin, pepper and fennel — are now within reach of small and medium producers.

Among post-harvest steps, drying carries the greatest weight for seed quality, since heating the seed too much or for too long drives off cuminaldehyde, the compound responsible for cumin's characteristic aroma. Sun-drying, the conventional approach, depends heavily on weather and carries a higher risk of microbial contamination. Controlled mechanical drying — whether by hot air or ultrasound-assisted air drying — has consequently drawn increasing research attention. Ultrasound-assisted systems run at 30-40 °C with moderate sonication power have been found to cut drying time, raise the effective moisture diffusivity, lower energy use by around 40%, and better preserve colour and rupture force in the dried product. In a related development, vacuum-based decontamination techniques aimed at lowering post-harvest microbial load have been shown to boost safety without harming either seed colour or essential-oil composition. Together, these findings argue for optimizing drying, cleaning and decontamination as a single, coordinated stage of cumin processing rather than as separate steps.

4.5. Effect of Seed Physical and Mechanical Properties on Machine Design

The Machine designers rely on both the physical properties of cumin seed — its size, bulk density, true density, porosity and friction angle — and its mechanical properties, including rupture force, deformation behaviour and thermal characteristics, as basic engineering inputs for conveying, harvesting, aeration, drying, storage, milling and cleaning equipment (Saiedirad et al., 2010; Singh and Goswami, 1998). Table 1 draws together the principal values reported for these properties in the literature.

Table 1: Selected physical and mechanical properties of cumin seed reported in the literature

Property	Reported Range	Source
Seed length	~4.6-5.6 mm	Singh and Goswami (2000)
Seed width	~1.2-1.8 mm	Literature review
Specific heat (-70...50 °C, 1.8-20.5% m.c., d.b.)	1330-3090 J/kg·K	Singh and Goswami (2000)
Thermal conductivity (-50...50 °C)	0.046-0.223 W/m·K	Singh and Goswami (2000)
Mean seed-detaching force	0.408 ± 0.146 N	Pathak et al. (2017)
Rupture force (5.7-15% m.c., d.b.)	11.96-58.2 N	Saiedirad et al. (2008)
Static friction coefficient, taproot-soil	≈ 0.766	Tai et al. (2025b)

Source: compiled by the author from Singh and Goswami (2000), Pathak et al. (2017), Saiedirad et al. (2008) and Tai et al. (2025b).

Incorporating such fundamental data into machine design makes it possible to optimize the cutting/uprooting force capacity of harvesting headers, the operating speed of threshing cylinders, and the energy efficiency of drying-aeration systems (Saiedirad et al., 2010).

5. RESULTS AND DISCUSSION

The literature reviewed in this chapter shows that cumin mechanization is advancing along three complementary fronts. First, the accumulation of quantitative data on the physical and mechanical properties of cumin seed and taproot (Singh and Goswami, 1998, 2000; Saiedirad et al., 2008, 2010; Pathak et al., 2017; Tai et al., 2025b) has provided engineers with the basic design parameters — rupture force, detaching force, friction coefficients and thermal properties — that were previously lacking for this crop. Second, precision-sowing research originally developed for related small-seeded spice crops such as sage and coriander has proven directly transferable to cumin and black cumin, indicating that a single family of conveyor-belt or fluted-roller metering units can, with calibration, serve the whole group of small-seeded spice crops (Değirmencioğlu and Özdemir, 2020; Turkusay and Yazgi, 2024, 2025, 2026; Varol and Değirmencioğlu, 2022). Third, and most decisively, dedicated cumin harvesters have moved from concept to field-validated prototypes, particularly within the cotton-cumin intercropping systems of Xinjiang, where harvest rates above 88% and damage rates below 8% have been reported (Man et al., 2025; Tai et al., 2025a).

Nevertheless, the reviewed studies also indicate that cumin mechanization technology remains at an early, largely experimental stage compared with that of cereals and oilseeds, and that most of the harvester-development work to date has been carried out under conditions specific to intercropping systems that differ from the sole-cropped, Mediterranean-climate conditions typical of Central Anatolia. This suggests that direct transfer of existing machinery to Turkish production conditions is unlikely to be straightforward, and that further work is required to adapt header geometry, operating speed and threshing parameters to local soil, climate and cropping-pattern conditions.

6. CONCLUSION

Set against cereal and oilseed crops, cumin cultivation remains only lightly mechanized, a consequence of the plant's fragile build, its uneven ripening and its tendency to shatter. Even so, the developments surveyed in

this chapter make clear that research into seed physics and mechanics, precision-seeding units and harvester design — much of it appearing in SCI-indexed journals — is steadily building the scientific foundation needed for cumin-specific mechanization. Reworking each stage of production, from seedbed preparation through to post-harvest drying and cleaning, on the strength of sound engineering data will do much to cut labour costs, limit harvest losses and safeguard product quality. Given that Türkiye ranks among the world's leading cumin producers and exporters, translating this expanding body of international knowledge into research, development and extension work suited to local conditions carries considerable importance.

- Designing uprooting or cutting headers that minimise shattering losses and suit cumin's small, delicate plant structure;
- Calibrating and extending the use of conveyor-belt or fluted-roller precision-seeding units for cumin;
- Extending the use of energy-efficient, oil-preserving post-harvest drying and cleaning systems, including controlled hot-air and ultrasound-assisted drying;
- Encouraging mechanization policies built around shared machinery access — machinery pools or cooperative arrangements — suited to small and medium-scale farms.

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Blue Bioeconomy and Algae: Fundamentals and Emerging Trends

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ABSTRACT

All organisms are part of the food chain, and organisms die. There are many interactions between organisms and the non-living environment. Algae produce their own food using sunlight, water, and carbon dioxide. This is crucial for humans and the bioecological balance of the entire world. This study focuses on algae, which have the potential to significantly expand their importance and use in the blue bioeconomy in the coming years. The benefits of aquatic environments have been increasing recently. Due to the growing population, it is essential to continue deriving sustainable benefits from aquatic environments. Algae possess valuable metabolites. Because they can be cultivated year-round, produced in areas unsuitable for agriculture, and are the most efficient systems for using water with solar energy, algae are produced biomass for use in many sectors. For the increasing global population and healthy nutrition, it is necessary to utilize algae more in the blue bioeconomy.

Keywords – Algae, Blue Bioeconomy, Hydrobiology, Sustainable Development

INTRODUCTION

Since the mid-twentieth century, the world population has been rapidly increasing. From approximately 2.5 billion in 1950, the population is projected to reach 8.3 billion in 2026. By 2050 year, the world population is expected to exceed 9 billion, resulting in increased demand for energy and natural resources, and consequently, a nearly fourfold increase in the global economy. In this context, rapid population growth, economic development, and rising per capita consumption levels are leading to the depletion of natural resources and the deepening of environmental degradation. Oceans and seas, covering more than two-thirds of the Earth's surface, make significant contributions to poverty reduction as sustainable sources of livelihood. Furthermore, they have become a fundamental element of sustainable development by enabling the development of innovative activities in areas such as food, energy, fisheries, and maritime transport. In this context, the blue economy has emerged as a key component of a new global dialogue about the role of coastal and oceanic waters in sustainable development. Since 2012, many developing countries have adopted the concept of the blue economy as a mechanism for achieving sustainable growth. In recent years, the concept of the blue economy has entered the agenda not only of international organizations such as the United Nations and the World Bank, but also of governments, academia, and the private

sector. Encompassing all economic activities related to seas, oceans, and coasts, the blue economy has become a noteworthy concept recently due to its significant contributions to the global economy, employment, and the potential for generating new technologies (Dereli, 2025). The aim of the blue economy concept is to ensure the sustainable use and management of the scarce resources offered by oceans and all other water resources to the living ecosystem, contributing to environmental health and adding value to economic growth and employment. The rapid increase in the world's population, rising living standards, easy access to resources, and changes in consumption habits are increasingly highlighting the importance of the blue economy. The blue economy approach aims to reduce environmental damage, protect the environment, and approach environmental problems from a different perspective by developing and expanding existing opportunities, and to increase abundance by preventing scarcity in order to ensure the sustainability of the living ecosystem. For the sustainability of life, it is emphasized that the best possible production and consumption system, considering the concept of health, should be produced locally. In the living ecosystem, seas, oceans, and other water resources are extremely important for all living beings. Two-thirds of the Earth's surface belongs to the oceans, and they produce almost half of the world's oxygen. Furthermore, seas and oceans help regulate the Earth's surface temperature and are an important source of food for humans. In parallel, seas and oceans also facilitate various economic activities. The blue economy encompasses all economic activities directly related to oceans and other water resources (Er, 2025).

Freshwater and saltwater environments, which constitute three-quarters of the world, have enabled the formation and development of many sectors. These sectors have different development processes and levels of development for each country. These levels of development are reflected differently in the overall economic structures of countries. At this point, the blue economy plays a leading role not only in environmental sustainability but also in the economic development of a country. The blue economy, in addition to ensuring the ecological balance of marine and ocean resources and the sustainability of the world as a global climate regulator, positively or negatively affects many sectors. These sectors affect main sectors such as tourism, fisheries, and energy, as well as other sub-sectors (Yıldırım, 2022). Due to reasons such as the unconscious use of water resources by humans, unplanned industrialization, and the uncontrolled release of chemical waste into nature, usable water resources are rapidly becoming polluted. The blue

economy is a holistic development approach that promotes growth by emphasizing the efficient use of marine resources in an optimal and effective way without compromising sustainability elements. At the heart of the global blue economy concept lies the principle of ensuring healthy oceans for future generations while simultaneously generating economic growth from the oceans. The blue economy encompasses numerous activities in oceans, seas, and coastal areas, ranging from tourism and fishing to the extraction of marine resources for cosmetics and pharmaceuticals, maritime transport, shipbuilding and marine equipment manufacturing, oil and mineral extraction, pure water production, carbon sequestration, and coastal development (Yılmaz, 2021). This underscores the indispensability of the blue economy.

Bioeconomy is a holistic sustainable development approach that aims to simultaneously support economic growth, environmental protection, and social well-being through the sustainable and circular use of renewable biological resources. The environmental goals of bioeconomy aim to reduce pressure on ecosystems and limit environmental risks in the long term by ensuring the sustainable management of natural resources. In this context, bioeconomy reduces consumption pressure on land, water, and energy resources by promoting the efficient use of renewable biological resources; it significantly reduces carbon intensity by decreasing dependence on fossil fuels. The carbon savings provided by biomass, biogas, and other bio-based products throughout their life cycle are a fundamental component of a sustainable transformation in the fight against climate change. Furthermore, the recovery and reintegration of waste into production processes both increases resource efficiency and provides an environmental management structure compatible with circular economy principles (Rizaei, 2025). Climate change threatens life worldwide. Climate change causes an increase in the temperature of aquatic environments. All organisms are negatively affected by this change. Climate change also affects aquatic environments, biodiversity, habitats, stocks, and sustainability. Excessive algal blooms in aquatic environments should be monitored, and people should be informed about this issue. Carbon capture technologies can mitigate the negative effects of climate change. Algae are the most useful organisms for carbon capture. The capital required for algae is more economical compared to other carbon capture technologies. Algae cultivation is simple and economical. To prevent the negative effects of climate change and leave a livable world for future generations, algae should be utilized and incorporated more

effectively (Dirican, 2026). Algae are versatile organisms in sustainable aquaculture.

Sustainable development is part of the blue economy. Developing the blue economy is a significant opportunity. The blue economy is based on the economic utilization of seas and oceans, as well as the environmental sustainability of seas, oceans, and coasts. Sustainable fisheries and aquaculture are central to the blue economy. Fisheries and aquaculture production are a vital component of coastal and rural economic prosperity globally. However, due to overfishing, illegal fishing, and climate change, the impacts on resources and ecosystems threaten both the sector and fish populations in the seas. Therefore, improving fisheries and aquaculture management is crucial to ensure that future generations continue to benefit from water resources and ecosystem services. Aquaculture is a rapidly growing and food-producing sector. Aquaculture is important for providing balanced and healthy nutrition, supplying raw materials to the industrial sector, creating employment, generating foreign exchange through high export potential, and ensuring the conservation of biodiversity through more efficient management of natural resources. Alternative solutions have been sought to activate sustainable development, and concepts such as the blue economy have emerged (Saygı, 2024). For a sustainable blue economy, sustainable fisheries and aquaculture stand out as priorities, offering employment opportunities and supporting growth through the sustainable expansion of production.

Algae are valued as dietary supplements due to their valuable metabolites, and their pigments, oils, fatty acids, and carbohydrates are also considered immune boosters. Because algae can be cultivated year-round, produced in areas unsuitable for agriculture, and are the most efficient systems for using water and solar energy, their mass production has accelerated in recent years for use as an energy source, fertilizer, feed raw material, and water treatment (Gökpınar et al. 2013). Algae are an important food source, especially in Asian countries. Algae live in oceans, streams, lakes, puddles, and similar environments. Algae are autotrophic, simple-structured, photosynthetic, mostly eukaryotic organisms with a cellulose cell wall. While containing various vitamins, algae are rich in niacin, iodine, potassium, iron, magnesium, and calcium. Some algae species are commercially cultivated and packaged for sale as dietary supplements. Algae have been a part of traditional foods in some countries for many years, and are used in various fields such as animal feed, fertilizer, natural food coloring, food additives, wastewater treatment, and the cosmetics industry.

Numerous algae species are used as a food source by humans in various parts of the world. Algae are consumed in various ways, including fresh, dried, and cooked. Containing most of the nutrients humans need, algae can double or triple their weight in a single day under suitable conditions. Algae are considered environmentally friendly organisms because they are easy to produce and utilize waste materials. The fact that algae are considered suitable for consumption in almost all religions suggests that they may play a significant role in meeting nutritional needs in the future (Alçay et al. 2017). It seems that algae and algae farming will occupy a very large place in the blue bioeconomy in the future. As the benefits obtained from aquatic environments increase every day, sustainable benefits from water must continue to be obtained in response to the growing population and changing consumption habits. In this context, any economic activity involving the use of aquatic bioresources to be evaluated as a product is also defined as “Blue Bioeconomy” (BBR, 2023). Algae occupy an important place among biological resources. Therefore, more focus should be placed on algae, which seem likely to occupy a significant place in the blue bioeconomy in the future. This study examines the blue bioeconomy and algae.

Blue Bioeconomy and Algae

At the heart of the bioeconomy lies biomass-based production, or economic approaches, using biotechnology. The bioeconomy is the sustainable production of biomass and its transformation into food, health products, other industrial goods, and energy. It is a growth model and strategy. The bioeconomy is defined as the production of renewable biological resources and the transformation of these resources and waste into value-added products such as food, feed, biology-based products, and bioenergy. Furthermore, the bioeconomy is a strategic growth model encompassing many sectors. It includes agriculture, forestry, fisheries, aquaculture, food, biotechnology, paper, chemicals, and energy sectors. Within this scope, the bioeconomy is based on life sciences, agricultural sciences, ecology, food sciences, social sciences, biotechnology, nanotechnology, information technologies, and engineering (Şen, 2016). The bioeconomy develops alternative renewable and sustainable solutions to achieve the sustainable development goals. In the bioeconomy, economic gain is achieved by generating added value from biological resources through biological processes such as biotechnology. The utilization of diverse biological resources and advancements in life sciences and biotechnology have been significant steps in the multifaceted progress and

prominence of the bioeconomy concept. The concept of bioeconomy was first used in a study published in 1913 by the British biologist Hermann Reinheimer (Canbulut, 2024). The relationship between bioeconomy and sustainable development is not limited solely to environmental and economic dimensions. Social dimensions such as community inclusion, local participation, access to information, and equitable resource sharing are also fundamental components of this relationship. Particularly in developing countries, the active participation of local communities in bioeconomic processes increases the sustainability and social acceptance of policies. The relationship between sustainability and bioeconomy is critically important for developing countries. This is because, on the one hand, these countries largely rely on natural resources, biomass, and low value-added agricultural production for their economic growth, while on the other hand, they are under pressure for sustainable development due to rapidly increasing populations, urbanization, food security problems, environmental degradation, and the negative effects of climate change. This situation shows that traditional growth models are no longer sufficient, and that bioeconomic transformation tools such as resource efficiency, the use of renewable biological inputs, technology-based value chains, and low-carbon production have become essential (Rizaei, 2025).

The bioeconomy plays a significant role in addressing environmental, social, and economic problems. Furthermore, by promoting entrepreneurship, the bioeconomy plays a crucial role in the rapid dissemination of innovative practices, increasing inter-sectoral competition, and fostering sustainable interaction networks. To achieve the goals of the bioeconomy, sectors such as agriculture, fisheries, aquaculture, food, forestry, biofuels, and bioenergy directly create added value, while sectors such as chemistry, textiles, plastics, pharmaceuticals, biotechnology, and waste disposal and management indirectly benefit. This is because these fundamental sectors are directly related to biodiversity, which directly impacts human well-being and serves as life support systems. Biodiversity provides the raw materials for these sectors, ensuring the continuity of production. Indirect sectors, which include services provided through production from biological resources, rely on biodiversity in production processes and the use of technology in these processes. The bioeconomy is considered a strategic sector that creates added value in both national and international economic systems, and biodiversity is adopted as a guarantee of the sustainability of this sector (Canbulut, 2024). Another dimension of the bioeconomy's environmental goals is the conservation of biodiversity and

the strengthening of ecosystem resilience. Policies such as sustainable agricultural practices, forest management, soil reclamation, the protection of aquatic environments, and the reduction of habitat loss are critical for the continuity of ecosystem services. In this context, the bioeconomy creates long-term environmental benefits such as improving soil health, preserving landscape integrity, and increasing adaptation capacity to climate stress. The bioeconomy offers a comprehensive set of environmental goals that integrate low-carbon production processes, sustainable management of natural resources, and ecosystem protection; thus, it creates a strategic transformation framework that reduces environmental degradation and strengthens ecological resilience (Rizaei, 2025). The blue economy is a comprehensive concept for co-governance. It is an economic model that aims to promote sustainable development by leveraging the economic potential of streams, seas, and oceans. The blue economy aims to raise living standards and protect ecosystem health. Each country's specific economic values and geographical diversity provide it with a wide range of economic opportunities. The role of advanced technology in facilitating this diversity is reflected in the region's economic performance by increasing production and export flexibility. The blue economy encompasses diverse economic activities as a result of various factors such as population growth, urban expansion, and healthcare demands. These activities ensure food security, which is among the basic services for humans and animals. Furthermore, it contributes to supporting new activities such as chemical production, cosmetics, therapeutic products, and fisheries and aquaculture, along with the use of biotechnology (Shalalda, 2026). The blue economy is an economic development model that integrates marine and terrestrial development, emphasizing the use of technology optimization to improve the level of marine resource utilization. Ocean and coastal-based economic activities and their associated growth potential are a significant driving force to support economies worldwide. Blue economy is an integrative concept (Buhan and Yeşilayer, 2022).

Recently, the bioeconomy has increasingly entered the policy agendas of more and more countries, transforming into a strategic development paradigm on a global scale. This process, spearheaded by the European Union, has been adopted by countries in diverse geographies such as the United States, Canada, Brazil, Argentina, Malaysia, South Africa, and China, and institutionalized through national strategy documents. Global pressures such as energy security, combating climate change, increasing efficiency in food and agricultural systems, sustainable resource

management, and transitioning to a low-carbon economy have been decisive in this widespread adoption. The bioeconomy is a development approach that aims at the sustainable production and processing of renewable biological resources to transform them into economic value. This approach is a holistic transformation strategy encompassing economic growth along with environmental sustainability, social welfare, and technological innovation. Furthermore, the bioeconomy offers strategic contributions to development goals such as combating climate change, energy security, food security, and rural development in developing countries. The components of the bioeconomy demonstrate an environmentally friendly and clean production approach (Rizaei, 2025). Particularly important for the fisheries and aquaculture sectors, the bioeconomy is a sustainable system.

Water resources are shaped by a dynamic known as the hydrobiological cycle. This dynamic affects aquatic environments and groundwater. Surface water is also a fundamental element in the global water cycle. Water resources are also part of the natural wealth of countries. Although not classified as seas, they encompass other water bodies such as streams, lakes, oceans, groundwater, and irrigation waterways. Furthermore, water resources support various economic activities such as tourism, industry, and agriculture. Compared to other transportation methods, water resources offer many economic and social benefits as an environmentally friendly means of transport. Streams are considered a link between oceans and land. Water evaporating from the earth's surface falls directly back onto oceans, seas, lakes, and streams as precipitation. Water evaporating from the earth's surface seeps through soil and other surfaces, mixing with groundwater and forming springs, eventually reaching lakes, seas, and oceans via streams. Therefore, streams are a crucial link in the hydrobiological cycle. The hydrobiological cycle is a complex process. Various types of pollution are inevitable at each stage of the hydrobiological cycle. Therefore, the composition of all natural waters is different. The hydrobiological cycle functions like a perfect purification plant, converting salty and polluted water into fresh water. Due to human activities, streams carry approximately 85 percent of the world's pollutants to the oceans. Renewable energy is the process of reducing carbon emissions from water resources, relying on energy known as marine electricity, which benefits from carbon neutrality by reducing fossil fuel consumption. The abundance of water resources depends on rainfall and the use of water management methods. Efforts to gain control over water resources due to pressures in climatic, social, and economic conditions can lead to political conflicts.

Lakes are also considered a rich environment in terms of nutrients. Lakes are factors that strongly influence stream flow and water quality. During floods or hydraulic changes in water resources, they carry sediments and nutrients, making lakes the final recipients of these sediments (Shalalda, 2026). Aquatic environments are one of the most important elements both nationally and internationally. They play a crucial role in protecting the physicochemical properties, biodiversity, natural structure, and social and economic resources of aquatic environments through the application of legal and administrative regulations. In the sustainable development approach, minimizing damage to nature and the environment and ensuring the sustainability of environmental factors are the main objectives (Aydin, 2021). To contribute to national economies, aquatic environments can be used for various purposes, while maintaining a balance between conservation and utilization. Holistic management and monitoring through bioecological planning are crucial for maintaining the sustainability of aquatic environments.

Blue bioeconomy is a sub-discipline that aims to create economic value through the sustainable use of biological resources obtained from marine and aquatic ecosystems. This field encompasses sectors such as fisheries, aquaculture, algal-based biotechnology, marine biomaterials, and marine-derived biochemicals. Marine ecosystems, particularly microalgae and seaweed, offer high biomass yields and can be used in the production of products such as biofuels, bioplastics, and fertilizers. This reduces pressure on land-based agriculture and energy sources. Blue bioeconomy stands out as a sustainable growth model that combines both economic development and ecological conservation goals. However, there are some structural obstacles to the development of the blue bioeconomy. Firstly, regulatory frameworks regarding the use of marine resources are not yet fully established. Furthermore, a strong research and development infrastructure, international collaborations, and funding mechanisms are necessary for the advancement of this field. The protection of marine ecosystems and the sustainable management of biodiversity are critical to the long-term success of the blue bioeconomy. Therefore, integrated policies that balance environmental, economic, and social dimensions will determine the future sustainability of the blue bioeconomy (Rizaei, 2025). Biofuels, biotechnology, ecological agriculture, food, pharmaceuticals and chemicals, ecomanagement, sustainable movements, and ecosystem protection are components of the bioeconomy. The biology with based economy adopts an interdisciplinary approach that combines biotechnology and the economy on

a science-society-industry axis, offering rational and practical alternative solutions to the sustainability problem that cannot be achieved due to the rapidly increasing population growth in the world. Furthermore, it is important in many areas such as agriculture, the food industry, the pharmaceutical industry, the cosmetics and textile industries, the design of indoor and outdoor gardens, environmental architecture, bioenergy, and landscape design, and is increasingly seen as valuable in sectors based on the optimum and new uses of biological resources. The sectors of the bioeconomy are defined as all sectors that enable the transformation of biomass. The agricultural sector, forestry, fisheries, aquaculture, food, biotechnology, and nanotechnology are included in this definition. Fisheries and aquaculture, with all their sub-sectors, are included within the blue bioeconomy (Canbulut, 2024). The products produced are effectively used in sectors such as food, pharmaceuticals, medicine, and energy. In this way, both the damage to the environment will be reduced and the financial returns of the sectors will increase. The blue bioeconomy, in particular, is of great importance both for our future and for sustainability.

Due to factors such as excessive population growth, industrialization, urbanization, economic activities, and technological advancements causing a number of environmental problems, the world has been seeking solutions, especially since the 1970s. In this context, sustainable development, which encompasses addressing economic, social, and environmental issues together, has become a prominent topic on the global agenda. Sustainable development emphasizes the need to consider the economic, social, and environmental dimensions together and is based on the understanding that the needs of the present should be met without compromising the ability of future generations to meet their own needs. Prioritizing the protection of water resources is crucial. Ignoring the environment while achieving economic growth and development can lead to disasters in the long run. Growth and development policies that disregard the environment will lead to further environmental degradation, and this environmental degradation will not only hinder the development of countries but also threaten the health and future of humans and all living beings. Indeed, any damage inflicted on seas, oceans, and other water resources, which are of great importance for the survival of living beings, also harms humans and all other living creatures. Therefore, appropriate and coordinated strategies and policies should be developed to leave a sustainable life for both present and future generations (Suluk, 2022). Pollution, habitat destruction, and climate change are significant threats to aquatic environments. Strengthening environmental

protection measures and promoting sustainable practices are vital to address these threats. There is significant economic growth potential in marine sectors, including fisheries, aquaculture, tourism, and renewable energy. Strategic investments and policy reforms can unlock this potential (Okşak, 2024). Damage to nature is not the only problem the world faces. The world's population, which is increasing at an accelerating rate every year, is causing food shortages. At this point, algae and their cultivation, which are high-value foods, are gaining importance (Yıldırım, 2022). Information and experience sharing should be carried out regarding the monitoring, collection, cleaning, cultivation, pollution reduction, and economic evaluation and development of algae. The development of sustainable algae management and the support of the blue bioeconomy worldwide are necessary.

Algae are organisms with a highly diverse appearance, both structurally and externally. The vast majority of algae live in aquatic environments. Algae are the major primary producers of organic carbon compounds in aquatic environments. Thanks to the pigments in their structure, algae convert carbon dioxide and water into carbohydrates under the influence of light. Thus, algae increase the nutritional value and dissolved oxygen levels in the aquatic environment. Algal production is limited by environmental factors, namely light, temperature, and nutrients. If these limiting factors are improved, the production level increases. However, exceeding a certain level of production naturally disrupts the environmental balance. Advanced treatment technologies that reduce nutrient concentrations and remove nitrogen and phosphorus, suitable for the conditions of aquatic environments, should be established. The natural water balance of aquatic environments must be protected, and even treated water should not be discharged into aquatic environments. Interventions in the natural cycle and balance of aquatic environments should be avoided. Nevertheless, algae form the first link in the food chain by ensuring their own development. Algae are important in terms of their contribution to production and their relationships with higher-level organisms. In addition, algae are used in the feeding of live feeds used in fish larva rearing. Algae form the basis of aquaculture production (Eryalçın, 2011). Algae play an important role in maintaining the balance of nitrogen, phosphorus, organic and inorganic compounds in the water. Algae are not only used in fish larva rearing; they are also used in sectors such as human food, medicine, and cosmetics. The goal of high-volume algae cultivation is to develop products of the desired quality with low capital investment. Optimal growth in algal

species occurs when suitable conditions are created in the cultivation systems. Many algal species have their own suitable growth and development conditions (Kargin, 2020). Algae cultivated for bioeconomic purposes are frequently used in the aquaculture, food, medicine, pharmaceutical, and cosmetic sectors.

In recent years, more and more studies have been conducted on identifying new algal species for production. Algae play important bioeconomic roles in aquatic environments. Many algal species, especially green algae, contain more protein than higher plants. In addition, algae contain important nutrients for human nutrition and for the nutrition of aquaculture organisms. Algae are used in the nutrition of terrestrial and aquatic organisms, as well as in improving water quality (Duru and Yilmaz, 2013). Algae are an important food source for the future. The biochemical structure of algae varies among species. Feed constitutes more than half of the cultivation capital. For this reason, the use of algae has been increasing in recent years as an alternative to high-capital and unsustainable feeds. Algae are important in the cultivation of animal organisms (Yenmiş, 2019).

Aquaculture is a key global food production system. Sustainable management of aquaculture resources is central to achieving development that protects food security, livelihoods, human dignity, and natural resources (Buhan and Yeşilayer, 2022). Micro and macro algae cultivation systems are being developed worldwide. While algae have already found significant use in cosmetics and feed technologies, they are also crucial in mitigating the effects of climate change and removing excess carbon dioxide from the atmosphere and water. Algae cultivation and harvesting are currently still small-scale. Globally, 36 percent of algal sector database entries originate from Europe. Despite this, the algae sector is largely comprised of newly established companies that are not yet operational. Regulatory environments for licenses and permits required for algae cultivation are not coordinated. Numerous regulatory factors exist at the national level. Costs are high for small-scale companies wishing to engage in algae cultivation. The use of information technology enables automated, high-precision monitoring. Monitoring should become standard practice for managing large-scale microalgal and macroalgal facilities. Algal ecosystems play a vital role in the carbon cycle. Algae act as carbon dioxide sequestrates worldwide. Significant natural marine algal ecosystems exist in the coastal waters of the European Union. However, this represents less than 25 per thousand of global human-caused marine algal production. Actions to integrate algae into climate policies have potential positive impacts on both the climate and the

environment. Such actions include conservation, restoration, and production. To ensure the European Union can best utilize the potential of marine algae to mitigate the effects of climate change, knowledge gaps need to be addressed. Existing natural algae ecosystems and their carbon footprints in Europe should be assessed. In addition to its small scale, the European marine algal sector is regionally unbalanced. The increasing demand for marine algal products cannot be met by producers due to various factors. These reasons discourage risk-averse investors and businesses from cultivating sea algae. The challenges facing the European sea algae sector are not biotechnology-focused, but rather related to management and market issues (BBR, 2023). Algae, while varying among species, are a highly valuable natural resource due to their rich content of various proteins, fats, antioxidants, vitamins, and minerals. Algae offer significant bioeconomic potential for sectors such as aquaculture, agriculture, food, pharmaceuticals, medicine, and cosmetics. The use of algae, which live in freshwater and saltwater environments, to provide raw materials to aquaculture, agriculture, food, pharmaceutical, medical, and cosmetic companies has been increasing in recent years. Such activities contribute to the bioeconomic development of countries internationally. Many researchers working in this field, defined as algal bioeconomy, are focusing on developing climate-friendly and circular products and biotechnologies for the aquaculture, agriculture, food, pharmaceutical, medical, and cosmetic sectors. Algae offer a multifaceted potential for these human-centered sectors. Algal bioeconomy is a highly suitable and open field for development. Currently, production is carried out using algae-based aquaponic technologies in cultivation systems. In addition, production is also carried out using algal fermentation biotechnologies. Algal fermentation biotechnologies are sustainable processes in which algae are processed in controlled systems with the help of microorganisms or nutrient solutions and transformed into high value-added components. Algae are grown in closed fermentation vessels or advanced bioreactors. Thanks to this controlled system, the algal cell wall is broken down and bioactive substances are released. Biological fertilizers, food, and colouring agents are produced from algae. Algae are of great importance for both the present and the future. National and international investments and incentives are crucial in the field of algal bioeconomy. Therefore, the more the algal bioeconomy is integrated into government policies, incentives, and investments, the more effective and long-term results can be achieved. Aquaculture is a sustainable sector in the blue bioeconomy. Oceans, streams, and lakes are vital for humans by providing bioecological balance in terms of food. As the world

population increases, the demand for food, and especially aquatic organisms, is also increasing. Aquaculture is a sustainable and strategic approach gaining global attention. The blue bioeconomy enables the sustainable use of aquatic environments to improve employment opportunities and protect the environment. In algal bioeconomy, the key is to balance economic benefits with the conservation and use of aquatic environments. Impacts such as climate change, water pollution, and overfishing are alarmingly prevalent in aquatic environments. Traditional practices are no longer sustainable. Therefore, algal bioeconomy has recently come to the forefront. Algal bioeconomy is based on bioecological principles, avoiding harmful chemicals and synthetic inputs. Instead, it focuses on organism health, water quality, biodiversity, and safe, environmentally friendly production. In recent years, healthier, safer, and more environmentally friendly products have been preferred. Globally, algal bioeconomy is still a developing sector with rapid growth potential. The key in algal bioeconomy is the adoption of holistic blue economy practices that benefit both the environment and people. Algae and the blue bioeconomy are helping to open doors to high-end markets by ensuring quality and traceability. In the field of algae and the blue bioeconomy, a path towards sustainable aquaculture should be pursued through research-based algae cultivation that leads to innovation. Such developments indicate that algae and the blue bioeconomy can become more viable and productive on a global scale. With the right investments and incentives, algae can become a pioneer in the blue bioeconomy, leading to a healthier, more balanced, and more sustainable economy.

CONCLUSION

With an increasing population, more products must be obtained from a unit area for healthy and balanced nutrition. The blue bioeconomy accelerates growth and product diversification produced by the community for production. The blue bioeconomy is an important foundation of economic sustainable development innovation. The blue bioeconomy is one of the most critical factors of environmental sustainability and development, as well as an important part of economic growth, social welfare, and strategic competitiveness. Algae are an important biological resource in this regard. In this context, growth and development in organisms are increased, while the occurrence of diseases is reduced. Healthier and more profitable products can be obtained with algae. It is necessary to benefit more from the

multifaceted structures of algae. This will make significant contributions to the blue bioeconomy.

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An Open-Source QGIS Plugin for Thiessen (Voronoi) Polygon-Based Areal Weighting of Irrigation Station Data

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ABSTRACT

Transforming localised hydro-meteorological data, such as precipitation levels or irrigation demands documented at dispersed locations, into a representative area-wide metric is a standard yet significant procedure in irrigation strategy and water-balance assessment. The Thiessen polygon method, which divides a research region into cells centred around stations by Voronoi (Dirichlet) tessellation, is among the traditional techniques for this conversion and is favoured for its geometric simplicity and little data needs. While QGIS offers an inherent Processing algorithm for creating Voronoi polygons, there is no readily available tool that integrates this algorithm with the workflow necessary for irrigation and hydrology professionals: trimming the diagram to a genuine service-area boundary, ensuring complete coverage of that boundary, and directly reporting the resultant area-weighted statistics. This section introduces the Thiessen Irrigation Weighting, a complimentary and open-source (GPLv2+) PyQGIS plugin designed to address this deficiency. It constructs Thiessen polygons from a station-point layer and rectifies two sources of silent errors identified during development: a boundary-coverage constraint that limits the diagram to the stations' bounding rectangle, and a default ellipsoid selection that may exaggerate reported areas by several percentage points at mid-latitudes. The plugin has surpassed 120 downloads since its debut on the official QGIS Plugin Repository in August 2026. An illustrative case derived from authentic, publicly accessible data for eleven district-centre stations in Tekirdağ Province, Türkiye, utilising NASA POWER precipitation climatology and the province's official boundaries, demonstrates the refined workflow, confirms its precision, and contextualises the approach within various areal-averaging methodologies.

Keywords – Thiessen polygon method; Voronoi diagram; QGIS plugin; PyQGIS; areal-weighted average; open-source GIS; irrigation water management

INTRODUCTION

Areal Representation of Point-Based Station Data

Precipitation, irrigation water needs, and outflow are typically quantified at a limited number of specific sites; nevertheless, numerous engineering and management issues, including reservoir management, irrigation planning, and flood prediction, necessitate a broader, basin- or district-level assessment. The most straightforward method, the arithmetic mean of all station values, overlooks the irregular spatial arrangement of gauges and may exhibit significant bias when stations are concentrated or the landscape is varied. Areal-weighting techniques rectify this by designating a zone of impact for each station and adjusting its reported value according to the proportion of the entire area that this zone encompasses.

The area of effect can be defined by various approaches, from simple geometric designs to statistically based interpolation surfaces, with the selection of technique contingent upon station density, data accessibility, and the precision needed for the decision being made. This requirement extends beyond the strict definition of hydrology: contemporary analyses of precision irrigation management highlight the transformation of limited point data into spatially continuous, actionable layers as a persistent obstacle in the operational GIS and remote-sensing processes for irrigation scheduling and water-use planning (Şener, 2018; Bwambale et al., 2022). This section subsequently examines the geometric technique utilised in the plugin introduced herein, the software environment in which it was created, and the particular deficiency that inspired its creation.

The Thiessen (Voronoi) Polygon Method

The geometric foundation of areal weighting is the Voronoi, or Dirichlet, tessellation, where a plane with a collection of points is divided into convex cells, ensuring that each point within a cell is nearer to its generating point than to any other (Dirichlet, 1850; Voronoi, 1908). Thiessen (1911) was the pioneer in implementing this methodology for meteorological networks, utilising the perpendicular bisectors of the segments connecting adjacent rain gauges to define the area of influence for each gauge; the mean areal value is subsequently calculated as the aggregate of each gauge's measurement weighted by the fractional area of its zone. The Thiessen method is appealing for irrigation districts and medium-sized watersheds due to its reliance solely on station coordinates, particularly in areas with sparse station density and a lack of supplementary data required by geostatistical techniques.

Comparative analyses indicate that superior methodologies, notably inverse-distance weighting and kriging, can exceed the performance of Thiessen polygons when a dense network and a recognised spatial correlation framework are present (Tabios and Salas, 1985), and enhancements like the percentage-weighting polygon technique, which allows zone boundaries to adjust according to the recorded values rather than being static, have been suggested and effectively evaluated for Turkish watersheds (Şen, 1998; Bayraktar et al., 2005). This discourse persists: a recent assessment of four interpolation techniques, comprising the Thiessen polygon method, inverse-distance weighting, ordinary kriging, and a spline-based approach, in the Chaohe River basin in China revealed that the geometrically simpler Thiessen and inverse-distance methods were surpassed by the more data-demanding options, while still being significantly less expensive to implement when only station coordinates are accessible (Guo et al., 2022). Nonetheless, the traditional, fixed-geometry Thiessen polygon remains a standard areal-weighting technique taught and utilised in irrigation engineering and hydrology, mostly due to its transparent, predictable output that is easily conveyed to laypersons.

QGIS, PyQGIS, and the Case for a Purpose-Built Plugin

QGIS has evolved from a modest hobby initiative launched in 2002 into the most extensively utilised free and open-source desktop Geographic Information System, prevalent in environmental science, agriculture, and public administration (Steiniger and Hunter, 2013; Rosas-Chavoya et al., 2022; Albut, 2024; Graser et al., 2025; Şener, 2025). The Processing framework inherently provides a native Voronoi Polygons algorithm, and its Python API, PyQGIS, facilitates the integration, enhancement, and encapsulation of this and other Processing algorithms within bespoke graphical applications without necessitating a compiled C++ development environment.

This accessibility is pivotal to a broader discourse advocating for free and open-source GIS in water-resource applications: as the software, along with the analytical tools developed upon it, can be examined, modified, and shared without charge, specialised plugins can be made available to practitioners, including irrigation engineers, agronomists, and extension officers, who lack GIS expertise and would otherwise be unable to utilise such decision-support capabilities (Steiniger and Hunter, 2013; Shao et al., 2017). The QGIS Plugin Repository has increasingly established itself as a prominent platform for publishing task-specific tools in recent years; notable instances include THYRSIS, a plugin designed for multi-scale hydrogeological flow and transport modelling (Renard et al., 2024), a collection of QGIS-based routines that facilitate input preparation for Python-driven event hydrological models (Almeida-Nauñay et al., 2025), and IAMAP, a plugin that enables deep-learning image analysis for QGIS users without necessitating programming expertise or specialised computing resources (Tresson et al., 2025). These instances illustrate a recurring trend: the worth of a QGIS plugin frequently resides more in the presentation of a pre-existing, complex workflow through a graphical interface that a subject matter expert can directly utilise.

In application, generating a Thiessen-based areal average for an actual irrigation service area using QGIS's inherent tools necessitates manually linking multiple Processing algorithms, specifically creating the raw Voronoi diagram, trimming it to a boundary, determining cell areas, and computing the weighted statistic in an external spreadsheet; furthermore, as outlined in the Materials and Method section, the default behaviour of the native algorithm may inadvertently yield a geometrically flawed outcome when an external boundary is present.

Aim and Contribution of This Chapter

This chapter details the conception, execution, and validation of Thiessen Irrigation Weighting, an open-source QGIS plugin created to eliminate these laborious processes for users focused on irrigation and hydrology. The particular contributions documented herein are:

- A graphical, single-dialog implementation of the full Thiessen area-weighting workflow inside QGIS;
- The identification and correction of two distinct sources of silent error in a naive PyQGIS implementation: a boundary-coverage limitation in QGIS's native Voronoi algorithm, and an ellipsoid-selection default that can inflate reported areas by tens of percent at mid-latitudes;
- A reproducible worked example built entirely from openly available real-world data, verified against an independently computed reference area; and
- A discussion of the plugin's place among alternative areal-interpolation methods and its early adoption, evidenced by more than 120 downloads from the official QGIS Plugin Repository within the first weeks of availability.

MATERIALS AND METHOD

Software Environment and Distribution

The plugin was created in Python 3 utilising the PyQGIS API and the Qt widget toolkit included with QGIS, aimed for QGIS version 3.16 and subsequent releases. It is distributed under the GNU General Public License, version 2 or subsequent (GPLv2+), aligning with QGIS's licensing, and its source code is preserved in a public GitHub repository. The plugin was presented to and made available on the official QGIS Plugin Repository (plugins.qgis.org) in August 2026, identified by the package name `thiessen_sulama`, and had accumulated over 120 downloads by September 2026 (Table 1).

Table 1: Fundamental technical attributes of the Thiessen Irrigation Weighting plugin

Characteristic	Value
Programming language	Python 3 (PyQGIS API, PyQt widgets)
Minimum QGIS version	3.16 (tested up to QGIS 3.44 “Solid”)
Core algorithm	native:voronoipolygons (QGIS Processing framework)
License	GNU General Public License v2 or later (GPLv2+)
Distribution channel	Official QGIS Plugin Repository (plugins.qgis.org)
Source code repository	GitHub (github.com/selcukalbut/qgis-thiessen-irrigation-weighting)
Downloads since release	More than 120 (as of September 2026)

Plugin Workflow

The plugin reveals a solitary dialogue. The user chooses (a) a point layer that signifies the measurement stations, (b) the numerical attribute to be weighted by area, such as rainfall depth or irrigation water demand, and,

optionally, (c) a polygon layer that outlines the irrigation zone or catchment boundary for clipping the diagram. Figure 1 encapsulates the processing logic activated upon the user's confirmation of the dialogue. The plugin utilises QGIS's inherent Voronoi-polygon algorithm via the Processing application programming interface, optionally truncates the outcome to the provided boundary using the native clipping algorithm, calculates the ellipsoidal area of each resultant cell with QGIS's QgsDistanceArea class, and adds three fields to the output layer: the cell area in hectares, its percentage of the total clipped area, and its weighted contribution to the overall mean.

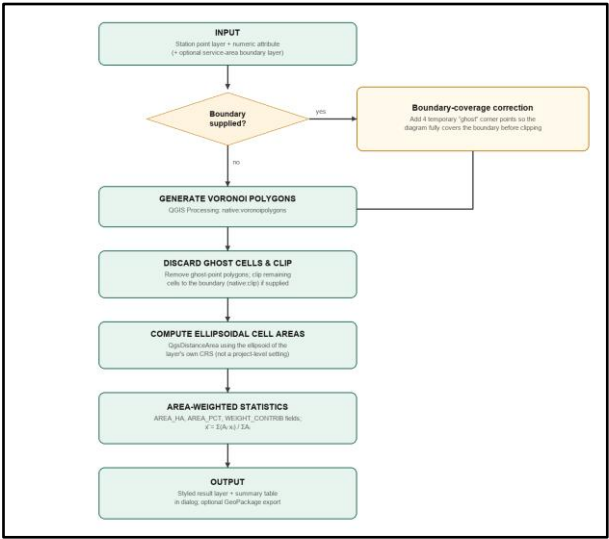


Figure 1: Processing logic of the Thiessen Irrigation Weighting plugin, from the input layers to the area-weighted output

The area-weighted mean is expressed as $\bar{x} = \sum(A_i \cdot x_i) / \sum A_i$, with A_i representing the ellipsoidal area of the i -th Thiessen cell and x_i denoting the recorded value from the corresponding station, aggregated across all n stations.

Correcting a Boundary-Coverage Limitation in the Native Voronoi Algorithm

Throughout the development and testing phases, a significant constraint of QGIS's inherent Voronoi-polygon algorithm was recognised: the algorithm generates the diagram solely within the bounding rectangle of the input points, augmented by a user-defined buffer percentage; it fails to automatically extend the diagram to encompass an externally provided boundary layer. When the buffer remains at its default setting and the boundary polygon exceeds the dimensions of the stations' bounding rectangle, which is typically the case as station networks seldom extend to the periphery of their designated area, the

ensuing clipping process does not influence any area beyond the stations' bounding rectangle, resulting in the reported area-weighted average and total area reflecting merely a portion of the actual service area. This conduct is not identified as an error by QGIS and generates no alert, hence it may easily escape the attention of a non-expert user.

To rectify this, the plugin enhances the station-point layer by incorporating four temporary "ghost" points positioned at the corners of a rectangle that adequately encompasses both the stations and the provided boundary prior to invoking the Voronoi algorithm. This compels the foundational diagram's limits to entirely encompass the actual boundary. The ghost points are marked with a concealed Boolean attribute, and the polygons created around them are eliminated just after the Voronoi diagram is constructed and prior to the clipping and area-weighting phases, ensuring they do not manifest in or affect the final outcome. The rectification was validated by juxtaposing the total clipped area indicated by the plugin with the independently calculated ellipsoidal area of the boundary polygon, conducted outside the plugin's code; in the Tekirdağ Province example detailed in the Results and Discussion section, the two figures aligned within rounding accuracy (6,993.92 km² versus an independently derived 6,993.89 km²), affirming that post-correction, the clipped Thiessen diagram accurately reflects the authentic service-area boundary rather than a random sub-rectangle.

Correcting an Ellipsoid-Selection Default That Silently Inflates Reported Areas

An additional, autonomous source of mistake was identified during the preparation of the independent reference area utilised to validate the aforementioned adjustment. The `QgsDistanceArea` class in QGIS is capable of calculating area using either a reference ellipsoid or, in the absence of one, resorting to a planar computation based on the layer's coordinate reference system; the initial implementation of the plugin requested the ellipsoid set in the active QGIS project (`QgsProject.ellipsoid()`). In a project where the coordinate-reference-system settings have remained unaltered by the user, reflecting the default condition of a newly established project, this invocation yields the exact string "NONE" instead of an ellipsoid identifier, so discreetly deactivating ellipsoidal measurement. The geographic coordinates generated a planar region that, lacking the cosine-of-latitude adjustment for east-west distances, exaggerated the actual ellipsoidal area by approximately one third at the 41°N latitude of the Tekirdağ example, with the magnitude of the error increasing at higher latitudes and diminishing to zero at the Equator. Due to the plugin's output and the initial "independent" verification both relying on the same fallback, the issue remained undetected until the verification was repeated using a clearly defined ellipsoid, independent of any project configuration.

The solution implemented across the findings presented in this chapter is to revert to the ellipsoid indicated by the data layer's coordinate reference system, utilising `QgsCoordinateReferenceSystem.ellipsoidAcronym()`, in instances where the project ellipsoid is not defined, instead of passively adopting a planar approximation. Area-weighted means calculated as a function of areas exhibit minimal sensitivity to this bias, as they uniformly scale each cell by a comparable factor at a specific latitude, thus neutralising the ratio; conversely, absolute area and hectare measurements are directly influenced and were erroneous in earlier iterations of the plugin prior to this amendment. This discovery emphasises a more general principle for PyQGIS plugin development: area and distance computations ought not to depend on a project-level UI configuration that the majority of users seldom adjust, but rather be firmly based on the data's inherent coordinate reference system.

RESULTS AND DISCUSSION

Worked Example

The plugin was showcased and validated utilising exclusively authentic, publicly accessible data for Tekirdağ Province in north-western Türkiye, ensuring that the example is repeatable independently rather than merely illustrative. Eleven station locations were established at the actual geographic coordinates of the province's district centers: Tekirdağ, Çorlu, Çerkezköy, Malkara, Muratlı, Şarköy, Hayrabolu, Kapaklı, Saray, Ergene, and Marmara Ereğlisi, sourced from OpenStreetMap. Each location was assigned the long-term average annual precipitation corresponding to its coordinates, obtained from the publicly accessible NASA POWER climatology API (the identical data source utilised by the author's accompanying ETo-calculator web application), by multiplying the stated annual mean daily precipitation rate by 365.25. The boundaries of the irrigation area corresponded to the official provincial boundary of Tekirdağ, derived from the Natural Earth public-domain administrative boundary information (Figure 2).

Executing the plugin with the station layer, the annual-precipitation attribute, and the provincial boundary yielded the dialogue output illustrated in Figure 3 and the clipped, choropleth-shaded Thiessen diagram depicted in Figure 4. The area-weighted mean annual precipitation was 606.35 mm, in contrast to an unweighted arithmetic mean of 616.61 mm across the same eleven locations (Table 2); the total clipped area of 6,993.92 km² corresponded closely with an independently calculated ellipsoidal area for the identical boundary polygon, differing by only 0.03 km² (refer to Materials and Method), and is approximately 10-13% of the province's officially reported land area of about 6,190-6,339 km², which is a predictable outcome of the broader, globally consistent generalisation employed by the Natural Earth boundary instead of a comprehensive cadastral survey. The disparity between the

weighted and unweighted means further demonstrates the significance of area-weighting in application: the two southernmost district centers, Hayrabolu and Malkara, encompass over a third of the province's reduced area yet reported some of the lowest precipitation figures in the dataset, thus a straightforward station average, oblivious to this discrepancy, exaggerates the overall provincial mean.

Table 2: Area-weighted annual precipitation results for the eleven real district centres of Tekirdağ Province

District centre	Annual precip. (mm)	Polygon area (ha)	Area share (%)
Hayrabolu	591.7	141,663.64	20.26
Malkara	591.7	124,922.76	17.86
Muratlı	599.0	74,698.71	10.68
Tekirdağ (centre)	599.0	68,819.00	9.84
Şarköy	588.1	66,668.93	9.53
Çerkezköy	661.1	51,222.03	7.32
Ergene	599.0	50,936.90	7.28
Çorlu	599.0	34,224.87	4.89
Saray	661.1	33,825.41	4.84
Kapaklı	661.1	27,760.14	3.97
Marmara Ereğlisi	631.9	24,649.58	3.52
Total / Weighted mean	606.35	699,391.98	100.00

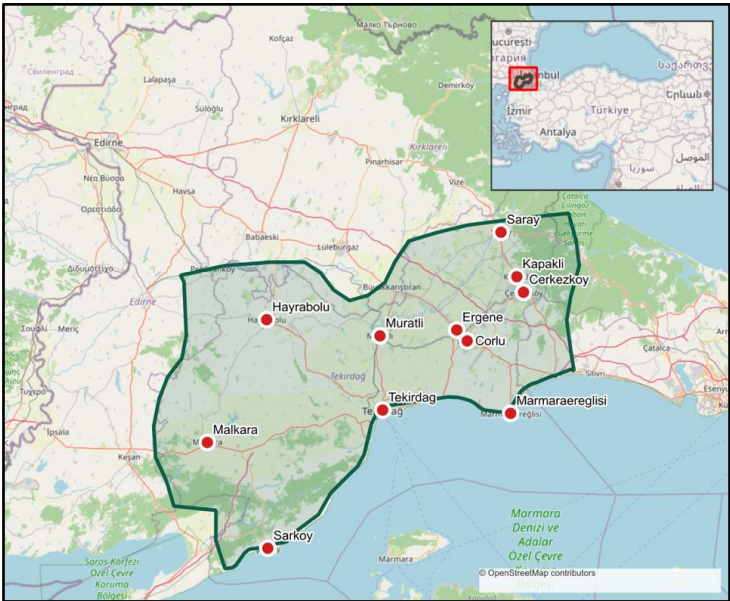


Figure 2: Study area, the real administrative boundary of Tekirdağ Province with its eleven real district-centre station points

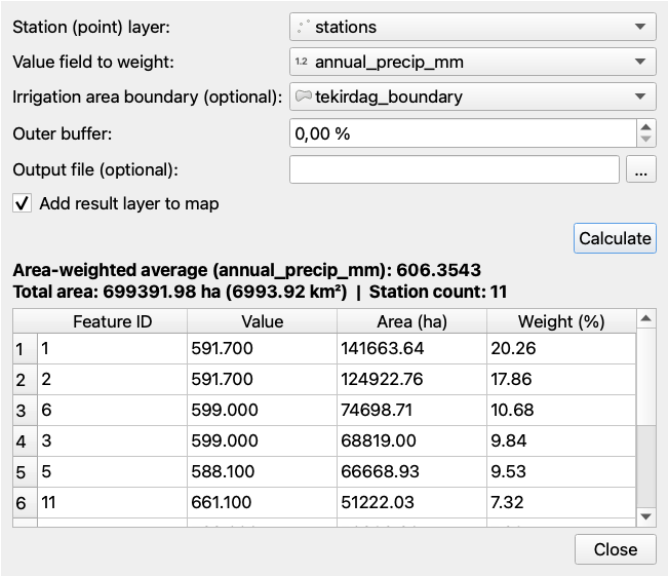


Figure 3: Graphical user interface of the Thiessen Irrigation Weighting plugin after running the area-weighting calculation on the real Tekirdağ Province dataset

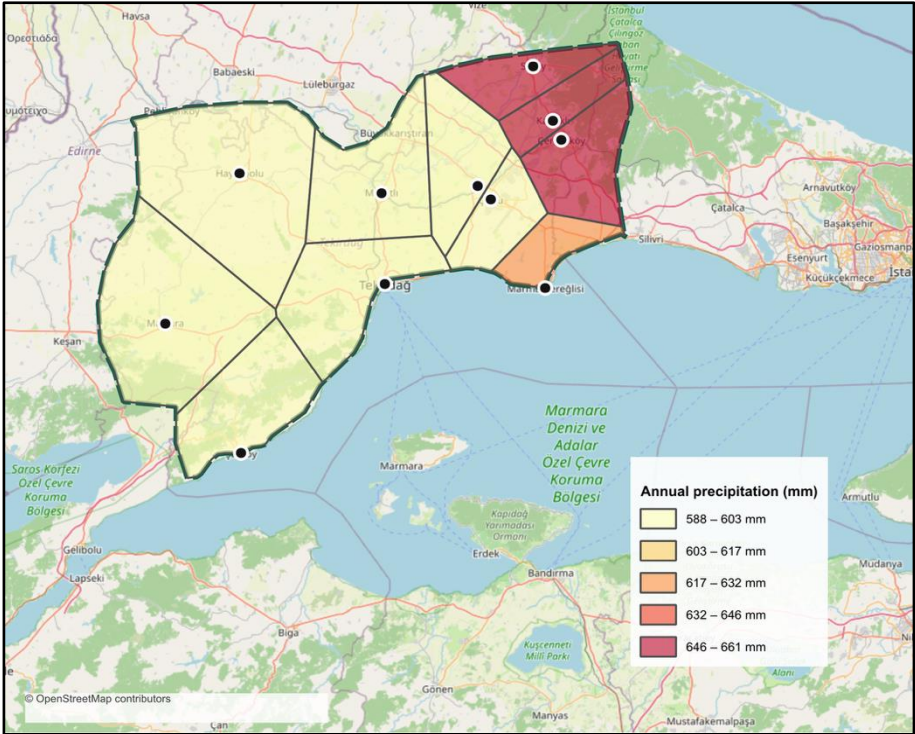


Figure 4: Thiessen (Voronoi) polygons for Tekirdağ Province, clipped exactly to the real provincial boundary and shaded by area-weighted-average annual precipitation (darker shading indicates higher precipitation)

Relation to Alternative Areal-Weighting Methods

The Thiessen polygon approach utilised in this context is exclusively geometric: it considers the spatial arrangement of stations without factoring in any physical phenomena, such as orographic precipitation augmentation, wind exposure, or irrigation system layout, which could cause the actual area of influence to differ from the perpendicular bisector design. In scenarios with a robust station network and a recognised spatial correlation framework, geostatistical techniques like ordinary kriging have demonstrated superiority over Thiessen polygons and inverse-distance weighting (Tabios and Salas, 1985); conversely, when the correlation structure is ambiguous or the network is limited, the Thiessen method serves as a justifiable standard.

An additional enhancement, the percentage-weighting polygon technique (Şen, 1998), allows for the adjustment of sub-area boundaries based on the comparative intensity of adjacent stations' measurements instead of relying solely on geometric principles, resulting in reduced discrepancies from actual catchment averages compared to the traditional Thiessen method when evaluated across ten stations in Southeastern Anatolia, Türkiye (Bayraktar et al., 2005). Enhancing the current plugin to include a percentage-weighting option as an alternative to the traditional model is a logical progression for future advancements, in addition to facilitating isohyetal interpolation and the simultaneous processing of various attributes or time intervals.

Adoption and Practical Implications

The plugin is available free of charge via the official QGIS Plugin Repository under a GPLv2+ license, thereby diminishing the technical obstacles that might hinder an irrigation engineer or agricultural extension officer from executing a precise, ellipsoidally accurate areal-weighting calculation, aligning with the overarching argument for free and open-source GIS as a means to equalise analytical capabilities in resource-limited environments (Steiniger and Hunter, 2013; Shao et al., 2017). In approximately one month post-release, the plugin garnered over 120 downloads, a modest yet promising initial sign of interest for a specialised, GUI-based Thiessen tool in the QGIS environment.

Due to the generic nature of the underlying workflow, station points, an optional service-area boundary, and a singular numeric attribute, the same plugin can be utilised for any point-sampled variable requiring area-weighted mean reporting, such as net irrigation water demand, groundwater-level networks, or soil-sample characteristics, and it can be integrated with reference-evapotranspiration methodologies like the FAO-56 Penman-Monteith approach (Allen et al., 1998) when the areal input consists of a station-based climatic variable used in irrigation-scheduling computations.

Conclusion

This chapter has introduced the Thiessen Irrigation Weighting, a complimentary and open-source PyQGIS plugin that consolidates the

traditional Thiessen (Voronoi) areal-weighting technique, along with adjustments for boundary-coverage constraints and a default ellipsoid selection in a rudimentary PyQGIS application, into a cohesive graphical workflow designed for irrigation engineers, hydrologists, and GIS professionals who may not be experts in GIS. A practical illustration constructed solely using authentic, publicly accessible data for Tekirdağ Province validated that the revised procedure accurately replicates the genuine service-area boundary and yields an area-weighted mean that significantly diverges from a mere arithmetic average. Surpassing 120 downloads from the official QGIS Plugin Repository shortly after its launch, the plugin serves as a modest yet tangible enhancement to the accessibility and reliable application of a century-old hydrological method, which remains prevalent in education, within the contemporary open-source GIS framework; forthcoming developments will broaden its scope to include various weighting schemes and supplementary output formats.

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