BİDGE Yayınları

Tarımsal Yapılar ve Sulamada Güncel Çalışmalar

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İçindekiler

BÖLÜM I

Golf Sahası Sulaması

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1. GİRİŞ

Golf günümüzde Avrupa'nın birçok ülkesinde profesyonel düzeyde oynanmaktadır. Avrupa Golf Federasyonunun verilerine göre en fazla saha (1815) ve lisanslı oyuncunun (651571) İngiltere'de olduğu görülmektedir. İkinci sırada, 727 golf sahası ve 640181 lisanslı oyuncu ile Almanya yer almaktadır. Bu ülkeleri Fransa, İskoçya, İsveç, İspanya, İrlanda ve İtalya takip etmektedir.

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Avrupa’daki 17 ülkenin toplam golf sahası sayısı 6000’nin üzerinde yer almaktadır (Salman, 2017; Anonim, 1).

Golf oyununun tanımına, tarihine ve Türkiye’deki durumuna kısaca değinilecek olursa; golf bir sopa yardımıyla belirli uzaklıkla bulunan deliğe topu en az atışla sokabilme oyunudur. Golf oyununun tarihsel süreci incelendiğinde, ilk olarak nerede oynanmaya başladığı konusunda farklı görüşler vardır. Bir görüşe göre 1368 ve 1644 yılları arasında Çin’de Ming Hanedanlığı döneminde değnek sopa ile vurularak oynanan Chuwan oyunu, golfun ilk başlangıcı olarak kabul edilmektedir. Oyunun Orta Çağda tüccarlar tarafından Avrupa’ya yayıldığı düşünülmektedir. Diğer bir görüşe göre de golf oyunu, Romalılar döneminde Sezar hükümdarlığı zamanında oynandığı düşünülmektedir (Salman, 2017). Bazı kaynaklar ise golf oyununun 1500’lü yıllarda İskoçya’da oynanmaya başlandığını göstermektedir (Karaböcek, 2022). Buradan da görüldüğü üzere golf oyununun ilk olarak nerede oynandığıyla ilgili net bir fikir birliği yoktur.

Golf oyunun ilk turnuvası 1552’de İskoçya’nın St. Andrews kentinde gerçekleşmiştir. İlk kuralları ise 1744 yılında Edinburgh turnuvaları için belirlenmiştir. Daha sonra bu kurallar 100 sene boyunca 30’dan fazla kulüp tarafından kabul edilmiştir. 1880’lerde sporda yönetim organları oluşturulmuştur. 1899’da ise Amerika Birleşik Devletleri Golf Birliği kurulmuştur (Alyssa, 2020; Karaböcek, 2022).

Türkiye’de ise ilk golf kulübü Constantinople Golf Clup, bugünkü adıyla İstanbul Golf Kulübü olarak kurulmuştur. 1990 yılında Klassis Golf Kulubü ve Kemer Golf Kulübü hizmete girmiştir (Salman, 2017). Türkiye'de günümüzde toplam 24 adet golf sahası vardır. Bu sahaların çoğunluğu Antalya'nın Belek mahallesinde yer almaktadır (TGF, 2023).

2. GOLF OYUNUN KURALLARI VE ÇİM SAHASININ BAKIMI

Golf sahasının bölümleri çeşitli isimler ile adlandırılmaktadır. Örneğin, başlangıç noktasına Tee, Parkurda içerisinde engellerin yer aldığı düz alana Fairway, sahanın kenarlarında yer alan daha az bakım isteyen alanlara Rough, Fairway içerisinde veya Green yakınlarında yer alan içi kumla kaplı çukurlara Bunker, topun gireceği deliğin bulunduğu alana Green, Greenin etrafını kaplayan alana da Approach isimleri verilmektedir (Watson, 2012; Şekil 1).

Şekil 1. Bir golf sahasının bölümler ve isimleri (Watson, 2012)

2.1. Green

Green, golf sahalarının en çok titizlikle bakımının yapıldığı bölümüdür (Watson, 2012). Bunun nedeni hem golf topunun girmesi gerektiği yer olması hem de yuvarlanma hareketinin herhangi bir engele takılmadan düz bir şekilde gerçekleşmesi gerekliliğidir. Aynı zamanda Greenlerin çok düşük seviyede biçilmesi de bakımını zorlaştırmaktadır (TGF, 2023). Genellikle iklim şartlarına bağlı olarak 4-5 mm arasında yükseklikte biçilmektedir (Salman, 2017). Bu nedenle Greenlerde kullanılacak çim seçiminde çok dikkatli olunması gerekmektedir. Bu alanlar neredeyse her gün biçilmektedir. Biçmek için kullanılan Green biçme makineleri rekreasyon alanlarını biçmek için kullanılan çim makinesinden farklılıklar göstermektedir (Anonim 2). En önemli farklılığı daha derinden biçebilme özelliği olmasıdır. Buna ek olarak, her Greende deliğin yerini belirtmek amacıyla bir bayrak bulunmaktadır. Hem aynı yerde oynamak istenmemesinden hem de aynı yerin sürekli oyuncu trafiği altında kalmasını engellemek için bu bayrakların yeri her gün değiştirilmektedir (TGF, 2023).

Greenlerde dikkat edilmesi gereken diğer hususlar şöyledir (TGF, 2023):

- Golf çantası daima Greenin yanında bırakılmalı,
- Topun Green üzerinde iz bırakıp bırakmadığı kontrol edilmeli. Gerekirse iz düzeltilmeli.
- Golf topunu çukurdan çıkarırken sopaları Green üzerine yaslanması gerekir,

- Bayrak direğini itina ile kullanırken ve Green'i terk etmeden önce usulüne uygun olarak yerine konulmalıdır.

Greenlerin bakımı oldukça zordur. Bu nedenle golf sahalarında en çok işlem yapılan bölümdür (Watson, 2012). Çimin yayılımının hızlanması ekiminde atılan tohumların üzerlerinin kaplanması için Greenlere kumlama işlemi yapılmaktadır. Bu işleme Topdress adı verilmektedir. Bu işlem düz bir zemin oluşturmak içinde yapılmaktadır. Serin iklim çim türlerinde genelde sonbaharda en az sayıda Topdress yapılırken, Bermuda çiminin serili olduğu Greenlerde yaz dönemi başlangıcında çimin yayılımını hızlandırmak için 4 ile 6 hafta aralıklarla topdress yapılmaktadır (Güntan, 2009).

Topdress işlemi özel olarak tasarlanmış makineler ile yapılmaktadır. Bu makinelerin arkasındaki kum doldurma haznesi bulunmaktadır. Bu hazneye kum doldurulur ve belirlenen seviyeye göre Green içerisine kumun dağıtımı gerçekleştirilir (Anonim 2). Böylece Green'in tüm her yerinde kumlama işlemi homojen bir şekilde dağılmış olacaktır.

2.2. Rough ve Fairway

Golf sahalarının kenarlarında, ormanlık alanlara ve yollara sınırı olan bölgelere Rough ismi verilmektedir (Güntan, 2009). Rough'ların uzunlukları genellikle atış sayısına göre farklılık göstermektedir Roughların kapladığı alanın ortasındaki geniş alanda da Fairwayler yer almaktadır (Salman, 2017).

Fairway ve Roughlardaki çim bitkileri farklı uzunluklarda olabilmektedir. Her iki bölümün çim biçme uzunlukları farklılık göstermektedir. Bu nedenle bu alanları farklı milim ayarında araçlar biçmektedir (Salman, 2017).

2.3. Bunker

Golf sahalarının parkurlarında Fairway veya Rough bölümlerinin büyük bölümünün içerisinde Bunkerlar yer almaktadırlar (Özokan, 2021). Oyunu zorlaştırmak ve oyuncunun kumda oynama becerisini test etmek için kullanılan engellerdir. Bunkerlar farklı boyutlarda bulunmaktadır (Güntan, 2009). Büyük ölçülere sahip Bunker'ları Sanpro ismi verilen araçla düzenlenmesi yapılmaktadır. Küçük Bunkerlar ise her gün saha çalışanları tarafından tırmıklanmaktadır. Ayrıca oyuncu Bunker'a girdiğinde bozduğu kumu tırmıkla düzeltmek zorundadır. Bu nedenle her Bunker'da belirli sayıda tırmık bulunmaktadır (Anonim, 2). Sürekli olarak Sanpro ve tırmıkla düzenlenmesinin nedeni hem dekoratif bir görüntü elde etmek hem de sahada örtülü olan çim bitkisinin Bunker içerisine yayılmasını engellemektir.

Bunker bakımı için uygulanan farklı yöntemler bulunmaktadır. Örneğin Bunkerların etrafındaki Fairway veya Rough makinelerinin giremediği yerlerdeki çimin Flymower ismi verilen çim kesme makinesiyle biçimi yapılmaktadır (Anonim 2).

Flymower makinesinin kestiği yerlerdeki Bunker içerine giren çim atıkları küçük alanlarda kullanılan Blower yardımıyla hava püskürterek Bunker dışına çıkartılmaktadır (Anonim, 2).

Golf sahalarında biçilen çim atıkları çim biçme makinesinin kovalarına doldurularak saha dışında uygun bir yere boşaltılarak uzaklaştırılır. Ancak bu yöntem çok fazla zaman kaybına neden olduğu için biçilen çim saha üzerinde bırakılır. Daha sonra püskürtme makineleri yardımıyla saha dışına uzaklaştırılır. Bu işlemi yapan makineye Blower ismi verilmekte ve genellikle geniş sahalardaki çimin temizlenmesinde traktörün arkasındaki kuyruk miline takılarak çalıştırılmaktadır ((Anonim, 2).

2.4. Tee (Başlangıç noktası)

Tee'ler golf oyunun başlangıç noktasına verilen isimdir (Şekil 2). Golf sahasının bu bölümünde bitiş noktasına yani Greendeki deliğe olan uzaklıklara göre farklı atış noktaları vardır. Her atış bölümü faklı renkte Tee markerlarla gösterilmektedir. Bu renkler sırasıyla beyaz, mavi, sarı, kırmızı şeklinde sıralanmaktadır. Bu renklerin bulunduğu yerlerin bitiş noktasına olan uzaklığı farklılık göstermektedir. Green sahasına en uzak mesafede olan yere profesyonel erkekler atış yapmaktadır. Burada beyaz Tee markerlar bulunmaktadır. Amatör erkekler sarı markerların bulunduğu bölgelerden atış yapmaktadır. Mavi Tee marker'lardan profesyonel kadınlar, kırmızı Tee markerlardan amatör kadınlar atış yapmaktadır (Salman, 2017).

Şekil 2. Golf sahalarındaki Tee ve Teemarkerlar

Tee'ler çoğunlukla iki günde bir 10-12 mm'den biçilmektedir (Salman, 2017). Ancak bulunduğu mevsime göre farklılık gösterebilmektedir. Tee'ler genelde Approachlarla aynı çim biçme makinesi tarafından kesilmektedir. Bu makineye Triplex ismi verilmektedir (Anonim, 2).

Tee'lerde topa vuruş esnasında zarar gören yerlere kumlama yapılmaktadır. Bu işlem Nisan aylarından sonra yaz döneminde sadece kumla, eylül ayından sonra kış döneminde kum ile tohumu karıştırıp kumlama işlemi yapılmaktadır. Bu yapılan işleme divotlama adı verilmektedir. Yaz aylarında sadece kumun kullanılmasının nedeni sıcak iklim çim bitkilerinin özellikle Bermuda çiminin kardeşlenme sayısının fazla olması ve kumun içerisinde rahatlıkla hareket edebilmesi ve tohum kullanmadan yayılabilmesini sağlamaktadır (Açıkgöz, 1994).

Divotlama işlemi Tee bölümlerine benzer şekilde Fairway alanlarında da zarar gören bölgesel yerlere yapılmaktadır. Divotlama işlemi çoğunlukla el ile zarar gören yere kum ya da kum-tohum karışımının atılması yoluyla yapılmaktadır.

3. GOLF SAHALARINDA DİĞER BAKIM ARAÇLARI

Golf sahalarında tohum ekimi eylül aylarının başında yapılır (Güntan, 2009). Green, Bunker kenarı gibi bölgelere atılan tohumu insan gücüyle kullanılan makineler vardır. Diğeri de traktörün arkasına monte edilip golf parkurunun geniş alanlarında tohum atmaya yarayan makineler vardır (Anonim, 3).

Golf parkurlarının tohumlanmasından önce veya çim sahasının havalandırılmasına ihtiyaç duyulduğunda çim alanına belirli derinlikte havalandırma işlemleri yapılmaktadır. Bu işlemi yapan makineye Vertidrain adı verilir. Golf sahasının geniş alanlarına traktörün arkasına bağlanmak suretiyle çalıştırılırken, Greenlere ise insan gücüyle çalıştırılan türleri vardır (Anonim, 2).

4. GOLF SAHASI SULAMASINDA KULLANILAN YAĞMURLAMA BAŞLIKLARININ ÖZELLİKLERİ VE TERTİP BİÇİMLERİ

Spor sahalarında kullanılan yağmurlama başlıkları rekreasyon alanlarında kullanılan başlıklardan özellik olarak farklılık göstermektedir. Bunun nedeni, daha geniş bir sahanın sulanması ve bu sahanın üzerinde spor faaliyetleri gerçekleştirildiği için mümkün olan en az sayıda yağmurlama başlığının kullanılması olarak gösterilebilir. Ayrıca kullanılacak olan yağmurlama başlığı sayısı sistem maliyetini de etkilemektedir. Bu nedenle büyük ölçekli spor sahalarında daha yüksek basınçla çalışan ve daha uzak mesafelere suyu atabilen başlıklar tercih edilmektedir.

Golf sahalarında kullanılan yağmurlama başlıklarını incelediğinde, genellikle uzak mesafelere su atabilen spesifik özellikler barındıran başlıklardır. Bu başlıkların uzak mesafelere suyu atabiliyor olması aynı zamanda yüksek basınç gereksinimi doğurmaktadır. Örneğin, Hunter (2015), Rainbird (2017) ve Toro (2023) gibi sulama firmalarının teknik katalogları incelendiğinde 20 m ile 30 m arasında atış mesafesi olan bir yağmurlama başlığının 4.5 ile 7.0 bar arasında bir basınç ihtiyacı oluşturduğu görülmektedir.

Golf sahalarında kullanılan yağmurlama başlıklarının atış açıları tam daire ve açışı ayarlanabilen yağmurlama başlıkları olarak iki tipi bulunmaktadır. Tam daire atış yapan başlıklar fairway yani sahanın orta kısımlarında kullanılırken, açısı ayarlanabilen başlıklar ise çoğunlukla golf sahasının kenarlarında veya Greenin içini ve dışını sulayacak şekilde tertiplenip kullanılmaktadır (Anonim, 4). Şekil 3'de görüldüğü gibi Green içini ve dışını sulayan başlıklar ayrı ayrı tertiplenir ve aynı hatta bağlı tertip edilmemektedir (Barrett ark., 2003). Açısı ayarlanabilen başlıkların çift tarafı sulayan ve tek tarafı sulayabilen olmak üzere iki farklı tipi mevcuttur. İki tarafı birden sulayabilen başlıklar genellikle ormanlık alan ve göl kenarları ile saha sınırına yakın yerlere yerleştirilirken (çoğunlukla Roughlara), tek tarafı sulayabilen başlıklar yol kenarı ile sahanın sınırına (çoğunlukla Tee'lere) yerleştirilir (Barrett & ark., 2003).

Şekil 3. Farklı atış özellikli yağmurlama başlıkları

Bazı yağmurlama başlıklarının nozul uçları belirli açılar ile yukarı ya da aşağı yöne doğru hareket ettirilebilir. Eğer rüzgârın çok olduğu bir ortam var ise nozul ucu aşağı yöne doğru eğer başlığın attığı suyun uzak mesafeye ulaşması isteniyorsa nozul ucu yukarı yöne doğru hareket ettirilebilir (Anonim, 4).

Golf sahalarında, rekreasyon alanlarında kullanılan selenoid vana genellikle kullanılmaz. Dolayısıyla her bir yağmurlama başlığı aynı zamanda bir selenoid vana görevi görmektedir.

Bir golf sahasının sulama programlaması oluşturulurken yağmurlama başlıklarının özelliklerinin bilinmesi etkin su kullanım açısından büyük önem taşımaktadır. Bu nedenle yukarıda bahsedilen yağmurlama başlıklarının özelliklerinin bilinmesi sulama randımanını arttıracak etkenler arasında yer almaktadır.

5. GOLF SAHALARINDA KULLANILAN AKILLI SULAMA SİSTEMLERİ

Türkiye'de küresel ısınmanın etkileri, artan nüfus ve kaynakların azalması özellikle suyun etkin kullanılmasını zorunlu kılmaktadır. Özellikle kullanılabilir durumda bulunan toplam su miktarının yaklaşık %77'si tarım alanlarında kullanılmaktadır (DSİ, 2022). Bu nedenle tarım alanlarında kullanılan su, en az kayıpla optimum fayda sağlanmak zorundadır. Ayrıca rekreasyon alanlarında spor sahalarında çim alanını sulamak için kullanılan sudan tasarruf edilecek yöntemler tercih edilmelidir. Davis & ark. (2009)'nin Florida'da yaptıkları bir araştırmada bitki su tüketimini (ET) belirlemek için kullanılan sensörler ile herhangi bir sensör kullanılmadan sulaması yapılan uygulamalar karşılaştırdıklarında, araştırmanın yapıldığı yılın kış döneminde %60, yaz döneminde ise %9 tasarruf sağlandığını saptamışlardır. Buradan da anlaşılacağı gibi rekreasyon alanları veya golf sahası gibi spor sahalarının sulanmasında sensörler ile uzaktan izleme sistemleri kullanılması sulama suyu tasarrufu açısından büyük önem taşımaktadır. Touil & ark. (2022) tarafından yapılan bir başka çalışmada akıllı izleme sistemleri olarak toprak nem sensörü, buharlaşma-terleme kontrolörleri ve yağmur sensörlerini kullanarak bitki büyümesini ve kalitesini korurken, önemli ölçüde su tasarrufu sağlamışlardır. Dolayısıyla akıllı bir sulama sisteminde toprak nem ile iklim koşulları ve kullanılacak bitkinin fizyolojik koşulları dikkate alınarak oluşturulan izleme ve kontrol mekanizmalarıyla sulama suyundan önemli oranlarda tasarruf saplanabilmektedir (Signh & ark., 2019).

Golf sahalarının büyük ölçekte çim ile kaplı olması oldukça fazla sayıda golf sahası parkuru bulunması sulama yönetiminin ve izlenmesinin tek bir merkezden yapılmasını zorlaştırmaktadır. Bu nedenle her parkurda bulunan yağmurlama başlıklarının ve sensörlerin kablolar ile bağlı olduğu bir sulama kontrol merkezi (Satellite) kullanılabilmektedir (Barrett & ark., 2003). Bu Satellite'lerden alınan sinyal kabloları bir merkez hatta toplanır. Merkez kontrol sistemine ulaştırılır ve bu sayede sulamanın kontrolü bilgisayardan programla yardımıyla veya wife yardımıyla cep telefonlarından yapılabilir (Anonim, 3).

5.1. Sensörler

a. Yağmur sensörleri

Yağmur sensörleri, yağıştan kaynaklanan suyu belirli bir derinliğe kadar biriktikten sonra planlanan sulama programının ya iptali ya da ertelenmesi için tasarlanmış cihazlardır. Bu cihazların amacı yağmurlu koşullarda sulamanın devam etmemesini sağlayıp fazla su tüketiminin önüne geçmektir (CBS, 2021).

b. Toprak nemi sensörü

Planlanmış bir sulama programının çalışmasına izin vermek veya ertelemek için sensörden gelen verileri değerlendirmektedir. Sensörün belirlediği nem eşik değerinin üzerine çıkarsa sulama programını kapatmaya göre tasarlanmıştır. Birden fazla sensör birden fazla alanı kontrol ediyor ise en çok su ihtiyacı olan bölgeye göre planlama yapılmaktadır. Kontrol cihazı, çalışma sürelerini fazla sulamayı sınırlandırmak için bölgelere göre ayarlanabilmektedir (McCready & ark., 2009).

Sensörler, toprak nemi belirlenen seviyenin üstüne çıktığında sulamayı durdurmakta ve altına indiğinde de o bölgeye özel olarak sulama programını aktif hâle getirmektedir. Böylece fazla ve/veya eksik su kullanımının önüne geçebilmektedir (CBS, 2021). Ancak, toprak özelliğine ve nem şartlarına göre iyi bir şekilde kalibrasyonunun yapılması gerekmektedir (Abdelfattah & ark., 2020).

c. Basınç, sulama akışı ve rüzgâr sensörleri

Rekreasyon alanlarında tasarlanan sulama sistemleri çoğunlukla toprakaltında yer almaktadır. Bu sistemlerde oluşan bazen yüksek basınçtan bazen de montajın doğru yapılmamasından kaynaklanan su sızıntıları ve/veya patlaklar meydana gelmektedir. Bu sızıntıdan ve/veya patlaktan meydana gelen su kayıpları fark edilene kadar devam etmektedir. Bu durum su kayıplarına neden olmaktadır. Bu nedenle borulu sistemlerde basınç ve sulama akışı sensörleri kullanılmaktadır. Sensörler, boru içerisindeki basınç arttığında basıncı düzenleyerek su kayıplarının önüne geçmektedir. Sulama akış sensörleri ise sistemdeki su kaçağını algılamakta ve kontrol cihazına sinyal göndermektedir (CBS, 2021). Böylece sulama sisteminde oluşan yüksek basınç düzenlenebilmekte ve su kaçağından anında haberdar olunabilmektedir. Buda su kayıplarını en aza indirmektedir.

Rüzgâr sensörleri ise rüzgâr hızı belirlenen sınırı aştığında sulama programını kesintiye uğratmakta ve sulamanın homojenliğini kontrol altına almaktadır. Böylece rüzgârdan kaynaklanan su kaybından tasarruf edilmektedir.

5.2. Merkezi kontrol sistemleri

Merkezi kontrol sistemleri, golf sahasında yerel kontrol cihazlarından aldığı sinyaller sayesinde sahanın sulama yönetimi tek bir noktadan sağlanmış olmaktadır. Bunun yönetimi cep telefonu veya bilgisayar ile sağlanabilmektedir. Bunun için her üretici firmanın geliştirdiği programlar bulunmaktadır. Firmaların golf sahalarının sulama yönetimi için ürettiği merkezi kontrol cihazlarını incelediğinde; sulama kontrolünü sağlayan cihazların özellikleri yağışın aktif olduğu anda sulamayı düzenleyerek su tasarrufu sağlamaktadır. Pompa istasyonunun 7/24 izlenerek pompa basınç ve debi değerlerine göre sulama ihtiyacını otomatik olarak değiştirmesini sağlar ve pompa istasyonu verimliliğini arttırmaktadır. Günlük hava durumu ve ET değerlerine göre sulama otomatik olarak ayarlanabilmektedir.

Merkezi sulama kontrolüyle ilgili yapılan bazı araştırmalarda merkezi kontrol sistemi kullanılan sulama alanlarında hem enerjiden hem sudan tasarruf sağlandığı ortaya çıkmıştır (Taştan, 2019). Sudan ve zamandan tasarruf edilmesi işçilik maliyetlerini de düşürmüş olmaktadır. Ayrıca yeşil alanlar korunmaktadır.

6. SONUÇ

Bir golf sahasının bölümleri Green, Fairway, Rough ve Tee'den oluşmaktadır. Golf sahasının en önemli bölümleri oyunun bitiş yeri olan Green ve başlangıç yeri olan Tee'lerdir. Kısa uzunlukta bırakılarak derinden biçim yapılması ve topun düz bir şekilde hareket etmesi istenmektedir. Bu yüzden bir golf sahasında en çok bakım yapılan bölüm Greenlerdir. Dolayısıyla bir golf sahasındaki çim sahasının bakımı; sulama, golf sahası biçim makineleri, bitki besleme, çim bitkileri bilgisi ve deneyimi olan yöneticiler tarafından yapılmalıdır.

Bir golf sahasında kullanılan sulama suyundan tasarruf etmek için toprağa verilecek sulama suyu miktarı toprak nemi ölçülerek belirlenmelidir. Ancak golf sahaları çok geniş bir yeşil alan olduğundan klasik yöntemlerle bitki su ihtiyacının belirlenmesi çok ciddi zaman ve iş kaybına yol açmaktadır. Bu nedenle topraktaki nemin, hava durumunun ve bitki fizyolojisinin uzaktan izlenebileceği ve ihtiyaç duyulan su miktarını saptayan yöntemler kullanılmalıdır. Bununla birlikte, sözkonusu akıllı yöntemlerin eksikliklerinin saptanıp daha iyi bir seviyeye getirilmesi gerekmektedir.

Golf sahası gibi geniş alanlarda tasarlanan sulama sistemleri, yüksek miktarda su taşıdıkları için büyük çaplı borular, yüksek debili yağmurlama başlıkları ve büyük pompalar kullanılmaktadır. Bu noktadan hareketle tasarlanacak sulama sisteminin hidrolik hesabı çok dikkatli yapılmalıdır. Aksi taktirde zaman içerisinde sulama sisteminde sıklıkla arızalar yaşanabilmektedir. Bu durumda hem ciddi bir maaliyet yükü hem de fazla su kullanımına neden olmaktadır. Dolayısıyla sulama sistemi, uzmanı kişiler tarafından tasarlanmalı ve sensörler yardımıyla sistem içerisindeki su sürekli takip altına alınmalıdır.

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BÖLÜM II

Rekreasyon Alanlarında Kullanılan Çim Sulaması

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1. GİRİŞ

Dünya nüfusunun artması ve bununla beraber büyük şehir merkezlerine göç, yıllar geçtikçe şehirlerdeki yapı stokunun artmasına neden olmuştur. Bu durum tarım ve yeşil arazilerin azalmasına neden olmaktadır. Böylece şehirlerde yeşil alan ihtiyacı ortaya çıkmaktadır.

Peyzaj çalışmalarının tarihi çok eski zamanlara dayanmaktadır. Özellikle Mezopotamya'da Babiller dönemine ait Babil asma bahçeleri günümüzde dünyanın yedi harikası arasında

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gösterilmektedir. Antik Mısır'daki peyzaj mimarisi incelendiğinde 10000 m uzunluğunda kare şeklindeki bu alanlarda genellikle Palmiye ve İncir ağaçları bulunmaktadır. Rönesans dönemi peyzaj mimarisinde ise Rönesans bahçeleri oluşturulmuş ve tepelerin en hâkim noktalarına yerleştirilmiştir.

Taşkın ve Bilgili (2020)'nin belirttiği gibi çim bitkileri; fonksiyonel, rekreasyonel ve estetik görünüm gibi işlevlerinin yanı sıra hava kalitesini arttırma, kirli havayı filtre etme, karbon depolama, yağmursuyu yönetimi ile su dengesini sağlama, havayı serinletme, insan sağlığı ve stres üzerine olumlu etki etme, konutların değerlerini arttırma, toprak erozyonu önleme ve toz stabilizasyonu sağlama, pestisit kullanımını azaltma, biyolojik çeşitliliği koruma gibi işlevleri de bilinmektedir.

Çim örtülerinin rekreasyon amaçlı olarak ilk kullanımı Pers ve Arap bahçelerinde rastlanmıştır. Elde edilen bilgilere göre İran'da sanatsal amaçlı bahçe desenli halılarda ve daha sonra Arap kültürünü simgeleyen bahçelerde, çim dokusunun temel unsur olarak kullanıldığını göstermektedir. Daha sonra, Yunanlılar ve Romalılar, İran'ın çim bahçelerini kendilerine uyarlayarak geliştirmişlerdir. XV. yüzyıl ile çim alanları İngiltere, Almanya, Fransa, Hollanda, Avusturya ve diğer Kuzey Avrupa ülkelerinde yaygınlaşmıştır. XVII. ve XVIII. yüzyıllarda çim bahçeleri, hobi bahçeleri ve diğer yeşil alanları oluşturmak amacıyla ilk kez kültüre alındığı dönem olarak düşünülmektedir (Kuşvuran, 2012). Eliot vd. (1992) tarafından yürütülen çalışmaya göre ABD'de ilk çim bitkileri araştırmaları 1885 yılında Connecticut'daki Olcott Turf Gardens'da yapılmıştır. Türkiye'de de bu alanda özel şirketler uzun yıllardır faaliyet göstermektedir. Son yıllarda çim alanlarındaki akademik çalışmaların sayısında artış görülmektedir. Bilimsel anlamda çim araştırmalarına 1946 yılında başlanmıştır (Kuşvuran, 2012).

Çim bitkileri fonksiyonel açıdan faydaları, toprağı kapladığı için erozyonu engeller ve bunun yanında toprakta tuttuğu su ve besin elementleri sayesinde verimli bir toprak yapısı oluşturmaktadır (Taşkın ve Bilgili, 2020). Çim bitkileri rekreasyon alanları spor sahaları villa vb. yerleşim yerlerinin bahçelerinde kullanılmaktadır. Çim sahalarının yeşil bir görünüm elde edilebilmesi ve basılmaya karşı dirençli olabilmesi için kullanılan tohumun ve çeşidin bakımının düzenli yapılması gerekmektedir (Açıkgöz, 1994).

Çim alanlarında çoğunlukla buğdaygiller familyasına ait türler kullanılmaktadır. Buğdaygiller familyası (*Gramineae)* 620 cins ve 10000 türü bulunmaktadır. Çim alanlarının yapımında çoğunlukla kullanılan bazı serin iklim türleri İngiliz çimi (*Lolium Perenne*), Çayır salkımotu (*Poa Preatensis)*, Kırmızı yumak *(Festuca rubra)* ve sıcak iklim türlerinde ise Bermuda otu (*Cynodon dactylon L. Pers)* gibi türler kullanılmaktadır (Açıkgöz, 1994).

Çim bitkisinin rekreasyon alanları, bazı spor sahaları, park ve bahçeler genel kullanım alanlarını oluşturmaktadır. Spor müsabakalarının oynandığı alanlarda her dem yeşil kalan ve basılmaya karşı dirençli olan çim türleri tercih edilmelidir. Aynı zamanda iklim şartlarına göre seçilecek çim türleri değişiklik göstermektedir.

Akdeniz ikliminin hâkim olduğu sıcak bölgelerde kuraklığa dayanıklı çeşitler tercih edilmelidir. Mutlu (2020) tarafından Antalya’da yapılan bir çalışmada Bermuda çiminin *(Cynodan dactylon (L) Pers. xC transvaalensis Burtt-Davy)*, Survivor’ın

Tifway'dan kuraklık stresi altında yeşil dokusunu daha uzun süre koruduğunu ve ilkbaharda da daha erken yeşillendiği saptanmıştır. Yılmaz vd. (2022) tarafından yürütülen bir başka araştırmada ise Sakarya'da Serin iklim çim bitkilerinden Festuca çeşidinin; Lolium, Poa, Agrostis çeşitlerine göre kuraklığa daha toleranslı olduğu saptanmıştır. Bu araştırmalardan da anlaşıldığı gibi çim türlerinin kurak şartlara dayanıklılığı azınlıktadır.

Çim bitkisi yüksek su ihtiyacı olan bir bitkidir. Bu nedenle çimin kullanıldığı alanlarda sulama sisteminin teknik detaylara uygun şekilde tasarlanması gerekir. Sulama sistemleri hem tarımsal hem rekreasyon alanlarında hem de çim bitkisinin kullanıldığı diğer alanlarda hidrolik kurallara uygun şekilde tasarlanması gerekmektedir. Çim alanlarını sulayan sulama sisteminin teknik kurallara uygunluk durumunun, uzmanı kişiler tarafından planlaması gerekmektedir. Çim sahalarının geniş alanları kaplıyor olması nedeniyle tasarlanacak olan sulama sisteminin doğru bir şekilde belirlenmesi gerekmektedir.

Bu çalışmada rekreasyon alanlarında kullanılan çim türlerinin genel özellikleri ve rekreasyon alanlarında uygulanan sulama sistemleri ele alınmıştır.

2. SERİN VE SICAK İKLİM ÇİMİNİN ÖZELLİKLERİ

2.1. Serin iklim çimi

Dünyada serin-yağışlı, serin-yarı nemli ve serin-yarı kurak iklimlerle bunların arasındaki geçiş iklimlerinde kullanılan ve ekim yatağındaki sıcaklığın 15-20 °C olduğu dönemde optimum gelişme gösteren çim türleri bu grupta yer almaktadır (Anonim 1). Havaların aşırı donlu ve kuru olmadığı kış aylarında iyi bir bakımla renklerini muhafaza edebilmektedir. Soğuğa oldukça dayanıklı olan serin iklim çim bitkileri karasal iklimin hüküm sürdüğü alanlarda başarı ile kullanılmaktadır (Özşafak ve Öner, 2013).

Serin iklim çim buğdaygilleri kendi türleri arasında iklim koşullarına uyumları farklılık göstermektedir. Varoğlu vd. (2016) tarafından İzmir Bornova'da yapılan bir çalışmada serin iklim çim buğdaygillerinden Festuca arundinaceae ve Lolium perenne'un pek çok çeşitleri kaplama derecesi, yaprak dokusu, yaprak rengi, yenilenme gücü açısından iyi sonuçlar verdiği saptanmıştır.

İngiliz çimi (*Lolium perenne*):

İngiliz çimi (*Lolium Perenne),* rekreasyon alanlarında en çok kullanılan türlerden birisidir. Yaprakları koyu yeşil tüysüz ve parlaktır. Serin iklim çim bitkisidir. Kısa ömürlü çok yıllık bir çim bitkisi olarak kabul edilmektedir. Hemen hemen tüm çeşitleri aşırı sıcaklık ve kuraklıktan olumsuz yönde etkilenmektedir. Gölge alanlara dayanımı zayıftır. Ayrıca Akdeniz ikliminin hâkim olduğu sahil kuşağında iyi bir gelişim göstermektedir (Demiroğlu vd., 2010).

İngiliz çiminin (*Lolium perenne)* en iyi gelişimi, su tutma kapasitesi yüksek topraklardadır. Nötr veya hafif asidik topraklarda (pH 6-7) iyi gelişmektedir (Anonim, 1). Taban suyu yüksek topraklarda iyi bir gelişim gösteremez (Özşafak ve Öner, 2013).

Çim alanları için özel olarak ıslah edilen, birim alanda çok kardeş geliştiren, ince yapraklı ve kısa boylu çeşitleri basılmaya ve çiğnenmeye karşı dirençlidir. Bu nedenle spor sahalarında çoğunlukla tercih edilmektedir (Anonim, 1). Park ve bahçeler, spor sahaları villa bahçeleri genellikle kullanım alanlarını oluşturur.

İngiliz çimi ile yapılan karışımlarda biçim zamanı ve biçim yüksekliği çok önem taşımaktadır. Biçimin 2 cm'den daha derinden yapılması İngiliz çiminin seyrekleşmesine ve kısa sürede ölmesine yol açmaktadır (Anonim, 1).

Çayır salkım otu (*Poa pratensis*):

Tüm dünyada en fazla kullanılan çim bitkilerinden birisidir. Uzun ömürlü bir çim bitkisidir. Çok sık ve ince yapılı bir yeşil alan oluşturur (Özşafak ve Öner, 2013). Serin ve nemli bölgelerde iyi gelişme göstermektedir. Sıcak ve kurak şartlarda büyümesi yavaşlamaktadır. Sulama suyu ihtiyacı fazladır, sulamanın düzensiz yapılması halinde renk bozuklukları görülmektedir (Anonim, 1).

Çayır salkım otu (Poa pratensis) kış şartlarına dayanıklıdır. Gölgeye dayanıklı değildir, basılmaya ve çiğnenmeye orta derecede dayanıklıdır. En iyi gelişimini nemli su tutma kapasitesi yüksek topraklardadır (Açıkgöz, 1994). Ayrıca drenajı iyi, verimli, nötr veya hafif asit (pH 6-7) topraklarda yetişmektedir. Drenajı bozuk, fazla asit topraklarda kısa sürede seyrekleşir (Anonim, 1).

Kurak şartlara dayanıklı bir çim türü değildir. Ayrıca basılmaya ve çiğnenmeye karşı dayanıklılık göstermemektedir (Açıkgöz, 1994). Serin iklim çim türleriyle karışım bitkisi olarak veya üstten tohumlama amacıyla kış dönemlerinde kullanılmaktadır.

Adi salkım otu (*Poa trivailis L.*):

Anavatanı Kuzey Avrupa'dır. Nemli ve serin bölgelerdeki ince yapılı su tutan topraklarda iyi gelişmektedir. İnce yapılı, açık yeşil renkli bir çim örtüsü oluşturmaktadır. Yatık bir şekilde gelişir ve sülükleriyle yayılmaktadır. Kurağa ve sıcağa dayanımı çok zayıftır. Buna karşılık soğuklardan zarar görmez. Gölgeye karşı dayanıklıdır.

Basılmaya ve çiğnenmeye dayanımı ise çok zayıftır. Kırmızı yumakla birlikte gölge alanlara ekimi önerilmektedir (Açıkgöz, 1994). Düzenli sulamaya ve gübrelemeyle gelişimini önemli ölçüde etkilemektedir. Kurak şartlar altında düzenli sulamasının yapılması gerekmektedir (Giovanni vd., 2017).

Kırmızı Yumak (F. rubra L.):

Rekreasyon alanlarında yaygın olarak kullanılan bir çim türüdür. İnce yapraklı ve kısa boyludur. Gölgeye karşı dayanıklıdır. Akdeniz iklim koşullarında Köksap gelişimi ve kromozom sayılarına göre üç sınıfta incelenmektedir. Bunlar Köksaplı Kırmızı Yumak (*Festuca rubra var. rubra),* Adi Kırmızı Yumak (*Festuca rubra var. commutata)* ve son olarak Narin Kırmızı Yumak (*Festuca ovina L.)* olarak sınıflandırılır (Açıkgöz, 1994).

Köksaplı kırmızı yumak (*Festuca rubra var. rubra)*; koyu yeşil renkte ince yapılı bir çim örtüsü meydana getirmektedir. Uzun ömürlü bir çim bitkisidir, nemli ve serin bölgelerde ve gölge alanlarda iyi gelişim göstermektedir. Basılmaya ve çiğnenmeye karşı orta derecede dayanıklıdır. Birim alanda az kardeşlenme oluşturur ve yeniden gelişim yeteneği zayıftır. Bu nedenlerle spor sahalarında tercih edilmez (Açıkgöz, 1994). Aşırı nemli ve kötü drenajlı topraklarda iyi gelişim göstermemektedir. Tuzluluğa karşı dayanımı çok zayıftır (Alagöz ve Türk, 2017). Ertekin vd. (2022) tarafından yürütülen bir çalışmada Kırmızı yumak türlerinin tuza dayanımlarını incelendiği araştırmada Köksaplı Kırmızı yumak (*Festuca rubra var. rubra)* türünün tuzluluğa daha toleranslı olduğu saptanmıştır. Tınlı ve asitik topraklarda iyi gelişim göstermektedir.

Adi kırmızı yumak (Festuca rubra var. Commutata):

Yumak şeklinde gelişim göstermektedir. İnce yapılı dik gelişen yaprakları narin ve çok kardeşlenmesi nedeniyle sıkı bir çim örtüsü oluşturmaktadır (Açıkgöz, 1994). Kuraklığa ve gölge şartlara dayanımı yüksektir. Asitik, verimsiz ve kumlu topraklarda iyi gelişim göstermektedir. Basılmaya ve çiğnenmeye karşı oldukça dayanıklıdır. Serin iklim koşulları altında rekreasyon alanlarında İngiliz çimi (*Lolium perenne),* Çayır salkımotu (Poa pratentis L.) ile karışım bitkisi olarak çoğunlukla tercih edilmektedir. Genelde olarak 3-5 cm yükseklikten biçilebilir, daha düşük seviyelerde biçime de dayanıklıdır (Açıkgöz 1994).

2.2. Sıcak iklim çim türleri

Bu gruptaki çimler için optimum yetişme sıcaklığı 15-27 °C'dir. Çimlenme, sürme, kardeşlenme, büyüme ve gelişme dönemlerinde serin iklim çim türlerinden daha fazla sıcaklığa gereksinim duyan çim bitkileridir. Bunların serin iklim çimlerinden en önemli farkları; toprak yüzeyine daha yakın (alçak) gelişmeleri, dipten biçmeye dayanıklı olmaları, köklerinin daha derine işlemesi, basılma ve ezilmeye, sıcak ve kurağa daha dirençli olmalarıdır. Sıcak iklim çimlerinin çoğunlukla vejetatif (yeşil organ, vb.) üretilmesine karşılık, serin iklim çimlerinin tohumla üretilmesi de dikkate değer bir farklılıktır. Subtropik ve tropik iklim kökenli olan sıcak iklim çim bitkileri, Türkiye'de Nisan ve Ekim ayları boyunca hüküm süren sıcak çevre koşullarında iyi gelişirler. Kasım sonrası ilk donlar ile Nisan başına kadar görülebilen geç donlar arasındaki sürede uyku halindedir (Anonim, 2).

Bermuda çimi (Cynodon dactylon L.):

Tropik veya subtropik bölgelerdeki çim alanlarda yaygın olarak kullanılmaktadır. Çok yayılıcı, ince yapraklı, sık bir çim örtüsü oluşturmaktadır. Köksap ve sülüklerle kısa sürede yayılmaktadır. Kurağa ve sıcağa dayanımı çok iyi soğuğa dayanımı ise zayıftır. Bermuda çiminin O °C'nin altında rengi sararmaktadır. Basılmaya ve çiğnenmeye dayanımı çok üstündür ve kendini yenileme yeteneği yüksektir. Ancak, gölgeye dayanımı zayıftır. Basılmaya karşı dayanımı yüksek olduğu için çoğunlukla golf, futbol, koşu sahaları gibi spor alanlarında kullanılır (Anonim, 2).

3. REKREASYON ALANLARINDA SULAMA

Tarım alanlarında yapılan sulama uygulamaları, çoğunlukla bitkisel üretim amaçlı ve etkin bir biçimde sulanmasıyla ilgilenir. Ancak rekreasyon alanları güzel ferahlatıcı görüntü oluşturmak amaçlı tasarlanan alanlardır. Dolayısıyla bu tür alanlar doğrudan insan ihtiyacına yönelik değil insanların zihinsel ihtiyaçlarını ve/veya temiz hava almalarını sağlayan yeşil alanlardır.

Çim bitkilerinin birçok türü ve çeşidi yüksek miktarda sulama suyuna ihtiyaç duymaktadır. Havanın nisbi neminin çok düşük olduğu yaz aylarında su ihtiyacı 10 mm'yi geçmektedir (Açıkgöz, 1994). Özellikle sıcak mevsimlerde sulama suyu ihtiyacı yükselmektedir. Bu nedenle sulama programlanmasının konusunun uzmanı mühendisler tarafından tasarlanması gerekmektedir. Çim bitkisinin bitki su tüketimi ve bitki su stresi üzerine yapılan akademik araştırmaları incelenecek olursa; Baştuğ ve Büyüktaş (2003) tarafından Antalya'da golf alanlarında kullanılan serin iklim çim bitkisi çeşitlerinin karışımı üzerine yaptıkları çalışmada %25 su kısıtı uygulanan konuda en yüksek renk kalitesine ulaşılmıştır. Bu konunun bitki su tüketimi 7.5 mm/gün olarak bulunmuştur. Emekli (2005) Antalya'da Bermuda (*Cynodon dactylon L.)* çiminin su stres indeksinin değerlendirilmesi üzerine yaptığı araştırmada A-Sınıfı Buharlaşma Kabı'ndan ölçülen buharlaşma miktarının %75 oranında sulanması durumunda, Bermuda çiminin mevsim boyunca kabul edilebilir renk kalitesini sürdürebileceği sonucuna ulaşmıştır. Aynı çalışmada Bermuda (*Cynodon dactylon L.)* çiminin buharlaşma miktarının %75'nin sulandığı konunun bitki su tüketim değeri 7.45 mm/gün olarak hesaplanmıştır. Aydınşakir vd. (2014) Antalya'da yaptıkları bir çalışmada Seaspray ve TifBlair çeşitlerinin bitki su tüketimi değerleri sırasıyla 6.7 mm/gün ve 6.8 mm/gün olarak hesaplanmıştır. Tam sulama konusu altın en yüksek görsel kaliteye ulaşıldığı bildirilmiştir. Sözkonusu araştırmaların ışığında, Antalya ili golf sahalarındaki genellikle serin ve sıcak iklim çim çeşitlerinin bitki su tüketim değerleri ortalama 7.5 mm/gün civarında bulunduğu görülmektedir. Ayrıca bazı çim çeşitlerinde kullanılabilir suyun %75'nin kullanılabileceği saptanmıştır. Ancak bu bilgilerin değişen iklim şartları düşünülerek benzer çalışmaların yapılması gereklidir.

Rekreasyon alanlarındaki çimin sulanması için büyük çoğunlukla yağmurlama sulama yöntemi tercih edilmektedir. Çalı grubunun sulanması için ise damla sulama yöntemi tercih edilmektedir. Rekreasyon alanlarında kullanılan yağmurlama sulama yöntemi unsurları yağmurlama sulama başlığı, selenoid vanalar, boru hattı, kontrol ünitesi ve pompa biriminden oluşmaktadır (Orta, 2017).

Çim alanlarında uygulanan yağmurlama sulama sisteminin planlanmasında en önemli unsurlarda biri yağmurlama başlığı seçimidir. Yağmurlama başlığı seçiminde yağmurlama hızının, toprağın su alma hızından düşük olmasına dikkat edilmelidir. Ayrıca tertip biçimini belirlerken başlıkların birbirlerini ıslatacak şekilde tasarlanması gerekmektedir. Aksi taktirde homojen bir sulama sağlanmamaktadır (Orta, 2017). Yağmurlama sulama sistemlerinde üç tip tertip biçimi bulunmaktadır. Bunlar kare, dikdörtgen ve üçgen tertip biçimleridir. Yağmurlama başlıkları, tertip aralıkları ve sistem kapasitesinin belirlenmesinde önemli bir unsuru oluşturmaktadır. Sistem maliyeti ve etkin bir su kullanımı açısından da yağmurlama başlığı seçimi önemli bir kriterdir.

Rekreasyon alanları ve spor sahaları birbirlerinden farklı boyutlarda olmaları ve kullanım amaçlarının farklı olması nedeniyle yağmurlama başlığı seçiminde farklı özellikte başlık tercih edilmektedir. Örneğin bir rekreasyon alanı sulanacaksa arazinin şekline ve ölçüsüne göre 2.5 m ve 5.5 m yarı çaplı sprey yağmurlama başlıkları veya 6.0 m'den 20 m yarıçapa kadar değişen sprinkler yağmurlama başlıkları tercih edilmektedir (Orta, 2017). Bir diğer yağmurlama başlığı türü de düşük yağmurlama hızına sahip yağmurlama başlıklarıdır. Bu başlıklar bir lateral hattında daha fazla başlık kullanılmasını sağlar. Böylece daha az sayıda vana kullanılmış olmaktadır. Düşük yağmurlama hızı nedeniyle birim zamanda sprey yağmurlaya göre daha az miktarda su taşıdığı için daha düşük çapta borular kullanılır. Ayrıca sprey yağmurlaya göre daha fazla su tasarrufu sağlamaktadır.

Rotorlar (veya döner sprinkler), bir döner başlıktan tek bir su akışı uygulamaktadır. Atış mesafeleri çoğu türde ayarlanabilir. Başlık yerleşiminde tam örtmeye dikkat edilerek suyun dağılımı istenen biçimde sağlandığında su homojen ve eşit bir biçimde toprak yüzeyine dağılmış olmaktadır. Burada asıl ikinci önemli konu rotor başlıklarda nozul değişimidir. Tam örtme ve nozul değişimi, bitkinin istemiş olduğu günlük sulama suyu miktarı ve başlık yağmurlama hızı dikkate alınarak hesaplanan başlığın çalışma süresinde sulama suyunun toprak yüzeyine eşit miktarda dağılması gerekmektedir. Böylece çim örtüsü üzerinde eş bir nem dengesi korunmuş ve her daim yeşil sağlanmış olmaktadır. Aynı zamanda gereksizce vanaların fazla çalıştırılıp çimde sararma olan yerler giderilmeye çalışılırken, gereksiz yere yapılan su sarfiyatı engellenmiş olmaktadır (Orta, 2017).

Sprey yağmurlama başlıkları ayarlanabilir açı ayarları bulunmaktadır. Su tasarrufu özellikleri, sislemeden kaçınmak için basınç ayarı içeren modelleri vardır. Bazı sprey yağmurlama başlıkları, suyun sistemdeki en alçak başlıktan dışarı akmasını engellemek suretiyle, erozyonu ve su sızıntısını gideren silecek contaları ve çek valfler gibi yerleşik cihazlara sahiptir. Rotorlarla olduğu gibi, düşük yağış hızlı püskürtme başlıkları belirli bir zamanda daha az su uygulayarak daha iyi toprak penetrasyonuna imkân vermektedir (Orta, 2017).

Rekreasyon alanlarında uygulanan yağmurlama sulama yönteminin uygulanmasındaki en büyük dezavantaj rüzgârlı ortamlarda oluşan sulama suyu kayıplarıdır. Bu durum önlemler alınmadığı ve doğru başlıklar seçilmediği taktirde sulama randımanının düşmesine yol açmaktadır. Balcı ve Orta (2018)'nın yaptığı bir araştırmada rüzgârlı ve rüzgârsız koşullarda çarpmalı, MP rotator, dişli rotor ve sprey yağmurlama başlıklarının su dağıtım desenleri belirlenmiştir. Elde edilen sonuçlara göre seçilen başlıkların rüzgârlı koşullarda eş su dağılım katsayısı sıralaması yüksekte düşüğe doğru dişli rotor, MP rotator, sprey ve çarpma yağmurlama başlığı biçiminde sıralanmıştır.

4. SONUÇ VE ÖNERİLER

Rekreasyon alanları ve spor sahaları iklim değişikliğinden en çok etkilenmesi beklenen alanlar arasındadır. Çünkü, bu alanlardaki çim türleri yüksek miktarda sulama suyuna ihtiyaç duymaktadır. Dolayısıyla ilk önce rekreasyon alanlarında kullanılan sulama suyu miktarından tasarruf edici önlemler alınmalıdır. Rekreasyon alanlarında veya spor sahalarında çim bitkisini seçerken kullanım amacına, iklim şartlarına ve bulunduğu konuma dikkat edilmelidir. Su kaynaklarının kısıtlı olduğu yerlerde kurak şartlara uygun çim türleri tercih edilmelidir. Çim türünü seçerken tek bir tür kullanarak ekim yapılmamalı, kullanma amacına göre çim türlerinin farklı oranlarda karışımları hazırlanmalıdır.

Çim türleri, serin iklim ve sıcak iklim olmak üzere iki sınıfa ayrılmaktadır. Türkiye'de Akdeniz koşullarında sıcak iklim türü olarak yaz aylarında Bermuda çimi kullanılmaktadır. Bu çim türünün en önemli özelliği hızlı bir şekilde kardeşlenip geniş alanlara yayılım sağlayabilmesidir. Bakımı da kolaydır. Serin iklim çim türlerinden İngiliz çimi (Lolium perenne L.), Çayır Salkım Otu (Poa pratensis L.), Kırmızı Yumak (F. rubra L.), Sülüklü Tavusotu (Agrostis Stoloniferea), Adi Salkım Otu (Poa trivialis L.), Çayır Yumağı (F. pratensis), Narin Tavusotu, Kamışsı Yumak (F. arundinacea), Kahverengi Tavusotu (Agrostis tenuis) gibi türler en çok tercih edilen çim bitkileri arasında yer almaktadır.

Çim bitkisi çoğunlukla rekreasyon alanlarında kullanılmakla birlikte gol, futbol, bowling ve tenis kortları gibi spor alanlarında da sıklıkla kullanılmaktadır. Özellikle golf sahalarında çok geniş alanlar çim örtüsüyle kaplıdır. Golf sahası çok yeşil alanı barındırdığı için sulama suyu ihtiyacı da çok fazladır. Bu nedenle sulama yönetimi çok büyük bir önem taşımaktadır.

Sulama sistemlerinin projelendirilmesi yapılırken kullanılacak malzemenin özellikleri bilinmeli, seçilen çim türünün iklim şartları gözetilerek düşük bitki su tüketimine sahip özellikte çeşitler tercih edilmelidir. Etkin bir su kullanımını sağlanması için sensörler yardımıyla sulama sistemi çim bitkisinin ihtiyaç duyduğu anda devreye girmesi gerekmektedir. Ayrıca sulama sisteminin hidrolik kurallara uygun biçimde tasarlanması gerekmektedir. Tüm bu konular dikkate alındığında, bir rekreasyon alanında çim yetiştiriciliği için sulama projelendirilmesinin uzman sulama mühendisleri tarafından tasarlanması gerekmektedir.

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BÖLÜM III

Redefınıng Water Resources: Innovatıve Water Harvestıng Strategıes In Agrıcultural Drought Management

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İlknur CEBECİ[2]

1. Introduction

Global water resources are increasingly under pressure due to factors such as population growth, economic development, urban expansion, and climate change. As global water demand continues to rise each year, existing water resources are being rapidly depleted. The agricultural sector, in particular, accounts for approximately 70% of the world's water consumption, making it the largest water

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user (FAO, 2020). This situation underscores the critical importance of efficient water management in agricultural production. With the increasing frequency of drought events due to climate change, agricultural production and food security are under threat, necessitating a reassessment of agricultural drought management strategies (IPCC, 2019).

Drought management in agriculture is of critical importance not only for the conservation of water resources but also for ensuring the continuity of sustainable agricultural production. Traditional water management methods are proving inadequate in the face of rapid climate change and increasing drought events, which highlights the growing need for innovative water management strategies (Mishra and Singh, 2010). In this context, water harvesting emerges as a significant strategy for evaluating alternative water resources and reducing the dependency of agricultural production on water (Rao et al., 2017). Water harvesting, which involves the collection and efficient use of alternative water sources such as rainwater, surface runoff, and groundwater, is recognized as a crucial tool in combating agricultural drought. However, for this strategy to be effectively implemented, regional conditions and agricultural requirements must be taken into consideration (Falkenmark and Rockström, 2004). Innovative water harvesting strategies not only ensure the preservation of water resources but also contribute to food security by improving water efficiency in agricultural production (Ray and Majumder, 2024; Tamagnone et al., 2020).

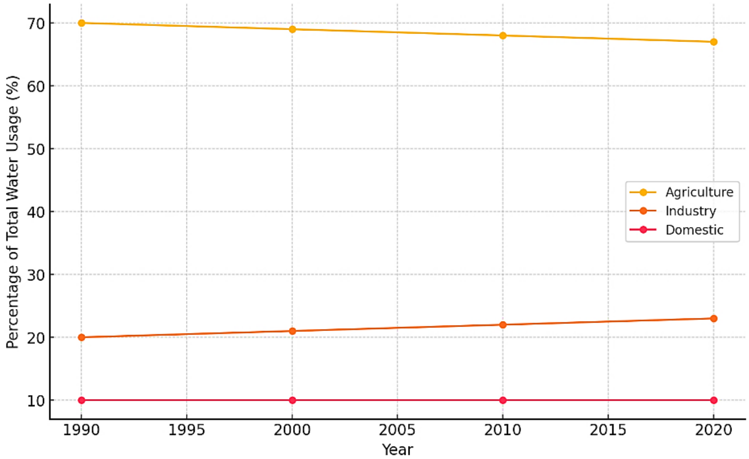


Figure 1. Global water usage by sector (1990-2020)

Globally, water resources are rapidly decreasing due to factors such as the growing population, industrialization, urbanization, and especially climate change. Water scarcity poses significant threats, particularly in the agricultural sector (Figure 1). Agriculture, accounting for approximately 70% of global water usage, is the largest consumer of water (FAO, 2020). However, the reduction in available water resources has emerged as one of the greatest challenges to maintaining sustainable agricultural production. The limitation of water resources not only reduces the efficiency of irrigation systems but also leads to substantial losses in agricultural production (Foley et al., 2011).

2. Traditional Water Managements

Although traditional water management strategies for combating agricultural drought have been adopted and applied by farming communities for many years, they are proving inadequate in the face of rapidly changing climate conditions and increasing water demand. Traditional methods generally rely on irrigation, dam construction, and groundwater usage. However, these approaches have led to the depletion of water resources, soil salinization, and environmental degradation in many regions (Madramootoo, 2012; Hussain et al., 2019). For example, excessive groundwater use has resulted in a drop in the water table, causing permanent water shortages in some areas (Gleeson et al., 2012). This indicates that traditional methods are not sustainable and are becoming increasingly risky due to the effects of factors such as climate change.

Traditional water management strategies, in order to guarantee water supply during drought periods, often rely on large-scale infrastructure projects, dams, and water distribution networks. These projects, however, may fail to ensure the equitable and fair distribution of water and often require significant costs. Additionally, such large projects can have negative impacts on ecosystems and threaten biodiversity (Richter et al., 2010). Rather than promoting efficient water use, traditional methods have frequently led to the over-exploitation of resources, causing water to be depleted rapidly during drought periods.

Another significant limitation is the low capacity of traditional water management strategies to adapt to the uncertainties brought about by climate change. Increasing temperatures, changing precipitation patterns, and more frequent drought events due to climate change require flexible and adaptive approaches in water management (Bates et al., 2008). Traditional methods are insufficient in adapting to these variable conditions, thereby jeopardizing the security of agricultural production. This clearly underscores the need for more innovative and sustainable water management strategies in agricultural drought management.

In conclusion, traditional water management strategies fail to provide long-term sustainable and effective solutions for combating agricultural drought. The pressures these methods place on water resources, along with their environmental impacts, indicate the need for more innovative and integrated approaches in water management. Modern strategies, such as water harvesting and circular water management, offer more effective and sustainable solutions for addressing drought, with the potential to ensure the continuity of agricultural production (Rockström et al., 2007).

3. Redefining Water Resources: Expanding the Concept of Water Harvesting

Traditional water resources are typically defined by rivers, lakes, groundwater, and water stored in dams. However, these resources are rapidly depleting due to factors such as population growth, climate change, over-exploitation of water, and environmental degradation, rendering them inadequate for sustainable agricultural production (Falkenmark and Rockström, 2004). Water harvesting expands this traditional definition, offering a new perspective on agricultural water management. By incorporating methods such as the collection and reuse of rainwater, surface runoff, and wastewater, water harvesting allows for the diversification of water resources. This approach provides alternative solutions for the conservation of water resources and the sustainability of agricultural production. For instance, rainwater harvesting is the method of collecting and storing water directly from the ground surface or from surfaces such as rooftops. This water can later be used for irrigation or other agricultural activities. In some arid regions of India, rainwater harvesting practices have reportedly led to significant increases in agricultural production (Patode et al., 2021). This demonstrates that water harvesting not only increases water resources but also enhances agricultural productivity.

3.1. Evaluation of Alternative Water Resources:

Water harvesting allows for the utilization of alternative water sources in agricultural water management. In regions where traditional water resources are inadequate or at risk of depletion, the use of alternative water sources is of vital importance. Rainwater harvesting, the collection of surface runoff, and the sustainable use of groundwater are among these alternative resources. Additionally, the treatment and reuse of wastewater for agricultural irrigation contributes to the more efficient use of water resources.

Rainwater harvesting plays a critical role in meeting water needs, particularly in regions experiencing water scarcity. It is estimated that the application of rainwater harvesting techniques globally could collect 80-90 billion cubic meters of water annually (World Bank, 2016). This amount could make a significant contribution to agricultural production in countries suffering from water shortages (Figure 2). Similarly, the collection of surface runoff prevents the rapid evaporation and loss of water, allowing for more efficient storage of water for use in agricultural production.

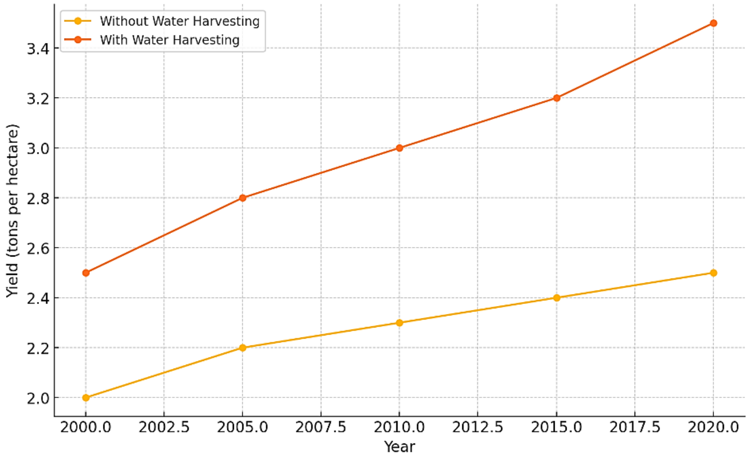


Figure 2. Impact of water harvesting on agricultural yield (2000-2020)

The sustainable use of groundwater is also an essential component of water harvesting strategies. Excessive groundwater use leads to a drop in the water table and threatens the sustainability of water resources (Gleeson et al., 2012). However, through water harvesting, groundwater can be naturally recharged, allowing for its sustainable use. The use of treated wastewater in agricultural irrigation is another alternative water source. In Israel, more than 50% of the water used for agricultural irrigation is obtained from treated wastewater, and this practice ensures the uninterrupted continuation of agricultural production in the country (Shelef, 2010). This example illustrates how water resources can be expanded through the recovery and reuse of wastewater.

3.2. The Potential Effects of Water Harvesting on Global Water Security and Its Role in Providing Solutions to the Water Crisis

Global water security is under serious threat due to increasing water demand and diminishing water resources. It is expected that global water demand will increase by 40% by 2030, necessitating more sustainable management of water resources (UN Water, 2020). Water harvesting contributes to water security by enabling the efficient collection, storage, and reuse of water. This strategy, particularly in regions facing water scarcity, allows for more efficient use of water and the creation of agricultural systems that are resilient to the water crisis.

Water harvesting offers innovative solutions to enhance global water security. For instance, in the Sahel region of Africa, which suffers from water scarcity, water harvesting practices have increased agricultural production and ensured food security for local communities (Rockström et al., 2010). In this region, water harvesting involves the collection and storage of rainwater and surface runoff, which is then used for agricultural irrigation during dry periods. This practice has made significant contributions to local economies and has emerged as a successful strategy in the fight against water scarcity.

The impact of water harvesting on global water security is not limited to the collection and storage of water; it also involves preserving the natural water cycle and sustainably managing water resources. Water harvesting strategies support the replenishment of water in nature and maintain the water cycle, offering long-term solutions to the water crisis. These strategies not only help conserve water resources but also improve water efficiency in agricultural production, thereby supporting food security (Falkenmark and Rockström, 2004).

In conclusion, water harvesting stands out as an important strategy that expands the traditional definition of water resources and offers innovative solutions in agricultural water management. The utilization of alternative water sources, such as rainwater, surface runoff, groundwater, and treated wastewater, plays a critical role in the creation of agricultural systems that are resilient to the water crisis. In this context, water harvesting holds great potential in ensuring global water security and developing sustainable solutions to the water crisis.

4. Innovative Water Harvesting Techniques

Water harvesting, which is based on the use of water collected after rainfall in various applications, can be classified into micro and macro systems for agricultural use and rooftop water harvesting for domestic use. Water harvesting, defined as a method for collecting, preserving, and storing local surface runoff for agricultural purposes (Boers and Ben-Asher, 1982), has the following primary objectives:

- Increasing productivity in areas with insufficient rainfall,
- Supporting afforestation activities to combat desertification and erosion,
- Providing drinking water for livestock,
- Supplying water for domestic use,
- Combating drought and minimizing its adverse effects,
- Conserving irrigation water in irrigated areas,
- Ensuring the proper use of limited water resources.

In areas where rainfed agriculture is practiced, changes in rainfall patterns negatively affect crop yields. Water harvesting systems are crucial for overcoming irregularities in rainfall. To increase the effectiveness of water harvesting, mulching is applied. For this purpose, textile, plastic, straw, and other organic mulch materials are used.

All water harvesting methods consist of three components: the water collection area, also known as the surface runoff area, the storage area, and the target area (Figure 3). The water collection area can range in size from a few square meters to several square kilometers. This area is the piece of land that channels part or all of the rainwater to the target area beyond its boundaries. It can be an agricultural, rocky, or marginal area, or even a rooftop or asphalt road. The storage area is where the rainwater is held and collected until it is used.

Figure 3. Basic components of water harvesting

Storage can occur in surface and subsurface reservoirs, as soil moisture in the soil profile, or in underground aquifers. The target area is where the harvested water is used. In agricultural production, the targets are plants and animals, while for domestic use, the targets are people and their needs (Oweis and Hachum, 2009).

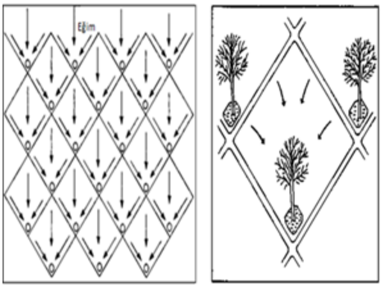
Water harvesting methods are classified in various ways based on their purpose, form, or storage method, but the most common classification is based on the size of the water collection area: micro-catchment and macro-catchment water harvesting methods. This section focuses on the micro-catchment water harvesting methods most commonly used in crop production.

4.1. Micro-Catchment Water Harvesting

Micro-catchment water harvesting involves collecting water within a smaller area or within the root zone of the plant, as compared to the larger water collection area (Table 1). In this method, the collected water is used as soil moisture for irrigation in the cultivation area located directly next to the surface runoff area, or it is stored for later use. In a severely dry year with no rainfall, an effective water harvesting system will support plant growth for much of the year. When selecting micro-catchment water harvesting methods, factors such as topography, climate conditions, and the crop to be cultivated are considered. In water harvesting techniques applied for crop production, mulching is used to enhance the effectiveness of rainfall harvesting and thereby increase yields. To collect more surface runoff, organic or inorganic mulching can be applied in the water collection area within the micro-catchment. Some commonly used water harvesting techniques in agriculture are illustrated in Table 1.

Table 1. Some water harvesting techniques and application methods

Water Harvesting Technique	Application Features

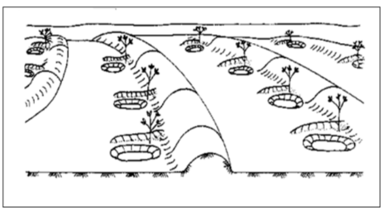


a) Small flow catchments (Negarim) (Critchley and Siegert, 1991)

This method is preferred for tree cultivation in areas with slopes of up to 5%, where a smooth topography is not required (Critchley and Siegert, 1991).

b) Semi-circular bunds (Bardın, 2012)

It is commonly used in grasslands, pastures, shrub plants, vegetable farming, and tree cultivation. This method is preferred in areas with flat topography, where the slope ranges from 0.5% to 5%. A limiting factor of this method is the difficulty of using machinery (Critchley and Siegert, 1991).

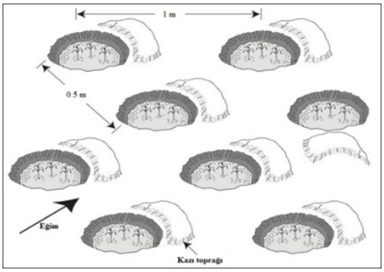


c) Contour bunds (Critchley and Siegert, 1991)

This method, used for trees, is a simplified version of micro-catchments. It can be constructed using machinery and is therefore suitable for larger areas. This method is preferred in areas with flat topography and slopes of up to 5%. It is not suitable for uneven or erosion-prone areas (Critchley and Siegert, 1991).

d) Inter-row systems (Cebeci et al., 2024)

It is the most suitable method for lands with a smooth topography. It is used for high-yield crops such as vegetables, row crops, and fruit trees (Oweis et al., 2001).



e) Small holes (Malesu et al., 2007)

This method, primarily used in pastures, is also suitable for annual plants. It is particularly well-suited for improving low-water-retaining, infertile soils (Oweis et al., 2001). Its main advantages are the ease of application in the field and the simplicity of maintenance (Anschuetz et al., 2003).

f) Surface flow strips

It is suitable for gently sloping areas. In arid regions with low yields, it is used to support the growth of field crops. This method is mechanized and requires minimal labor (Oweis et al., 2001).

5. The Strategic Importance of Water Harvesting in Agricultural Dought Management

Drought, in its simplest definition, is when precipitation falls below normal levels. Meteorological drought is defined as a natural event where precipitation significantly drops below recorded normal levels, leading to negative impacts on land and water resources and causing disruptions in the hydrological balance (GDM, 2024). The key characteristics of drought are its uncertain onset and end, cumulative increase, simultaneous impact on multiple sources, and its high economic cost. Drought brings numerous economic, environmental, and social effects, including crop and production losses, delays in economic development, reductions in food production and stocks, difficulties in obtaining financial resources, losses in the contribution of rivers and canals to shipping, the high cost of developing new and additional water resources, the expense of water transport, losses in farmers' incomes, unemployment, depletion of energy resources, losses in industries directly dependent on agricultural production, soil and wind erosion, degradation of water quality, impacts on livestock quality and natural habitats, and ultimately food shortages, increased poverty, migration, social unrest, and a decline in living standards in rural areas.

The impact of drought in agriculture is different from other sectors. This is because the effects of drought are first observed in agriculture, as crops require rainfall not just over the entire year, but specifically during their growth periods. *Agricultural drought* is defined as the lack of sufficient water in the soil during the period when the plant requires it.

Drought is a silent disaster, and by the time it arrives, it may already be too late to act. Therefore, it is crucial to prepare for drought rather than waiting for it to occur. In this regard, practices that minimize the risk of drought in agriculture should be prioritized. Some of these practices include the use of drought-resistant varieties, mulching to preserve soil moisture, direct seeding into stubble, and water harvesting. In regions where rainfed agriculture is practiced, micro-catchment water harvesting systems are vital for mitigating the effects of agricultural drought and compensating for irregular rainfall during periods when crops have the greatest need for water. The water collected through harvesting can be utilized during critical periods when plants are most sensitive to water shortages. Additionally, combining water harvesting with mulching in crop production minimizes evaporation losses. This way, even with limited rainfall, the collection of available rainwater through water harvesting ensures plant growth during dry periods.

Due to global climate change, rising temperatures, changes in rainfall patterns, loss of surface water, and increasing drought periods are threatening the availability of water resources. While the natural and agricultural water requirements of plants will increase, the reduction in water resources demonstrates the necessity of more effective water management in the future. In this context, there is a recognized need to integrate climate change adaptation into water resource management policies, including basin-level water management, inter-sectoral water distribution, water conservation, monitoring water use, expanding observation networks, and increasing large-scale artificial storage structures (Anonymous, 2024). The benefits of water harvesting, which has been applied for centuries using traditional methods in arid and semi-arid areas, are now supported by scientific research. In this regard, water harvesting is increasingly included in climate change policies and is one of the recommended practices for combating drought.

6. Successful Innovative Water Harvesting Projects and Practices

Water harvesting, an important technique for addressing the risks to agricultural production posed by drought and insufficient water resources, has been the subject of numerous studies and field applications in many countries, yielding significant results (Table 2). The contribution of various water harvesting practices applied under different land conditions to increasing crop yields is noteworthy.

Table 2. Some successful water harvesting practices

Country	Crop	Water Harvesting Method	Effectiveness of Method	Reference
South Africa	Corn	Surface runoff strips (1-1.5-2-3 m) and mulch (bare, 12%, 39%, 64% and 96% organic mulch)	3 times increase in surface runoff efficiency for 1m strip width	Tesfuhuney et al. (2013)
Kenya	Wheat	Plastic and straw mulch with inter-row systems	60-163% increase in wheat yield in all mulched water harvesting applications	Wang et al. (2016)
China	Wheat	Inter-row systems (3 different ridge widths) with plastic mulch	Yield increase at a ridge width of 40 cm: 11.8%-13.6%, at a ridge width of 60 cm: 20.6%-23%, at a ridge width of 80 cm: 4.5%-3.4%.	Ren et al. (2016)
Türkiye	Melon	Inter-row systems (3 different ridge widths) with plastic and straw mulch	30.5%-66% increase in soil moisture	Cebeci et al. (2017)

Türkiye	Squash	Inter-row systems (3 different ridge widths) with plastic mulch	18.8%-209.3% increase in crop yield.	Ünlükara et al. (2021)
China	Potato	Inter-row systems (3 different ridge widths) with plastic mulch	158.6-175.0% increase in crop yield.	Wang et al. (2008)
Türkiye	Melon	Plastic mulch with inter-row systems	84.5%-111.8% increase in crop yield.	Cebeci et al. (2024)
Libya	Australian Atriplex	Contour ridges and negarim	2.3%-11% increase in biomass	Razzaghi (2011)
Nigeria	Citrus	Negarim	Surface runoff coefficient 0.48	Ayanshola and Dauda (2019)
Iran	Pasture	Negarim and bankette	20% increase in soil moisture	Dastorani et al. (2017)

7. Future Perspectives: Sustaining and Expanding Innovation

The development of future water harvesting technologies is of great importance for agricultural drought management and the sustainability of water resources. The integration of technologies such as artificial intelligence (AI), machine learning (ML), and the Internet of Things (IoT) into water harvesting processes can enable more efficient use of water resources. For example, AI-based models integrated into water management systems can predict agricultural water demand and ensure the optimal distribution of water based on these predictions. According to a report by McKinsey Global Institute, AI and ML-based solutions can achieve up to 20% water savings in agricultural water use (McKinsey Global Institute, 2021). This is a critical development, particularly for regions experiencing water scarcity. Blockchain technology, on the other hand, emerges as an important innovation for monitoring water resource usage and increasing transparency in water management. By facilitating the tracking and management of water usage, this technology ensures that water harvesting processes are more secure and efficient (Janssen et al., 2021).

The continuation and widespread adoption of innovation are directly linked to the development of policies that support water harvesting. Incentives and regulatory frameworks for water harvesting can accelerate the adoption of these technologies. For example, 30% of the funds allocated to water management projects within the European Union's Horizon 2020 program have been directed towards the development of water harvesting and recovery technologies (European Commission, 2020). Such policies encourage the broad application of water harvesting technologies and support innovation in water management. Similarly, the encouragement of water harvesting projects by local governments helps promote the wider use of these technologies in agriculture. Policymakers can increase the adoption of these strategies by using tools such as tax reductions, subsidies, and technical support to promote water harvesting (OECD, 2021).

Water harvesting strategies also have the potential to offer sustainable solutions to climate change. Climate change is causing significant shifts in the water cycle and complicating the management of water resources. For example, the IPCC (2021) report predicts deviations of 15-20% in global precipitation patterns due to the effects of climate change. While this makes water resource management more complex, it also highlights the importance of water harvesting strategies. By enabling the local storage and reuse of water, water harvesting can enhance water security and help mitigate the negative impacts of climate change. For instance, innovative water harvesting projects implemented in the Rajasthan region of India have resulted in water savings of up to 30% in areas facing water scarcity and a 20% increase in agricultural production (Wani et al., 2021). Such examples demonstrate how water harvesting strategies can support sustainability in the context of climate change and their potential to provide long-term solutions.

In the future, the sustainability and widespread adoption of water harvesting strategies will depend on the integration of technology, policy, and climate change factors. This process will play a crucial role in ensuring more efficient use of water resources and in achieving global water security and agricultural sustainability goals. The large-scale adoption of innovative water harvesting strategies has the potential to become an effective tool in combating climate change, and innovations in this field are expected to make agricultural production systems more resilient and sustainable in the future.

8. Conclusion

Water harvesting has emerged as a vital strategy in addressing the increasing challenges posed by water scarcity, agricultural drought, and climate change. As global demand for water continues to rise, driven by population growth, urbanization, and shifting climate patterns, traditional water management approaches are proving inadequate. In response, innovative water harvesting strategies offer a sustainable alternative for improving water efficiency, enhancing agricultural productivity, and contributing to global water security.

By expanding the concept of water resources to include alternative sources such as rainwater, surface runoff, and treated wastewater, water harvesting has demonstrated its potential to alleviate the stress on conventional water supplies. In regions suffering from irregular rainfall and drought, micro-catchment systems and other innovative techniques have enabled the storage and use of water in critical periods, ensuring the continuity of agricultural production even in adverse climatic conditions.

The integration of advanced technologies like artificial intelligence, machine learning, and blockchain into water harvesting practices offers further opportunities for enhancing efficiency and transparency in water management. These innovations, supported by policy frameworks and government incentives, will be crucial in promoting the widespread adoption of water harvesting techniques and ensuring their long-term sustainability.

As the effects of climate change intensify, the need for resilient agricultural systems becomes more urgent. Water harvesting, with its ability to improve water use efficiency, mitigate drought impacts, and support food security, holds the potential to play a key role in the global effort to adapt to and combat the water crisis. Going forward, the continued development and dissemination of water harvesting technologies will be instrumental in achieving sustainable agricultural practices and securing water resources for future generations.

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BÖLÜM IV

Etlik Piliç Kümeslerinde Tünel Havalandırma: Etkili Tasarım Kriterleri ve Uygulamaları

Ali ÇAYLI[1]

Giriş

Modern kanatlı yetiştiriciliğinde, tünel havalandırma sistemleri, iç ortam iklimini yönetmede kritik bir bileşen olarak önem taşımaktadır. Bu sistemler, hayvanların ısı stresini minimize etmek ve yüksek sıcaklıkların üretkenlik üzerindeki olumsuz etkilerini azaltmak için geliştirilmiştir. Tamamen kapalı kümeslerde hava hareketinin etkili bir şekilde sağlanması, özellikle sıcak havalarda, tavukların sağlığını ve performansını doğrudan etkiler (Boyacı, 2018; Büyüktaş, Atılgan, & Tezcan, 2016; Hellickson & Walker, 1983; Lindley & Whitaker, 1996). Bu sistemde, egzoz fanları kümesin bir ucuna, hava girişleri ise diğer uca yerleştirilir.

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Hava, bu açıklıklardan çekilerek ve sistem boyunca yönlendirilerek hareket eder. Tünel havalandırma sistemi, hayvanların seviyesindeki hava hızını nispeten sabit tutarak, kümes boyunca tekdüze bir hava hareketi sağlar. Bu tekdüze hava hareketi, hayvanlar soğutma etkisi oluşturarak sıcaklık stresini azaltır. Yapılan çalışmalar, hayvanların nispeten yüksek hava sıcaklıklarında bile hava hareketi yoluyla etkili bir şekilde soğutulabileceğini göstermiştir (Bucklin, Jacob, Mather, Leary, & Naas, 2009; Bustamante, García-Diego, Calvet, Torres, & Hospitaler, 2015; Drury, 1966)

Drury (1966), yüksek ortam sıcaklıklarında artan hava hareketinin piliçlerde kilo alımını iyileştirdiğini, bu iyileşmenin hava hızının kareköküyle neredeyse orantılı olduğunu keşfetmiştir. Wilson, Albright, and Walker (1983), tarafından yapılan bir araştırma, kapalı kümeslerdeki hava hızı, yan duvar girişlerinden kümes merkezine doğru hareket ettikçe genleşme nedeniyle yüzde 50'den fazla azaldığını ortaya koymuştur. Ayrıca hava hareketinin sağladığı faydalar hava sıcaklığı yaklaşık 40°C'ye ulaşana kadar belirgindir. Hava sıcaklığı 40°C'nin üzerine çıktığında, artan hava hareketi aslında ısı stresini artırabilir, çünkü hava sıcaklığı hayvanın vücut sıcaklığından daha yüksek olmaktadır (M. Czarick & Tyson, 1990). Ayrıca tünel havalandırma en yüksek kademedeyken, kümes boyunca sıcaklık farkı 2.8°C'yi aşmamalıdır (Aviagen, 2019).

Tünel havalandırmanın otomasyon ile kontrol edilmesi durumunda, kontrol sistemleri, kümes ortamının uygunluğunu değerlendirmek için tek başına yeterli olmamalı aynı zamanda kanatlıların davranışları da gözlemlenmelidir. Ortam çok soğuk olduğunda, hayvanlar bir araya toplanır ve üşüdüklerini belirten gürültülü, stresli sesler çıkarırlar. Uygun ortamda ise, kanatlılar eşit dağılım gösterir ve çıkardıkları sesler memnuniyetlerini ifade eder. Ortam aşırı sıcaksa, hayvanlar ısı kaynağından uzaklaşır ve bitkin görünürler. Ayrıca sessizleşerek, hızlı soluk alıp vermeye başlarlar. (Aviagen, 2019).

Tünel havalandırma sistemleri, çevresel kontrol açısından geleneksel kümeslere göre önemli bir avantaj sunsa da sistemin etkinliği büyük ölçüde tasarım ve işletim kalitesine bağlıdır. Geleneksel kümeslerde, hava değişimi ve dağıtımı genellikle kontrol edilemezken, tünel havalandırmalı bir kümes, işletmecisine çevre üzerinde yüksek düzeyde kontrol imkânı sağlar. Ancak, havalandırma sistemi uygun şekilde tasarlanmazsa veya kurulumda hatalar yapılırsa, üreticilerin çevresel koşulları kontrol etme yeteneği sınırlı kalabilir ve bu da üretim kalitesini olumsuz etkileyebilir. Tünel havalandırma sistemlerinin avantajlarını tam anlamıyla kullanabilmek için, bu sistemlerin detaylı bir şekilde tasarlanması, uygulanması ve bakımının yapılması gerekmektedir.

Bu çalışma, etlik piliç kümeslerinde tünel havalandırma sistemlerinin kullanımının performans ve kümesin çevre koşullarına etkilerini incelemeyi amaçlamaktadır. Literatür araştırması yoluyla mevcut bilgileri ve uygulama örneklerini değerlendirerek, bu sistemlerin verimlilik üzerindeki etkilerini kapsamlı bir şekilde inceleyecektir. Çalışmanın hedefi, tünel havalandırma sistemlerinin avantajlarını, potansiyel zorluklarını ve bu teknolojinin en etkili şekilde nasıl kullanılabileceğine dair bilgi sağlamaktır.

Hava Hızı

Tünel havalandırma sistemlerinde hava hızı, kanatlı hayvanların konforu ve sağlığı açısından kritik bir parametredir.

Kümesin bir ucundan diğer ucuna ilerleyen hava, soğutma etkisi yaratarak hayvanların hissettiği sıcaklığı doğrudan etkiler. Uygun hava hızı sağlanamadığında kanatlılar sıcaklık stresi veya üşüme etkisi ile olumsuzluklar yaşayabilirler, bu da üretim performanslarını olumsuz yönde etkileyebilir. Özellikle hava hızı düşük olduğunda, soğutma etkisi yetersiz kalır ve hayvanlar sıcaklık stresine maruz kalır. Diğer taraftan, hava hızı çok yüksek olduğunda ise kanatlılar gereğinden fazla soğuyarak üşüme riskiyle karşılaşabilir. Bu nedenle, hava hızının düzenli olarak ölçülmesi ve izlenmesi, havalandırma sisteminin verimliliğini değerlendirmenin yanı sıra olası sorunların önceden tespit edilmesine olanak tanır. Böylece, kümes ortamındaki hava koşullarının kontrolü sağlanarak kanatlıların optimum sıcaklık seviyesinde tutulması mümkün olur (Boyacı, 2018; Drury & Siegel, 1966; Furlan, Macari, Secato, Guerreiro, & Malheiros, 2000; Lott, Simmons, & May, 1998; May, Lott, & Simmons, 2000; Yahav, Straschnow, Vax, Razpakovski, & Shinder, 2001).

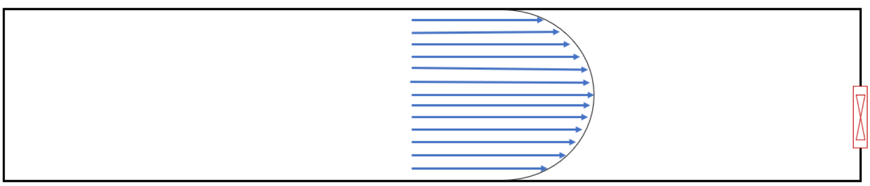
Tünel havalandırma sistemleri belirtilen hava hızı ve hava değişim oranını karşılamak üzere tasarlanmıştır. Ancak, gerekli hava hızı söz konusu kanatlı sınıfına bağlıdır. Çizelge 1'de, çeşitli kümes hayvanı sınıflarının yetiştirilmesi için önerilen hava hızı verilmiştir (Daghir, 2008).

Çizelge 1. Tünel havalandırmalı kümesler için tavsiye edilen hava hızları

Kanatlı Tipi	**Hava Hızı ($m\ s^{-1}$)**
Etlik Piliç	2.5–3
Yarka	1.75–2.25
Damızlık Broyler	2.25–3

Hindi	2.5–3

Çizelge 1'deki veriler, farklı kümes hayvanı sınıfları için önerilen hava hızlarının değiştiğini göstermektedir. Etlik piliç ve hindi gibi büyük kütlelere sahip türler için önerilen hava hızları genellikle 2.5–3 m s^{-1} arasındadır; bu da bu hayvanların vücut sıcaklığını optimum seviyede tutmak için bir soğutma etkisi sağlar. Bu hız, piliçler (1.75–2.25 m s^{-1}) gibi daha küçük kanatlılar için daha düşük tutulur, çünkü bu sınıftaki hayvanlar daha düşük hava akışında uygun bir ısı dengesini koruyabilirler. Damızlıklar için de benzer bir hava hızı aralığı (2.25–3 m s^{-1}) öngörülmektedir. Bu farklılıklar, her hayvan sınıfının havalandırma gereksinimlerinin biyolojik özelliklerine göre farklı olduğunu ve tünel havalandırma sistemlerinin bu gerekliliklere göre dikkatlice ayarlanması gerektiğini göstermektedir. Tünel havalandırmalı yapılar tasarlanırken en az 1.8 m s^{-1} hava hızının kullanılması tavsiye edilmektedir (Drury, 1966). Bununla birlikte tünel havalandırmalı bir kümesteki hava hızı, herhangi bir kesitte hareket ederken, sürtünme nedeniyle kesit düzlemin her noktasında aynı değildir (Şekil 1).



Şekil 1. Tünel havalandırmalı bir kümeste hız profili

Hava hızı, kesitin merkezinde en yüksek olup, duvarlar, zemin ve tavana yaklaştıkça sürtünme etkisiyle azalmaktadır. Kanatlıların bulunduğu seviyede yeterli hava hareketini sağlamak için, zemine yakın hızdaki bu düşüş dikkate alınmalı ve ortalama hava hızı, hedeflenen hızdan en az %10 daha yüksek olmalıdır. Eğer ortalama hava hızı bu gereksinimi karşılamıyorsa, egzoz fanlarının sayısının artırılması ya da hava akışını yönlendiren deflektörlerin kullanılmasıyla hız arttırılabilmektedir (M. Czarick & Tyson, 1990).

Tünel Fan Kapasitesi ve Hava Hızının Hesaplanması

Tünel havalandırmalı bir kümesin minimum fan kapasitesi, giriş havalandırmalı kümeslerde olduğu gibi ısı dengesi yöntemiyle belirlenir. Bu yöntem, piliçlerin kesim ağırlığına ulaştığında en sıcak günde, kümesin tünel girişi ile tünel fanları arasında 2,8°C'den fazla bir sıcaklık farkı olmamasını sağlar. Bu durumda hava hızı, toplam fan kapasitesinin kümesin en kesit alanına bölünmesiyle belirlenebilir. En kesit alanı ise kümesin genişliği ile ortalama yüksekliğinin çarpılmasıyla hesaplanabilir (M. Czarick, III & Fairchild, 2008; Olgun, 2011; Tekinel, Kumova, Alagöz, & Demir, 1988).

$$\text{V} = \frac{Q}{A} \times \frac{1\,h}{3600\,s}$$

Eşitlikte, V hava hızı (m s^{-1}), Q fan kapasitesi m^3 h^{-1}, A kesit alanı (m^2) göstermektedir.

Örneğin 3.0 m yüksekliğe ve 16.0 m genişliğe sahip bir kümeste 35,000 m^3 h^{-1} kapasiteli 4 fanın çalışması durumunda hava hızı;

$\text{V} = \frac{4\times(35000\,m^3/h)}{3\,m\times 16\text{ m}} \times \frac{1\,h}{3600\text{ s}}$ => $V = 0.81\,m/s$ olarak hesaplanabilir.

Tünel havalandırmalı bir piliç kümesindeki hava hızı, genişliği ve yüksekliği de dahil olmak üzere kesit alanından önemli ölçüde etkilenir. Daha büyük kesit alanları genellikle daha düşük hava hızları ve azaltılmış konvektif soğutma ile sonuçlanır. Bir kümes, uygun hava değişimi için yeterli fan kapasitesine sahip olabilirken, büyük bir kesit alanı soğutma için yeterli hava hızına ulaşmayı engelleyebilir. Bu nedenle, tünel kümeslerinin daha düşük yükseklikte tavanlara sahip olması tercih edilir. Ek olarak, belirli bir taban alanı için, uzun ve dar bir tasarım, kısa ve geniş bir tasarımdan daha etkilidir, çünkü bu kesit alanı ile ilgilidir. Aynı taban alanına sahip iki kümes –biri uzun ve dar, diğeri kısa ve geniş– hava değişimi için aynı fan kapasitesine ihtiyaç duyacaktır. Hesaplanan minimum tünel fan kapasitesi, istenen hava hızına ulaşmak için yetersizse, fan kapasitesini artırmak gerekecektir. Aşağıdaki denklem, istenen hava hızına ulaşmak için gereken tünel fan kapasitesini belirlemek için kullanılabilir (M. Czarick, III & Fairchild, 2008).

$$\mathrm{Q} = \mathrm{V} \times \mathrm{A} \times 3600$$

Eşitlikte, Q fan kapasitesi $m^3\ h^{-1}$, V kümeste istenen hava hızı ($m\ s^{-1}$), A kesit alanı (m^2) göstermektedir.

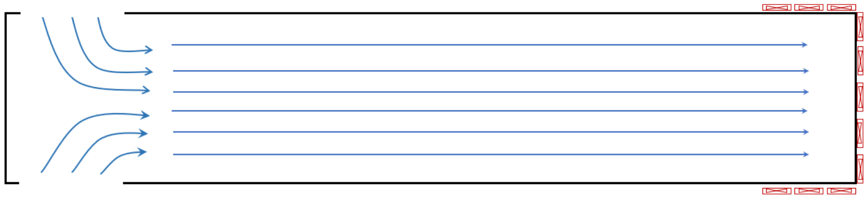
Örneğin 3.0 m yüksekliğe ve 16.0 m genişliğe sahip bir kümeste hava hızının 2 $m\ s^{-1}$ olması isteniyorsa, kümesteki fan kapasitesi;

$$\mathrm{Q} = 2\,\frac{\mathrm{m}}{\mathrm{s}} \times (16.0\ \mathrm{m} \times 3.0\ \mathrm{m}) \times 3600\ \frac{s}{h}\,,$$

$\mathrm{Q} = 172800\ m^3\ h^{-1}$ olarak hesaplanabilir.

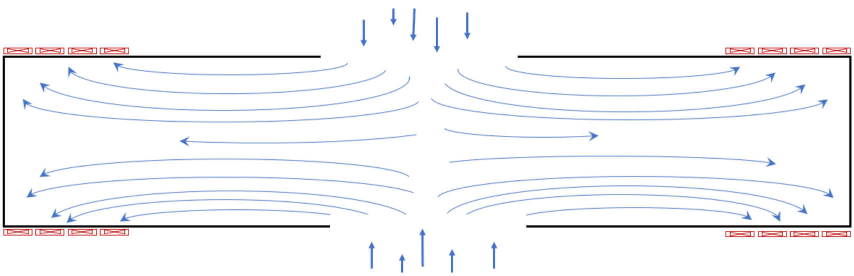
Fanların ve Hava Girişlerinin Yerleşimi

Fan ve hava girişlerinin yerleşimi, uygun hava sirkülasyonu ve sıcaklık kontrolünü sağlamak açısından kritik öneme sahiptir. Uzunluğu 150 metreye kadar olan kümeslerde, havanın yalnızca bir uçtan çekilmesi en uygun yöntemdir. Çünkü bu yaklaşım ile maksimum hava hızı sağlanabilmekte ve ölü hava noktaları en aza indirilebilmektedir (Şekil 2).



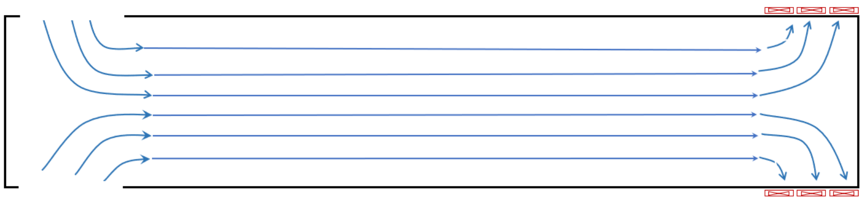
Şekil 2. Eşit hava akışı

Ancak, uzunluğu 150 metreyi aşan kümeslerde, fanların sadece kümesin kısa kenar duvarlarına yerleştirilmesi, aşırı yüksek hava hızı ile ön ve arka taraflar arasında önemli sıcaklık farklarına yol açabilir. Bu durumlarda, fanların kümesin merkezinde, yan duvarlara yerleştirilmesi ve girişlerin kümesin uçlarında olacak şekilde tasarlanması daha uygun olacaktır (Şekil 3).



Şekil 3. Çift yönlü tünel havalandırma sistemi

Çift yönlü tünel havalandırmada, tünel girişi ortada, fanlar ise binanın yan duvarın uçlarına yerleştirilmelidir. Bu durumda her iki yöndeki hava hızı ihtiyaç duyulan hızın yarısına düşecektir. Egzoz fanlarının kümesin uçlarına simetrik olarak yerleştirilmesi gerekir. Eğer fanlar yalnızca bir tarafa yerleştirilirse, fanların tam karşı köşesinde bir ölü hava noktası oluşur. Bu, havanın dışarı atılmadan hemen önce fanlara doğru hareket etmesinden kaynaklanır. Kümesin arka kısmında genellikle hava sıcaklığı daha yüksek olduğundan, bu bölgedeki yetersiz hava hareketi, ölüm oranlarını artırabilir. Bu nedenle, bazı egzoz fanlarının uç duvara yerleştirilmesi avantaj sağlar. Yan duvarlara fan yerleştirildiğinde, uç duvara yakın üçgen şeklinde minimal hava hareketi olan bir bölge oluşur (Şekil 4). Tüm fanlar çalışıyorsa bu bölge küçük olmakta, ancak daha az fan çalıştırıldığında bu bölge önemli ölçüde büyümektedir (M. Czarick & Tyson, 1990).



Şekil 4. Egzoz fanlarının yakınında ölü hava noktası

Tünel Hava Giriş Alanı

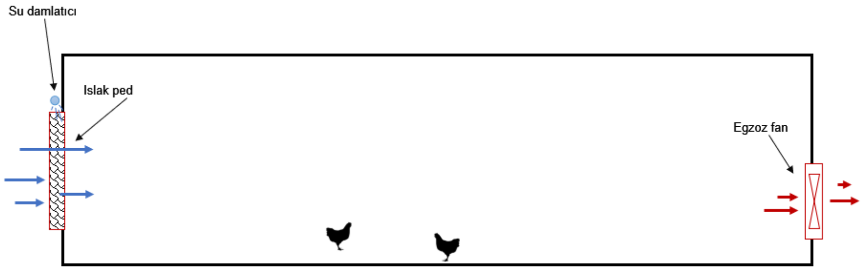
Tünel havalandırma sisteminin başarılı bir şekilde çalışması için doğru miktarda hava giriş alanı oluşturmak çok önemlidir. Fazla ya da yetersiz giriş alanı hem üretim hem de fan performansı üzerinde olumsuz etkiler oluşturabilmektedir. Soğutma için sisleme nozulları kullanılan kümeslerde, giriş alanının genellikle kümesin en kesit alanına eşit olması tavsiye edilir. Örneğin, genişliği 16 metre ve ortalama yan duvar yüksekliği 3 metre olan bir kümes, 48 m^2 bir en kesit alanına sahiptir.

$$En\ Kesit\ Alanı = Ortalama\ Yan\ Duvar\ Yüksekliği \times Kümes\ Genişliği$$

Bu durumda, tünel havalandırma için yaklaşık 48 m^2 bir giriş alanı gereklidir. Giriş alanı, kümesin en kesit alanına eşitse, kümese giren havanın hızı, kümes boyunca ilerleyen hava hızına yakın olur. Giriş hızı çok düşükse, girişlere yakın olan kanatlılar yeterli soğutmayı alamaz. Düşük giriş hızı ayrıca giriş yakınında üretilen sisin askıda kalma süresini azaltır, bu da yataklık neminde artışa ve evaporatif soğutma verimliliğinde azalmaya yol açabilmektedir. Öte yandan, giriş hızı, kümes boyunca ilerleyen hava hızından önemli ölçüde yüksekse, hayvanlar daha fazla soğuma sağlamak amacıyla girişlere doğru yönelebilir. Gittikçe daha fazla hayvanın girişlere yakın toplanması, yemlik ve suluk alanı başına düşen hayvan sayısını artırmakta ve bu durum, hayvanların gerekli yem ve suya ulaşmasını zorlaştırarak üretim verimliliğinin azalmasına yol açabilmektedir. Ayrıca, bazı raporlara göre bu tür kümelenmeler, ölüm oranlarında artışa neden olabilmektedir (M. Czarick, III & Fairchild, 2008; M. Czarick & Tyson, 1990; Lacy & Czarick, 1992).

Evaporatif Soğutma Pedleri

Evaporatif soğutma, kurak ve/veya yarı kurak iklimler için enerji açısından verimli bir soğutma çözümü olarak yaygın olarak kullanılmaktadır. Buharlaştırıcı soğutma pedleri, hava basıncı düşüşünü en aza indirmek amacıyla büyük boşluklara sahip genellikle lifli malzemelerden veya selülozik esaslı malzemelerden yapılmaktadır (Boyacı & Akyüz, 2019). Pedler, bina hava girişinin üzerine dikey olarak monte edilir. Pedin alt kısmı bir tahliye oluğu, üst kısmında ise eşit aralıklarla delikleri olan bir su dağıtım borusu bulunur. Suyu, oluktan pedin üstündeki dağıtım borusuna aktarmak için bir sirkülasyon pompası kullanılır (Şekil 5).

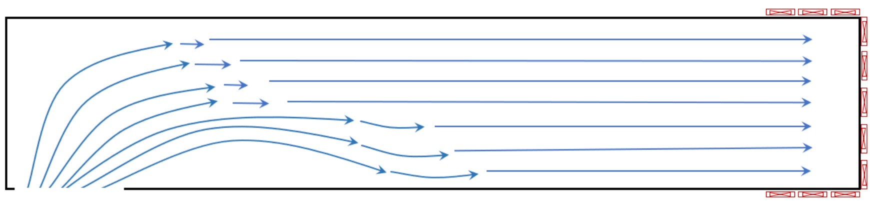


Şekil 5. Etlik piliç kümesinde direkt evaporatif soğutma sistemi

Ticari evaporatif soğutma pedleri, malzeme ve yapı özelliklerinde farklılık göstermektedir. Pedlerin performansı genellikle doygunluk etkinliği, basınç düşüşü, sıcaklık düşüşü ve işlenmiş havadaki nem artışı, su buharlaşması ve tüketimi, soğutma kapasitesi, performans katsayısı ile ısı ve kütle transfer katsayılarıyla karakterize edilmektedir (Tejero-González & Franco-Salas, 2021). Soğuma etkisi, suyun doymamış havayla temas etmesi ile oluştuğu için buharlaştırıcı soğutma doğal bir olgudur ve çoğu hayvan ve bitki tarafından sıcaklıklarını kontrol etmek için uygulanmaktadır. Antik medeniyetlerden beri, insanlık ortam sıcaklığını konfor koşullarına düşürmek için bu basit ve ekonomik soğutma tekniğini kullanmıştır (Boyacı & Akyüz, 2019; Watt, 2012).

Evaporatif soğutma pedleri, enerji açısından verimli, ekonomik, kompakt boyutlu ve hafiftir. Oluklu kağıtlarla üretilen pedlerin bu avantajları, tarımda, endüstride, ev aletleri gibi çok çeşitli uygulamalarda kullanılmaktadır (Malli, Seyf, Layeghi, Sharifian, & Behravesh, 2011). Bu pedleri kullanılırken, ped alanının doğru miktarda belirlenmesi, tünel havalandırma sisteminin etkin çalışması açısından çok önemlidir. Fazla veya yetersiz ped alanı hem üretim hem de fan performansı üzerinde olumsuz etkiler yaratabilir. Tünel havalandırmalı bir kümes için gerekli ped miktarı, fan kapasitesine ve ped kalınlığına bağlıdır. Daha kalın pedler sıcaklık düşüşünü ve dolayısıyla doygunluk etkinliğini ve soğutma kapasitesini artırsa da basıncı düşürmekte dolayısıyla fan gereksinimini artırmaktadır (Jakubowski, Boyacı, Kocięcka, & Atılgan, 2024; Tejero-González & Franco-Salas, 2021). Örneğin 10 cm kalınlığındaki bir ped için, her 450 $m^3\ h^{-1}$ hava akış kapasitesine 0.1 m^2 ped alanı hesaplanmaktayken, eğer ped 15 cm kalınlığında ise her 700 $m^3\ h^{-1}$ hava akış kapasitesine 0.1 m^2 ped alanı hesaplanmalıdır (M. Czarick & Tyson, 1990).

Ayrıca evaporatif soğutma pedleri, kümesin her iki tarafına yerleştirilmelidir. Karşılıklı iki hava akımının kümese girmesi, gelen havanın daha iyi karışmasını sağlar. Pedlerin yalnızca bir tarafta yer aldığı bazı kümeslerde, gelen havanın pedlerden geçip kümesin karşı tarafında kaldığı ve neredeyse kümesin yarısına kadar ilerlememiş olduğu gözlemlenmiştir (Şekil 6). Bu durum, kümesin iki tarafı arasında %50'ye varan bir hava hareketi dengesizliği oluşturmaktadır (M. Czarick & Tyson, 1990; Drury, 1966; Wilson et al., 1983; Zimmerman & Snetsinger, 1975).



Şekil 6. Evaporatif soğutma pedlerinin yakınında ölü hava noktası

Evaporatif soğutma sistemlerinde soğutma verimliliğini aşağıdaki eşitlikle hesaplanabilir.

$$\eta = (t_{out,db} - t_{in,db})/(t_{out,db} - t_{out,wb}) \times 100$$

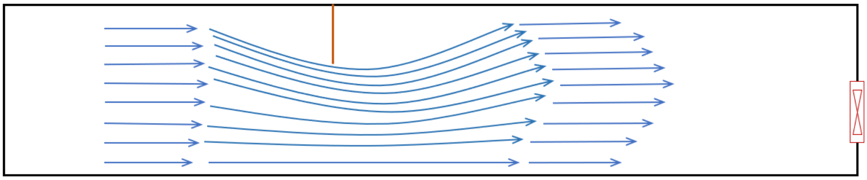
Eşitlikte, η soğutma verimliliğidir (%), $t_{out,db}$ dış kuru termometre sıcaklığıdır (°C), $t_{in,db}$ hava girişinin hemen önünde ölçülen kuru termometre sıcaklığı (°C) ve $t_{o,wb}$ dış ortam havasının ıslak termometre sıcaklığıdır (°C) (ASHRAE, 2011).

Örneğin dış ortam sıcaklığı 38°C, pedlerden kümese giren hava sıcaklığı 28°C ve dış ortam ıslak termometre sıcaklığı 24°C ise serinletme etkinliği;

$$\eta = \frac{38°C - 28°C}{38°C - 24°C} \times 100 \quad => \quad \eta = \%71.4 \text{ olarak hesaplanır.}$$

Hava saptırıcıları

Hava saptırıcıları (deflektör), geleneksel olarak yalnızca açık tavanlı binalar için önerilmiş olsa da ek fan kapasitesi olmadan yer seviyesinde hava hızını artırmak ve kümes genelinde hava hızı üniformitesini iyileştirmek için kullanılmaktadır. Ancak, hava akışı önündeki bu ek kısıtlamalar statik basıncı artırmakta ve fan performansını düşürebilmektedir (Purswell, Luck, & Davis, 2014). Hava saptırıcılar genellikle perde malzemesinden yapılmakta ve tavandan yan duvarların üst kısmına kadar monte edilmektedir. Kesit alanındaki sağlanan bu azalma, saptırıcının çevresindeki hava hızını artırmaktadır (Şekil 7). Hızdaki artış, genellikle saptırıcının önündeki bir açıklık yüksekliği kadar mesafeden, saptırıcının rüzgâr yönünde dört açıklık yükseklik mesafesine kadar görülebilir (M. Czarick & Tyson, 1990). Eğer saptırıcılar sık sık, yani 12 metre veya daha kısa aralıklarla yerleştirilirse, hava hızındaki artış kümesin her yerinde daha tutarlı hale gelebilmektedir (Ward & Eng, 2013).



Şekil 7. Kümeste hava saptırıcı etkisi

Hava saptırıcılar, özellikle büyük kesit alanına sahip kümeslerde daha etkili olmaktadır. Asma tavan olmayan kümesler de asma tavan olan kümeslerle aynı hava değişim hızına ihtiyaç duyar; ancak, kesit alanı yaklaşık olarak %20 daha büyük olduğundan, elde edilen hava hızı önemli ölçüde daha düşüktür olacaktır.

Hava saptırıcıları, etkili kesit alanını azaltarak ve hava hızını artırarak, minimal maliyetle ek bir avantaj sağlayabilmektedir. Ayrıca hava saptırıcıları 122 metreden daha kısa kümeslerde hava hızını artırmak için de kullanılabilir. Bu tür kümeslerde genellikle havalandırma sisteminin kapasitesi, ısı yükü düşük olduğundan, daha azdır ve kümesteki hava hızı genellikle minimal düzeydedir. Hava saptırıcıları ile daha fazla egzoz fanına ihtiyaç olmadan, hayvanların üzerindeki hava hızını artırabilmektedir. Ancak hava saptırıcılarının kurulumu sırasında dikkatli olunmalıdır. Eğer saptırıcının altındaki hava hızı yüksek olursa, üretim sorunlarına neden olabilir. Ayrıca, saptırıcılar arasındaki statik basınç düşüşü, fan performansını etkileyebilecek kadar büyük olabilir. Bu sorunlardan kaçınmak için, saptırıcıların altındaki hava hızının 3 m s^{-1}'nin altında tutulması gerekmektedir (Albright, 1990; M. Czarick & Tyson, 1990).

Sonuç

Kanatlılarda konveksiyon, radyasyon ve iletim yoluyla ısı kaybı, yalnızca çevre sıcaklığı hayvanın termonötr bölgesinin altında veya içindeyse etkilidir. Çalışmalar, havanın hacmi ve hızı arttırıldığında hayvanların konveksiyon yoluyla ısı kaybının arttığını göstermektedir. Ayrıca, bina yönü, çatı eğimi, çatı çıkıntısı, peyzaj, bina yüksekliği, bina genişliği, bina uzunluğu vb. gibi mimari unsurların uygun şekilde dikkate alınmasının, kanatlılarda optimum üretim için gerekli olduğu bildirilmiştir. Ek olarak kümes tasarımlarına, tünel havalandırmalı evaporatif soğutma sistemlerinin dahil edilmesi, hayvanların genel olarak performanslarını optimize etmede olumlu sonuçlar vermektedir. Sonuç olarak, çevre sıcaklığının hayvanlar için aşırı yüksek olduğu durumlarda tünel havalandırma sistemi, sıcak iklim bölgelerindeki kümeslerde üretim performansını olumlu etkilemektedir. Ancak, etkili bir havalandırma sistemi tasarlamak için hayvanların ürettiği ısı, giriş açıklıklarının boyutları ve egzoz fanının konumu ile kapasitesinin doğru bir şekilde hesaplanması büyük önem taşımaktadır.

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BÖLÜM V

Artificial Intelligence Applications in Livestock Farming

Müge ERKAN CAN[1]

Introduction

Artificial intelligence (AI) has become a key technology in the promotion of sustainable farming, providing creative answers to the economic, social, and environmental problems that modern agriculture faces. AI can improve precision agriculture by enabling real-time decision-making for effective animal farming by improving efficiency, animal welfare, and sustainability using data analytics, machine learning, and predictive modeling. AI-powered systems, such as machine learning algorithms and computer vision, enable precise monitoring of animal health, behavior, and well-being in real-time. Through sensor networks, wearables, and automated

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data collection, AI can track vital signs, detect early signs of illness, and predict outbreaks, allowing for timely interventions and reducing the need for antibiotics. The incorporation of AI into autonomous machinery can save labor costs and boost operational effectiveness, thereby encouraging sustainable farming practices in both large-scale and smallholder farms. Through the reduction of greenhouse gas emissions, water conservation, and biodiversity preservation, these technologies assist in lessening the environmental effects of conventional agriculture. However, there are issues with data accessibility, digital literacy, and financial constraints for farmers in developing nations that come with the extensive use of AI in farming.

AI systems can monitor crop growth, soil health, and weather conditions by utilizing sensors, drones, and satellite imagery. Through better nutrition management, weight increase monitoring, and feeding schedule optimization, AI is also improving the efficiency of feed management and resource utilization. The economic sustainability of livestock operations is enhanced by the productivity gains and labor cost reductions brought about by robotics and automation in tasks like milking, cleaning, and herding. AI also aids in the creation of environmentally friendly farming techniques that minimize greenhouse gas emissions, conserve water, and enhance waste management.

Critical issues facing agriculture today include water scarcity, climate change, environmental degradation, and reliance on non-renewable energy sources. Extensive landscaping and alteration can endanger the health of people and animals, diminish biodiversity, and contaminate air and water sources (Betts & et al., 2017, Qi & et al., 2018). Therefore, a global agricultural mutation is required to move from traditional methods to contemporary mechanized ones (Godfray & et al., 2014). These methods view agricultural farms as factories and regard plants and animals as units of production (Juhola & et al., 2017, Pardey & et al., 2014).

With an emphasis on environmental, social, and economic sustainability, various nations have taken an interest in the development of sustainable agriculture (Lu & et al., 2015, Helander & Delin, 2004). To make the shift to a more sustainable and intelligent agriculture sector, clever inventions will be required (Mana, 2023). The goal of AI is to create tools and systems that can think and act like human intelligence (Lu & et al., 2018, Parekh & et al., 2020). AI has recently been demonstrated to be crucial for data and services in a number of industries, including trade (Keshta, 2022), education (Zheng & et al., 2023), and health (Zhou & Lund, 2023, Mana & et al., 2024).

Specific studies conducted on this topic examined crop, water, soil, and livestock optimization as well as the application of AI and machine learning in agriculture (Benos & et al., 2021). Key components of promoting intelligent and sustainable farming are the preservation of ecosystems, the adoption of contemporary technology, efficient resource management, and the provision of strong services in AI-based agriculture (Lampridi & et al, 2019, Mana & et al., 2024).

In order to maintain agricultural sustainability and increase crop yields while protecting the environment, farming practices must be enhanced, optimized, and modernized (Zecca& et al., 2019).

Aspects of sustainable agriculture such as crop recognition (Waldchen & et al., 2018, Pushpanathan & et al., 2021), crop disease diagnosis (Abade & et al., 2021, Yuan & et al.,), weed detection (Wang & et al., 2019, Su, 2020), water management (Virnodkar & et al., 2020, Sun & Scanlon, 2019), animal health (Garcia & et al., 2020, Li & et al., 2020), and livestock production (Ellis & et al., 2020, Lovarelli & et al., 2020) have all benefited from the use of machine learning techniques (Mana & et al., 2024).

Rather than in livestock production, the past 20 years have seen a major dissemination of smart farming technology in arable farming (Walter & et al., 2017, Borchers & Bewley, 2015, Rutten & et al., 2018). On the other hand, there is a significant possibility for smart livestock technology to be distributed in the future (Umstätter & et al., 2020).

This paper discusses both the opportunities and obstacles for AI in the livestock sector and the potential of AI-driven tools and techniques to optimize farming practices, as well as the use of branches of artificial intelligence (machine learning, deep learning, and fuzzy logic etc.).

1. Artificial Intelligence, Smart Technologies, Machine Learning and Livestock Farming

Artificial intelligence subsets such as machine learning and deep learning are essential in many sectors, including livestock farming. In machine learning, models that can map inputs to outputs utilizing algorithms are created using training data. These models, are then applied to produce outputs based on new inputs (Süslü, 2020).

Deep learning has not been widely used yet in livestock farming; instead, data analytics has been the main AI use to far. The majority of current technology receives data from various sensors and processes it using statistical models, analytical models, and computation automation to produce meaningful information. Using camera systems to analyze animal feces and send an alert if droppings are becoming unhealthy in the barn, calculating predicted water consumption for an animal based on the previous three days, planning feed orders so that they are placed at the right time to allow for enough space in the feed silos, controlling the ventilation system, sending data to customers, keeping records, sharing data with veterinarians, monitoring pulleys, and shining a laser to prevent any clumps in the barn to prevent smothering are some examples of these kinds of situations.

Machine learning is being used not only for wildlife monitoring but also for many other elements of livestock farming, such as precision agriculture, yield prediction, and disease diagnosis. Machine learning algorithms are able to recognize patterns and trends in data from sensors, satellite photos, and historical records. This allows for proactive decision-making and optimal resource allocation. Developments in machine learning have great potential to make livestock farming a more productive, sustainable, and ecologically friendly sector as this field of study develops. Through the utilisation of data-driven insights, stakeholders can effectively tackle the intricate issues confronting the agriculture industry and create novel avenues for innovation (Dilaver & Dilaver, 2024).

One area where artificial intelligence is being used more and more is the milk booth in animal husbandry. Using smart sensors with AI capabilities, the automated milking equipment can assess the quality of the milk and highlight any irregularities in the product (Costa & et al., 2012).

Dairy is combining cow, milk, and herd intelligence with their sensors and artificial intelligence technology. They provide a range of sensors, including the Sense Time Solution sensor, which tracks everyday behaviors including ruminating, eating, and walking patterns, as well as those that track a cow's health and identify heat and calving. With the use of a range of easily accessible sensors, farmers can now keep an eye on changes in animal movements, food intake, sleep cycles, and even air quality in animal shelters. This sensor, when paired with artificial intelligence software, provides users with early, proactive answers to problems. In addition to collecting data on diet, health, and reproduction, the sensor provides farmers with solutions tailored to each individual cow (Nääs & et al., 2010).

Monitoring livestock health is crucial to contemporary agriculture since it ensures animal welfare and yields high-quality goods. Modern artificial intelligence methods eliminate the need for conventional training by using cameras and sensors to continuously assess the health of animals. AI-based solutions provide a number of benefits over traditional techniques, including the ability to spot trends and possible health issues before they worsen. (38, 39). These systems can be built using a variety of models and technologies, including Distributed Ledger Technology, edge computing, and the Internet of Things (Lovarelli & et al., 2020).

Internet of Things (IoT) sensors, in particular as a component of smart farming technologies, are anticipated to play a significant role in livestock production with respect to efficiency and animal welfare (29, 41). IoT connects the physical and virtual worlds, concentrating on wireless communication via intelligent devices like sensors. These IoT-based sensors usually make use of both local and global network infrastructures, which makes wireless communication possible and allows IoT systems to function completely autonomous (Rutten & et al., 2018, Akbar & et al., 2020, Iwasaki & et al., 2019, Langer & et al., 2024).

IoT-based sensors are used in dairy farming in a variety of ways. For instance, collar sensors monitor the behavior of individual animals, lameness detectors identify lameness in cows in real time, and rumen sensors track temperature, movement, and digestive activity. These IoT technologies are intended to monitor animal behavior and health, maximize milk supply, and optimize resource utilization (Rutten & et al., 2018, Yeates, 2017, Langer & et al., 2024). It has been demonstrated that these technologies are more accurate at detecting lameness than farmers are (Taneja & et al., 2020) and as a result, they could serve as a valuable source of information for farmers, veterinarians, and farm consultants alike regarding the health of their animals (Rojo-Gimeno & et al., 2019, Langer & et al., 2024).

As mentioned before, a vital component of livestock productivity is animal health. An effective and economical method of tracking animal well-being is to use sound analysis that can potentially be mechanized for large-scale farming (Mcloughlin & et al., 2019). Machine learning algorithms, such as convolutional neural networks for face-to-face recognition, have become extensively employed. For instance, the review (Benjamin & Yik, 2019) listed pertinent sensors for measuring animal health, including accelerometers, thermistors, microphones, and 2D and 3D cameras, and it demonstrated how these technologies can be utilized to enhance pig health, benefiting the animals as well as the industry. In conclusion, this research demonstrates how cutting-edge technology can enhance livestock production efficiency and promote animal welfare (Mana & et al., 2024).

A number of studies have been explored on the use of energy in dairy farms, emphasizing the value of prediction models for analyzing energy use and assessing the results of changes to management techniques and infrastructural equipment. Adoption of grazing-based dairy systems is generally associated with a 35% reduction in energy consumption, according to the research (Shine & et al., 2020, Mana & et al., 2024). Energy usage in dairy farming has been predicted using a variety of techniques, such as support vector machines, random forest ensembles, artificial neural networks, and CART decision trees (Shine & et al., 2020, Shine & et al., 2019).

Fuzzy logic is the use of relevant information to control and decision-making systems that closely resembling human thought patterns (Chen & Pham, 2020). It is frequently utilized in automatic control systems, information systems, image recognition, optimization (Altaş, 1999). Numerous applications of fuzzy logic in the field of animal husbandry have been examined in literature. In these researchs, suggested a system to classify mastitis disease in cows entering the automatic milking system using fuzzy logic classification Cavero & et al., (2024), described a fuzzy logic-based decision support system called Sustainable Pantanal Farm to assess the sustainability of cattle farms, developed a new fuzzy logic model to observe the mammary health of goats (Zaninelli & et al., 2015), and proposed a fuzzy logic-based system that evaluated health conditions and milk quality using online electrical conductivity data from sensors (Zaninelli & et al., 2015).

Robotic system integration is transforming conventional agricultural methods in the livestock husbandry industry by increasing productivity, boosting sustainability, and improving animal welfare. For example, robotic feeders ensure more accurate and economical use of resources by optimizing feed distribution based on real-time data about the nutritional demands of individual animals. Artificial intelligence (AI) and sensor-equipped automated milking systems allow for continuous monitoring of milk quality, yield, and cow health. This reduces the need for manual work and gives farmers valuable information into how to increase productivity.

Robotic systems improve animal wellbeing by enabling continuous health monitoring through wearables, sensors, and machine vision technologies, in addition to optimizing resource use. These systems monitor behavior patterns, assess vital signs, and identify early illness indicators. By doing so, they enable prompt interventions and slow the progression of disease without overusing antibiotics. Additionally, robotic herding devices are being developed to automate animal movement and lessen the stress that comes with using conventional methods. Robotic cleaning systems contribute to better environmental conditions and a reduced risk of disease transmission in barns and animal enclosures by maintaining hygiene.

AI applications in livestock farming will be able to expand into the fields of machine learning, deep learning, and sensor data analysis as more data becomes available. AI in livestock management is not a luxury or an extravagance; rather, it is a necessity to productive and sustainable agriculture. It guarantees the welfare of animals, maximizes the use of resources, and gives farmers the ability to make decisions that have an impact on the whole agricultural ecosystem. The use of AI in cattle management will be crucial as we move toward a future where innovation and quantifiable excellence coexist and form the basis of more intelligent, resilient, and sustainable livestock sector management.

2. Precision Livestock Farming

"Individual animal management by continuous real-time monitoring of health, welfare, production/reproduction, and environmental impact" is the definition of Precision Livestock Farming (PLF) (Berckmans, 2014). The combined use of one or more tools in integrated systems is included in PLF. Over the past 20 years, there have been technological advancements in areas including wireless communication networks, Internet access availability, internet of things, and information and communication technologies that have made this possible (Terrasson & et al., 2017). From its early uses for electronic milk meters to innovative wearable sensors and integrated systems capable of reliably detecting an animal's physiological and reproductive status through behavior analysis, rumination monitoring, and online real-time data harvesting, the PLF sector has rapidly changed over the last few decades (Halachmi & et al., 2019). In order to help farmers better manage one or more production inputs or detect and intervene before the start of clinical sickness, the information gathered is expanded upon and made available to end users on laptops and smartphones (Andonovic & et al., 2018). PLF is currently primarily designed for intensive farming systems, particularly those that operate indoors. In these situations, farm structures and facilities are well adapted to the demands of modern digitization, including restricted space, easy access to electricity, control over environmental conditions, and information and communication technologies. But PLF could also be very helpful in pasture-based systems, particularly during seasonal grazing, when the physical size, unpredictability, feed base density, and remoteness of pasture-based systems can make it challenging for farmers to regulate their animals (Aquilani & et al., 2022).

Precision livestock farming is emerging as a result of expanding study and applications of technology. Images, noises, and movements captured by sensors (cameras, microphones, and accelerometers) are merged with algorithms to monitor animals in a non-intrusive manner in order to assess their well-being and forecast their productivity. This remote livestock monitoring can offer quantifiable and timely warnings of low welfare conditions that need a stockperson's attention (Benjamin & Yik, 2019).

Precision livestock farming is the automated remote detection and monitoring of identifiable individuals for the purpose of ensuring the health and wellbeing of the animals through real-time analysis of tracking data, photos, sounds, body condition, weight, and biological metrics in livestock (Berckmans, 2014, Neethirajan, 2017, De Montis & et al., 2017). This allows for the possibility of early disease or physiological condition identification at the farm level. Precision livestock farming is not a new science (DeShazer & et al., 1988) but thanks to advancements in computer science, low-cost off-label sensors from the video game industry, and growing computer capacity for data processing and capture, its knowledge, applications, and availability have expanded significantly (Nasirahmadi & et al., 2017, Berckmans, 2014, Banhazi & et al., 2012).

To gain a deeper comprehension of the potential effects of contemporary technology on precision livestock farming, one must possess a fundamental understanding of remote monitoring sensors, algorithm development, and machine learning. Remote sensors that monitor or record data from groups or individual animals include cameras, microphones, thermometers, accelerometers, and heat sensors. Algorithms are then used to process the sensor data that has been saved on external storage or transferred straight to a processing node (much like when you transfer images from a digital camera to a computer). A formula or sequential series of actions used to solve a particular problem or class of problems is called an algorithm. An algorithm is a computer procedure that uses inputs to determine outputs and informs a computer exactly what to do to solve a problem. The first step in the process is for programmers to write the algorithm, which tells the computer what to do in order to solve a problem. The ability of an algorithm to convert sensor data, or "feature variable," into a biological output determines how valuable the algorithm is to farmers (Benjamin & Yik, 2019).

3. Concerns About AI

AI adoption in animal husbandry confronts obstacles despite its potential, such as ethical worries about data privacy and surveillance and the cost of these technologies for small-scale farms.

New farming techniques made possible by smart farming technologies are expected to increase productivity while improving farming efficiency (Tullo & et al., 2019, Lovarelli & et al., 2020, Walter & et al., 2017). In addition, they should reduce the amount of manual labor and resource inputs while concurrently improving animal welfare (Griepentrog, 2021). While digitalization's fundamental importance for agriculture is widely acknowledged, there is still some uncertainty regarding its actual effects and implications for a more sustainable and efficient production, for example, because of errors or unintended effects on farmers, animals, and society (Kehl & et al., 2021, Van der Burg & et al., 2019, Klerkx & et al., 2019, Visser & et al., 2021). Furthermore, rather than in animal production, the past 20 years have seen a major dissemination of smart agricultural technology in arable farming (Walter & et al., 2017, Borchers & Bewley, 2015, Rutten & et al., 2018). On the other hand, there is a significant possibility for smart livestock technology to be distributed in the future (Umstätter & et al., 2020, Langer & et al., 2024).

Langer & et al. (2024) conducted an online survey among 212 German dairy farmers identify prevailing acceptance barriers and examine whether cognitive and affective influencing factors, combined into a single behavioral model, can explain the acceptance, and therewith precondition for adoption, of Internet of

Things (IoT)-based animal sensors. The findings indicate that there are differences in acceptability barriers between IoT-based sensor users and non-users. Nonetheless, the two parties believe that the biggest obstacle is the high cost of investment. Moreover, the findings suggest that acceptance decisions are influenced by positive expected emotions as well as cognitive variables. The willingness to employ IoT-based animal sensors is positively influenced by attitude and behavioral control, which are the primary determinants of the idea of planned behavior. The findings highlight the importance of emotional aspects for dairy farmers' acceptance of IoT-based animal sensors, in addition to technical specifications and cognitive attitudes. Researchers emphasize that these findings are important for manufacturers, policymakers, and agricultural and digital associations.

Many stakeholders anticipate that IoT-based animal sensors will enhance dairy production since sustainable milk output, cow welfare, and good animal health are essential to dairy farms' long-term survival (Akbar & et al., 2020, Unold & et al., 2020). But little is still known about the true effects of digital technology use on animal welfare and the true value to farmers of these advantages.

To improve data transfer and decision-making, the necessity of developing similar standards in large-scale livestock farming systems has been discussed recently. Adoption of farm-integrated techniques and farmers alike was encouraged, as was agreement on the conditions for data sharing (Bahlo & et al., 2019). Farmers and other regional stakeholders would be able to realize the rewards of efficient data sharing in this way (Mana & et al., 2024).

There are a number of possible worries associated with implementing AI systems, such as the initial cost, the need for specialized equipment and technical skills, ethical issues, and uncertainty over job migration (Stahl, 2021). Notwithstanding these difficulties, using AI in precision livestock farming systems can greatly improve both the process of making decisions and the wellbeing of the animals. AI assists farmers in streamlining their livestock management systems by offering data on animal behavior, nutrition, and surroundings.

Robotic technology adoption in animal husbandry also tackles important environmental issues. These technologies contribute to lessening the environmental impact of cattle production by cutting down on waste, decreasing overfeeding, and improving resource efficiency. Methane emissions and water use are especially reduced. However, there are several obstacles to the widespread use of robotics in livestock management. These include high initial costs, complicated technology, and worries about animal privacy and data security. Important factors to take into account include the possible labor relocation in rural areas and the digital divide between smallholders and large-scale industrial farms.

It is anticipated that robotic technology and artificial intelligence will be widely used in livestock farming in the future. The livestock farming industry will achieve increased sustainability and efficiency with the rise of automated and intelligent farms. However, in order to use these technologies successfully, more research and development work is required. Artificial intelligence applications and robotic systems in cattle farming are potential technology for the industry's future (Dilaver & Dilaver, 2024).

Conclusions

Livestock farming is not an exception to the way artificial intelligence (AI) has emerged as a game-changing technology in several industries. Traditional agricultural methods are changing as a result of the advances and efficiency brought about by the incorporation of AI into livestock management systems. AI technologies, including computer vision, machine learning, and data analytics, have shown great promise in addressing some of the long-standing issues in livestock farming, including sustainability, resource management, animal health monitoring, and productivity improvement.

One of the most noticeable effects of AI in livestock production is the boost of productivity. AI-powered automated feeding systems are capable of calculating the best feed schedules and quantities depending on the requirements of individual animals. By using precision agriculture techniques, feed is used more effectively, minimizing expenses and waste, and guaranteeing that animals get the nourishment they need for healthy growth. Herd production can be increased by using AI-based herd management systems, which can monitor animals in real-time and provid

Another crucial area where AI solutions have demonstrated great potential is animal health monitoring. Movement patterns, habits, and vital signs can be continuously tracked thanks to technologies like wearables and AI-driven sensors. Predictive algorithms can be used to identify illnesses, stress, and other health issues early on, allowing farmers to take immediate action. This lowers death rates, raises animal care standards, and makes livestock farming more financially viable overall. Preventing the transmission of contagious diseases within a herd is crucial in large-scale farming, and it is made easier with the ability to recognize abnormalities in behavior or physical conditions. e individualized care.

Additionally, AI is essential to enhancing environmental sustainability in cattle ranching. Because of its substantial impact on water use, land degradation, and greenhouse gas emissions, livestock raising is frequently criticized. By improving resource management, AI-driven solutions are assisting in the mitigation of these problems. AI systems, for instance, may monitor energy, water, and soil conditions. By doing so, they can provide farmers with information that helps them make decisions that will have the least negative influence on the environment. Artificial intelligence (AI) can contribute to more sustainable farming methods by anticipating the optimal feed-to-yield ratios and grazing patterns, which can help reduce resource waste. Additionally, there is growing interest in the function AI plays in livestock genetic improvement. Farmers may choose the finest breeding pairs to improve desired qualities like disease resistance, growth rates, and milk production with the aid of AI-powered genetic data analysis. This accelerates the breeding process and provides healthier, more productive animals while retaining biodiversity within herds.

The application of AI in livestock production is not without its difficulties, despite these encouraging advancements. The high initial expenditures of technology, farmers' lack of technical expertise, and privacy and ownership issues are a few of the things preventing its wider adoption. Moreover, acquiring and employing these cutting-edge technology may be difficult for small-scale farmers, particularly those in developing nations, which could widen the digital divide in agriculture.

In conclusion, by increasing output, encouraging sustainability, and improving animal welfare, AI applications in livestock farming have the potential to transform the industry. Even though there are still difficulties, implementing AI-driven solutions has considerably more advantages in the long run than disadvantages. The livestock farming industry is expected to adopt these advances more widely due to the continuous advancements in AI technology and improved accessibility. This will ultimately result in a food production system that is more resilient, sustainable, and efficient. AI's incorporation into livestock farming is more than just a technical advancement; it signifies a fundamental change in the way we view and conduct animal agriculture.

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BÖLÜM VI

Nutrient Management in Vertical Farming Systems: Innovations and Challenges

Meriç BALCI[1]

1. INTRODUCTION

Vertical farming is the practice of growing crops in vertically stacked layers or other vertical arrangements, often incorporating controlled-environment agriculture (CEA) technologies (Benke & Tomkins, 2017; Chole et al., 2021; Engler & Karti, 2021; Vatistas et al., 2022). This method allows for agricultural activities in urban settings with limited space, offering potential solutions to challenges such as food security and sustainability (Despommier, 2010; Oh & Lu, 2023). Research emphasizes the importance of vertical farming in urban agriculture, food security, and sustainability. Particularly, the efficiency in water and soil usage makes vertical farming increasingly relevant in the face of global challenges like climate

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change and population growth (Januszkiewicz & Jarmusz, 2017; Kozai, 2018; Kozai et al., 2019; Maheshwari, 2021; Joensuu et al., 2024).

Nutrient management is a critical factor that directly affects crop yield and quality in vertical farming systems. The precise formulation of nutrient solutions is essential to provide plants with the necessary macro and micronutrients in appropriate amounts. In vertical farming systems such as hydroponics, aeroponics, and aquaponics, where plant roots are directly exposed to nutrient solutions, careful adjustment of nutrient management is mandatory. The success of nutrient management not only determines plant growth but also influences the overall sustainability of the system (Hosseini et al., 2021; Jones, 2014).

The purpose of this review is to examine the current literature on nutrient management in vertical farming systems, focusing on innovations and challenges in this field. This review will analyze studies that explore the interactions between different plant species and nutrient management strategies, and based on these findings, recommendations for optimal nutrient management in vertical farming systems will be provided. Additionally, potential areas for future research will be identified to contribute to the scientific knowledge base in this area.

2. METHODOLOGY AND LITERATURE REVIEW APPROACH

The methodology for this review is based on a systematic literature review approach. Initially, peer-reviewed journal articles, conference papers, and academic theses on vertical farming and nutrient management were searched. The research focused on publications from 2010 to 2024, using widely recognized academic databases such as Web of Science, Scopus, and Google Scholar.

Among the selected studies, those addressing innovative nutrient management strategies and their associated challenges in vertical farming systems were prioritized. Furthermore, opinions from leading academics in the field have been included and integrated into the overall flow of the review.

3. OVERVIEW OF VERTICAL FARMING SYSTEMS

3.1. History and Development of Vertical Farming

The concept of vertical farming has evolved over the past few decades, driven by the need to address food security challenges and urbanization. The early idea of vertical farming was introduced by Dr. Dickson Despommier in the early 2000s, who envisioned multi-story buildings dedicated to growing crops in urban areas (Despommier, 2010). His work highlighted the potential for vertical farming to reduce the environmental footprint of agriculture by minimizing land use and reducing transportation costs. Since then, vertical farming has undergone significant technological advancements, with innovations in controlled-environment agriculture (CEA) and the integration of advanced systems for lighting, climate control, and nutrient delivery (Benke & Tomkins, 2017; Al-Kodmany, 2018; Kozai, 2018; Kozai et al., 2019; Chole et al., 2021; Engler & Karti, 2021; Vatistas et al., 2022).

3.2. Types of Vertical Farming

Vertical farming systems can be broadly categorized based on the method of plant cultivation. The three primary types are hydroponic, aeroponic, and aquaponic systems, each offering unique advantages and challenges (Birkby, 2016).

3.2.1. Hydroponic Systems

Hydroponic systems are an efficient vertical farming method that allows plants to grow in nutrient-rich water solutions instead of soil. With precise control over nutrient levels and water use, they are particularly suitable for urban areas. By providing high yields with minimal water and space usage, hydroponic systems are widely preferred in vertical farming. (Jones, 2014). Sharma et al. (2019) described hydroponics as a suitable technique for high-density urban farming systems, while Van Gerrewey et al. (2021) emphasized its role in enabling year-round production within the vertical farming model. Resh (2022) discussed the advantages of hydroponics in producing high-quality food with minimal resources in both home and commercial settings. Safeyah et al. (2023) examined verticulture hydroponics, highlighting its role in enhancing agricultural knowledge and skills, especially in resource-limited urban areas.

As vertical farming continues to expand, hydroponic systems stand out as a key approach for sustainable, high-yield food production in urban landscapes.

3.2.2. Aeroponic Systems

Aeroponic systems suspend plant roots in the air and mist them with nutrient solutions, taking hydroponics a step further; this increases oxygen access to the roots, promoting faster growth and higher yields. Lacckireddy et al. (2012) highlighted the advantages of aeroponics in commercial food production, emphasizing resource efficiency and high crop potential, while He (2015) reported that these systems can maximize production with minimal water usage in space-limited urban environments. Despommier (2017) noted that aeroponics in vertical farming reduces soil-borne diseases and the need for pesticides, making it a sustainable option, while Eldridge et al. (2020) found that precise misting in aeroponic systems optimizes nutrient delivery and root development. Fasciolo et al. (2023) introduced an intelligent aeroponic system designed for sustainable indoor farming, emphasizing the need for advanced monitoring to maintain the precise conditions required by aeroponics. Highly water-efficient, these systems use 95% less water than traditional soil-based farming but require proficient management and monitoring systems to ensure optimal performance (AlShrouf, 2017).

3.2.3. Aquaponic Systems

Aquaponic systems create a sustainable model by combining hydroponics with aquaculture, allowing fish and plants to coexist symbiotically. In this system, fish waste serves as a nutrient source for plants, while plants filter and purify the water for the fish, maintaining ecological balance. Love et al. (2015) suggested that profitability and maintenance requirements are major challenges to the commercial sustainability of aquaponic systems, while Wongkiew et al. (2017) highlighted that nitrogen cycling and water quality are crucial for supporting sustainable plant growth, despite the management complexities involved. Khandaker and Kotzen (2018) emphasized the importance of substrate selection in aquaponic systems to enhance nutrient retention, noting that optimal choices could boost productivity in vertical farming applications. Goddek et al. (2019) focused on the scalability of aquaponic systems, concluding that large-scale applications require careful attention to technical and logistical aspects, suggesting that aquaponics could become a strong model for future food production. Lastly, Maryam (2023) evaluated the viability of aquaponic vertical farming in urban areas in Oslo, asserting that this approach holds substantial potential for sustainable urban agriculture based on environmental and economic factors.

3.3. Advantages and Disadvantages of Vertical Farming

Vertical farming offers numerous advantages, particularly in addressing the challenges of urban food production. Van Gerrewey et al. (2021) argue that vertical farming presents significant potential as a sustainable solution, especially in densely populated urban environments. Key advantages include efficient land use, reduced water consumption, and the ability to grow crops year-round in controlled environments, which Kozai (2018) describes as a hallmark of the "next generation indoor farm." By enabling local production within cities, vertical farming can also reduce the carbon footprint associated with food transportation. Additionally, Birkby (2016) highlights that vertical farms can conserve resources and bring fresh produce closer to consumers, enhancing food security.

However, there are also considerable disadvantages. These systems often involve high initial capital costs and significant energy consumption for artificial lighting and climate control. Moreover, they require technical expertise for effective operation, a challenge noted by Kalantari et al. (2017; 2018) in their discussions on sustainability. Khalil and Wahhab (2020) point out that while vertical farming has advantages over traditional horizontal farming in terms of sustainability, the financial and technical demands remain a barrier to broader adoption.

The economic viability of vertical farming is still a topic of debate. Banerjee and Adenaeuer (2014) examined the economic implications, suggesting that achieving cost-efficiency at scale is challenging. de Oliveira (2023) developed a decision support system to assess the economic viability and environmental impact of vertical farms, highlighting areas where improvements could enhance profitability and sustainability. Benke and Tomkins (2017) suggest that while vertical farming holds significant promise, its success will ultimately depend on continuous innovation and strategic investments in sustainable practices.

4. NUTRIENT MANAGEMENT

4.1. Plant Nutrient Requirements

Nutrient management in vertical farming is critical for optimizing plant growth and achieving high yields. Plants require a balanced supply of essential nutrients, which can be categorized into macro and micronutrients (Marschner, 2012).

Macronutrients are the primary nutrients required in large quantities for plant growth. These include nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S). Nitrogen is essential for vegetative growth and chlorophyll synthesis, while phosphorus is crucial for energy transfer and root development. Potassium plays a significant role in water regulation and enzyme activation (Marschner, 2012; Taiz & Zeiger 2015). In vertical farming systems, the availability of these macronutrients must be carefully managed to avoid deficiencies or toxicities, which can significantly impact plant health and productivity (Jones, 2014).

Micronutrients, although required in smaller amounts, are equally important for plant health. These include iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), and chlorine (Cl). Each of these elements plays a specific role in plant physiological processes, such as enzyme function, photosynthesis, and hormone regulation (Marschner, 2012; Taiz & Zeiger, 2015). In controlled-environment agriculture (CEA) like vertical farming, the precise control of micronutrient levels is essential to prevent imbalances that can lead to disorders like chlorosis or stunted growth (Resh, 2022).

4.2. Preparation and Optimization of Nutrient Solutions

The preparation and optimization of nutrient solutions are essential in vertical farming, as they must provide balanced macro-and micronutrient concentrations tailored to each crop's specific needs. A universal method for achieving precise compositions, initially developed by Steiner (1961), serves as a foundation for modern nutrient management. Optimization involves controlling factors like pH to ensure nutrient availability, with cost-effective pH measurement tools playing a crucial role in efficient monitoring (Hinojosa-Meza et al., 2022).

Another key parameter is electrical conductivity (EC), which indicates the concentration of dissolved salts and directly impacts nutrient uptake. Maintaining optimal EC levels is essential to improve yield and plant health, with adjustments tailored to growth stages in vertical farming systems for enhanced efficiency (Hosseini et al., 2021; Sulaiman et al., 2021; Van Quy et al., 2018).

Advanced nutrient management systems often utilize automated dosing and real-time monitoring to maintain consistent nutrient availability. Luna Juncal et al. (2020) developed a mobile nitrate monitoring station, enabling high-frequency data collection for precise nutrient adjustments, which supports continuous and tailored nutrient management. Fan et al. (2022) reviewed the benefits of real-time monitoring in maintaining optimal soil and nutrient conditions in controlled environments, highlighting how these technologies enhance plant productivity. Swathy et al. (2024) emphasized that real-time nitrogen monitoring can improve nitrogen use efficiency and support ecosystem sustainability. Silva et al. (2024) further emphasized the need for advanced sensing tools that accurately measure key nutrients like nitrogen, phosphorus, and potassium, essential for precision fertilization and sustainable agriculture.

These studies collectively underscore the critical role of precision in nutrient solution preparation and optimization, highlighting how advanced monitoring and control systems enable consistent, high-quality crop production while enhancing sustainability in vertical farming.

4.3. Nutrient Delivery Systems

In vertical farming, nutrient delivery systems are designed to efficiently supply the nutrient solution to the plant roots. The most common systems include drip irrigation, nutrient film technique (NFT), and deep water culture (DWC). According to Mohammed and Sookoo (2016), the NFT system is particularly popular for commercial production due to its continuous flow of nutrient solution, which enhances oxygen availability to the roots. De Castro Silva et al. (2021) provided a global overview of the NFT system, emphasizing its adaptability for a range of crops and vertical setups. Rozilan et al. (2021) described the design and fabrication of NFT systems, underscoring the importance of careful construction to ensure even nutrient distribution in vertical farms. Longkumer et al. (2022) examined the effects of nutrient levels in NFT systems for lettuce, highlighting its efficiency in controlled environments. Gillani et al. (2023) compared the energy-use efficiency of NFT and DWC, finding that NFT is particularly suited for high-density setups due to its reduced water and nutrient usage.

Carrasco et al. (2024) explored the integration of NFT systems and automation in container-based vertical farming, noting that automation can further optimize nutrient delivery and enhance leafy green production. Vought et al. (2024) analyzed the dynamics of nutrient composition in NFT systems, emphasizing the need for precise nutrient management to maintain healthy plant growth. According to Jones (2014), the NFT system's continuous flow of nutrient solution reduces the risk of nutrient stagnation, while Mohammed and Sookoo (2016) pointed out its benefit of improving oxygen availability to the roots. However, maintaining consistent nutrient levels across all plants in a vertical system requires careful design and regular maintenance of the delivery system (AlShrouf, 2017).

Deep water culture (DWC) is another nutrient delivery system used in vertical farming, allowing plants to grow with roots fully submerged in nutrient-rich water. Jüttner et al. (2022) developed an indoor farming cultivation process using DWC and other methods, finding it effective for plants like Rhodiola rosea in controlled environments. Sahoo et al. (2022b) implemented an IoT-integrated DWC system, demonstrating how real-time monitoring can enhance nutrient efficiency in indoor farms.

Each of these nutrient delivery systems offers unique advantages in optimizing plant health and productivity within vertical farming environments. Selecting the right system and implementing it carefully are critical to maximizing the efficiency of vertical farms in sustainable food production.

4.4. Nutrient Recycling and Reuse

Nutrient recycling and reuse are essential practices in sustainable vertical farming systems. Given the high resource efficiency goals of vertical farming, the ability to recycle nutrient solutions can significantly reduce input costs and environmental impact. According to Maucieri et al. (2018), hydroponic systems that incorporate nutrient recycling techniques in aquaponics demonstrate both environmental and economic benefits by conserving water and nutrients. Kozai (2018) and Kozai et al. (2019) emphasized that nutrient reuse is crucial for achieving the sustainability objectives of smart plant factories, where precision control of nutrient flows minimizes waste.

Techniques such as recirculating hydroponic systems allow for the reuse of nutrient solutions by filtering and rebalancing nutrient concentrations before returning them to the plants. Savvas and Gruda (2018) noted that this approach, common in soilless culture, conserves water and minimizes environmental impact by reducing the need for fresh nutrient inputs. Bugbee (2003) discussed that while recirculating systems are effective in maintaining nutrient balance, they require precise management to ensure plants are consistently supplied with essential nutrients.

Bittsanszky et al. (2016) addressed a specific challenge in nutrient recycling: overcoming ammonium toxicity, which can arise when certain nutrients accumulate over time. Rufí-Salís et al. (2020) conducted an environmental assessment on nutrient recovery in urban agriculture, highlighting the importance of nutrient recycling in reducing the overall footprint of vertical farms. Halbert-Howard et al. (2021) evaluated recycled fertilizers for hydroponic tomato cultivation, noting that while these fertilizers reduce greenhouse gas emissions, careful management is needed to maintain nutrient quality and prevent any negative impact on crop growth.

However, effective nutrient recycling requires careful monitoring to prevent the buildup of unwanted compounds or pathogens in the system. Miller et al. (2020) found that nutrient deficiencies can occur when recycling solutions, necessitating routine testing and adjustment to ensure optimal plant health. Asaduzzaman et al. (2022) discussed the challenges and opportunities in nutrient recycling within hydroponics, stressing that advanced monitoring systems are key to balancing nutrient levels and promoting sustainable crop production in controlled environments.

5. INNOVATIONS

5.1. Advanced Nutrient Delivery Systems

Innovation in nutrient delivery systems is crucial for optimizing plant growth in vertical farming. These systems ensure that plants receive the right amount of nutrients at the right time, reducing waste and improving efficiency.

5.1.1. Automation and Robotics

Automated climate control is another vital technology in vertical farming, maintaining optimal temperature and humidity for year-round production and enhancing efficiency, especially in large-scale operations (Chole et al., 2021; Anand et al., 2022; Ahamed et al., 2023). Hedley (2015) highlighted that precision agriculture technologies allow for accurate nutrient application, which can enhance crop yields while reducing environmental impact. Benke and Tomkins (2017) emphasized that controlled-environment agriculture, including automated nutrient management, holds potential to address food production challenges, though economic and technological barriers still limit widespread adoption. Antille et al. (2018) provided an overview of sensor-based nitrogen management technologies, noting that these sensors enable precise nitrogen application, which can improve crop performance and sustainability. Contreras et al. (2020) evaluated the effectiveness of automated fertigation systems using electrotensiometers to enhance water and nutrient productivity in horticultural crops. Similarly, Cho et al. (2020) presented an automated nutrient solution management system that allows real-time control of macronutrient concentrations to support optimal plant health. Mahadevaswamy et al. (2021) discussed an automated system for soil nutrient measurement and irrigation control, which they found useful for optimizing resource use and maintaining consistent nutrient levels in the soil.

Robotics also play a significant role in handling repetitive tasks in vertical farming, such as nutrient mixing, distribution, and plant care, thereby reducing labor costs and minimizing human error. Kushwaha et al. (2016) examined the potential of robotics in agriculture, noting that robotic technology can assist in automating complex tasks and increasing operational efficiency. Vakilian and Massah (2017) developed a farmer-assistant robot for nitrogen fertilization management in greenhouse crops, which supports precise nutrient application to promote crop growth. Sahoo et al. (2022a) provided a comprehensive review of robotics applications in agriculture, emphasizing the role of robotics in addressing labor shortages and improving precision across farming processes. Finally, Nadafzadeh et al. (2024) designed and tested a robot for monitoring specific nutrient levels, such as iron, in greenhouse-grown spinach, demonstrating its potential to enhance precision in nutrient management and support sustainable practices.

5.1.2. Sensor and Monitoring Technologies

Sensor and monitoring technologies are an integral part of advanced nutrient delivery systems, providing real-time data on various parameters to optimize plant growth in vertical farming. Brar and Kaur (2016) highlighted the significant contributions of region-specific nutrient adjustments in improving crop productivity, emphasizing the positive impact of precision nutrient management on efficiency. Similarly, Cho et al. (2018) developed an on-site ion monitoring system that enables real-time nutrient adjustments in hydroponic nutrient management, thereby enhancing plant health and increasing efficiency. Likewise, Ban et al. (2020) demonstrated the development of a nutrient solution management system aimed at optimizing nutrient distribution in plant factories, showcasing how this technology can improve production efficiency with precise nutrient allocation. Verma et al. (2020) advocated for the adaptation of region-specific nutrient management techniques to align with crop requirements, suggesting that this approach enhances resource use efficiency and improves product quality.

The integration of these technologies with IoT platforms allows for remote monitoring and management, enhancing the efficiency and reliability of vertical farming systems (Brar and Kaur 2016; Balducci et al., 2017; Cho et al., 2018; Chuah et al., 2019; Ban et al., 2020; Verma et al., 2020; Abhay et al., 2021; Mate, 2021; Ahmad et al. 2022; Anand et al. 2022; Hasan & Manohar, 2022; Rathor et al., 2024; Sasmal et al., 2024)

5.2. Smart Nutrient Management

Smart nutrient management involves the use of advanced technologies such as IoT and AI to optimize the nutrient delivery process. These technologies enable more precise control, reducing resource use while maximizing crop yields.

5.2.1. IoT and Data Analytics

The Internet of Things (IoT) has enabled large-scale data collection and analysis in vertical farming, providing real-time insights into plant growth conditions, nutrient levels, and environmental factors that are crucial for crop health. By combining IoT with data analytics, farmers can identify patterns and make data-driven decisions to optimize nutrient distribution and enhance system efficiency. For instance, Chuah et al. (2019) implemented a smart monitoring system in vertical farming that integrates IoT to manage environmental and nutrient parameters, enabling precise adjustments that support healthy plant growth. Similarly, Kumar et al. (2020) examined an Arduino-based automated hydroponic system, demonstrating IoT's potential to effectively manage nutrient levels through real-time monitoring, thus improving nutrient application accuracy.

Continuous monitoring of these factors allows farmers to make informed decisions and quickly respond to deviations from optimal conditions. IoT-based platforms also enhance remote monitoring and management capabilities in vertical farming systems, as illustrated by Abhay et al. (2021), who showcased IoT's role in simplifying crop monitoring for small-scale home vertical farms. Likewise, Mate (2021) explored an IoT-based irrigation and soil nutrient management system that automates nutrient distribution, which in turn has the potential to boost crop productivity by ensuring consistent nutrient supply. Chin and Audah (2017) developed an IoT-based monitoring system for vertical farming, enabling remote and automated control of essential parameters. Further, Ahmad et al. (2022) introduced a solar-powered IoT fertigation system designed to improve water and nutrient efficiency, highlighting IoT's sustainability benefits. In urban and vertical farming contexts, Anand et al. (2022) discussed the use of Agro-IoT systems to meet urban food demands sustainably, underlining the role of IoT in enhancing efficiency. Hasan & Manohar (2022) also emphasized the importance of a site-specific IoT nutrient management system, which tailors nutrient distribution to crop requirements and thus optimizes overall resource use.

Moreover, Rathor et al. (2024) provided a comprehensive review of IoT and AI-driven technologies in vertical farming, underscoring their potential to streamline nutrient and environmental management. Sasmal et al. (2024) further explored advances in IoT and machine learning, noting that these tools can enhance plant care and nutrient efficiency in controlled environment agriculture. Together, these studies highlight IoT's transformative role in vertical farming by enabling precise nutrient and environmental management, fostering sustainable practices, and improving productivity through real-time, data-informed decision-making.

These innovations highlight the potential of IoT to enhance sustainability and efficiency in vertical farming.

5.2.2. AI-Assisted Optimization

Artificial Intelligence (AI) is increasingly being employed to optimize nutrient management in vertical farming by analyzing data from sensors and historical records to accurately predict nutrient needs and adjust delivery systems. Saad et al. (2021) reviewed automation systems in urban smart vertical farming, highlighting both the advanced AI-driven technologies used in nutrient management and solutions to address the associated challenges, emphasizing AI’s potential to enhance efficiency in nutrient delivery. Similarly, Son et al. (2021) explored advancements in nutrient management modeling and concentration prediction for soilless culture, demonstrating how AI-based systems can improve precision in nutrient application and contribute to more stable crop yields.

In their examination of precision management techniques, Hasan et al. (2022) focused on AI applications for nutrient delivery optimization, aligning with Siropyan et al. (2022), who introduced an AI-driven management system specifically for vertical farming that refines nutrient management for enhanced productivity. Siregar et al. (2022) further emphasized AI's role in supporting precision agriculture within vertical farming, underscoring its capacity to maintain optimal nutrient and environmental conditions, which is essential for sustainable growth.

Kabir et al. (2023) examined technological trends in vertical farming, noting that AI and automation are pivotal in overcoming engineering challenges and enhancing operational efficiency. In line with this, Bhamare and Bansal (2024) discussed AI and computer vision applications, emphasizing their role in promoting sustainability and precision in nutrient management. Rathor et al. (2024) provided a comprehensive review of IoT and AI-driven technologies, illustrating their potential to streamline nutrient delivery and increase the resilience of vertical farming systems.

Together, these studies highlight AI's transformative impact on vertical farming by enabling precise, data-informed nutrient management, ultimately fostering sustainability and efficiency across the system.

5.3. Sustainable Nutrient Solutions

Sustainability is a key focus in the development of nutrient management systems for vertical farming. Innovations in nutrient recycling and the use of organic and natural nutrient sources are central to creating more sustainable farming practices.

5.3.1. Nutrient Recycling Technologies

Nutrient recycling is essential for reducing waste and enhancing the sustainability of vertical farming systems. Closed-loop systems, for instance, enable the recapture and reuse of nutrients, reducing dependency on synthetic fertilizers and conserving resources. These systems filter and purify nutrient solutions before reapplying them to plants, which minimizes environmental impact. Birkby et al. (2016) highlighted the significance of nutrient management systems that prioritize resource conservation, emphasizing the need for sustainable approaches in vertical farming. In line with this, Savvas and Gruda (2018) examined soilless culture technologies in greenhouse systems, underlining the role of advanced nutrient management strategies as crucial for sustainable agricultural practices.

Miller et al. (2020) examined the recycling of nutrient solutions in hydroponic systems, noting that while this process conserves resources, it may lead to nutrient deficiencies if not carefully managed. Similarly, Rufí-Salís et al. (2020) assessed the environmental benefits of nutrient recovery in urban hydroponics, showing that nutrient recycling plays a key role in enhancing sustainability within urban farming environments. Halbert-Howard et al. (2021) focused on the application of recycled fertilizers in hydroponic tomato cultivation, finding that these practices not only improve resource efficiency but also reduce greenhouse gas emissions, thereby supporting sustainable production.

Van Gerrewey et al. (2021) examined nutrient management practices in vertical farming, noting how effective recycling strategies can significantly boost both sustainability and crop yield. Asaduzzaman et al. (2022) reviewed the opportunities and challenges of nutrient recycling in hydroponic systems, underscoring its essential role in maintaining sustainable, controlled environments. Shenoy et al. (2023) expanded on this by exploring innovative phosphorus recovery technologies from sewage sludge, demonstrating their potential for nutrient recycling applications in hydroponic farming systems.

Collectively, these studies highlight the transformative impact of nutrient recycling technologies in vertical farming, emphasizing their ability to promote sustainable practices, reduce resource consumption, and mitigate environmental impact.

5.3.2. Organic and Natural Nutrient Sources

The use of organic and natural nutrient sources is gaining popularity in vertical farming as a sustainable alternative that not only supplies essential nutrients but also enhances overall system health. Organic fertilizers, compost teas, and biochar are widely used to support nutrient needs while providing benefits like soil health improvement in soil-based systems or adding beneficial microbes in soilless systems. Pant et al. (2012) highlighted the biochemical properties of compost tea, noting its positive impact on pak choi yield and demonstrating how compost quality directly influences nutrient management effectiveness.

These organic solutions are frequently combined with nutrient recycling technologies to promote a more integrated, sustainable approach to nutrient management. Barber et al. (2018) examined biochar's dual role as a filter and a fertilizer, showing how it helps close nutrient cycles and supports nutrient reuse in vertical farming systems. Likewise, Huang et al. (2019) emphasized the importance of nutrient recovery from organic waste as part of sustainable soil management strategies, focusing on the benefits of recycling organic materials for enhanced nutrient availability. Alternative nutrient sources are also being explored to broaden the range of sustainable inputs. Ashraf (2020) investigated the use of human liquid bio-waste as a fertilizer in urban indoor agriculture, finding it effective in promoting Swiss chard growth within vertical systems, thus presenting a viable organic nutrient solution. Similarly, Syaranamual et al. (2024) studied mustard plants' response to various media compositions, such as topsoil, biochar, and manure, illustrating the potential of diverse organic materials in providing sustainable nutrient solutions for vertical farming.

Together, these studies underscore the role of organic and natural nutrient sources in creating more sustainable nutrient management practices, enhancing resource efficiency, and supporting overall system health in vertical farming..

5.4. Energy Efficiency and Resource Use

Energy efficiency and resource use are critical considerations in vertical farming, where the need for artificial lighting and controlled environments can lead to significant energy consumption. Innovations in this area focus on reducing energy use while maintaining optimal growing conditions.

5.4.1. Energy-Efficient Systems

The success of vertical farming relies heavily on advanced technologies, with LED lighting playing a crucial role by providing the optimal light spectrum for plant growth (Wong et al. 2020). LED systems not only improve plant productivity and growth quality but also contribute to energy efficiency and pathogen control in hydroponic environments. Massa et al. (2008) reported that LED lighting significantly enhances plant productivity by allowing control over light spectra and intensity, optimizing plant growth in controlled environments. Kim et al. (2020) demonstrated that ultraviolet (UV) LED light sources can be effectively used to sterilize harmful microorganisms in hydroponic systems. They argued that UV LED technology is an efficient, sustainable method for managing microbial contamination, thereby supporting plant health and productivity in controlled environments like vertical farms. Nguyen et al. (2021) investigated the effects of white LED lighting with specific shorter blue and green wavelengths on the growth and quality of lettuce cultivars in a vertical farming system. They found that tailored LED light spectra can enhance both the growth and quality of lettuce, suggesting that adjusting wavelengths can be a beneficial strategy in vertical farming to optimize crop yield and nutrient content. Furthermore, Olvera-Gonzalez et al. (2021) proposed pulsed LED lighting as an energy-saving technique for vertical farms, maintaining plant productivity while reducing energy consumption. Nájera et al. (2022) also noted that LED lighting in vertical farming systems enhances the bioactive compound content and productivity of vegetable crops, making it ideal for sustainable crop production.

Additionally, advances in HVAC (heating, ventilation, and air conditioning) systems allow for more precise climate control with lower energy consumption. Graamans et al. (2017) compared resource use efficiency between plant factories and traditional greenhouses, with a particular focus on energy and climate control requirements, including HVAC systems. The study highlighted that while plant factories offer year-round production with precise environmental control, they tend to consume more energy than greenhouses, primarily due to artificial lighting and HVAC demands. The authors concluded that, although plant factories are efficient in land and water use, optimizing HVAC and energy systems is essential to improve their overall resource efficiency and sustainability.

5.4.2. Water Management Innovations

Innovation in water management is crucial for maximizing the efficiency and sustainability of vertical farming systems. Although these systems are designed to use water more efficiently than traditional farming, there is always room for improvement. Technologies like fogponics, which delivers water and nutrients through a fine mist, represent a significant advancement in reducing water consumption. Uddin and Suliaman (2021) emphasized that their smart fogponics system not only optimizes nutrient delivery but also minimizes water use, making it an energy-efficient choice for indoor agriculture.

To further enhance water sustainability, recycling systems that capture and purify water for reuse have become increasingly integrated into vertical farming operations. Germer et al. (2011) introduced the concept of "Skyfarming," showcasing how water recycling and other innovations in vertical farming can increase food production in urban areas with limited resources. Building on this, Suwastika et al. (2022) developed a fogponics system that utilizes IoT and fuzzy logic, demonstrating its potential for precise control over water and nutrient distribution in vertical farms. Sinha and Kumar (2024) expanded on fogponics applications, presenting a framework suited to compact urban spaces, which emphasizes efficient water use in indoor gardening. Similarly, Suganob et al. (2024) explored the integration of artificial intelligence with fogponics, suggesting its applicability for controlled environments such as space farming, where precise water and nutrient management is vital.

Collectively, these advancements in water management demonstrate the potential for sustainable and efficient practices in vertical farming, setting a foundation for future innovations in resource conservation and optimized food production.

6. CHALLENGES

6.1. Optimization of Nutrient Solutions

Optimizing nutrient solutions is a critical challenge in vertical farming, where precise nutrient management is essential for ensuring plant health and maximizing yield.

6.1.1. pH and EC Control

Vertical farming systems face significant challenges in maintaining optimal pH and electrical conductivity (EC) levels in nutrient solutions to ensure effective nutrient uptake by plants. pH fluctuations can critically impact nutrient solubility, leading to deficiencies or toxicities that inhibit plant growth (Jones, 2014). Despite the availability of pH measurement tools, Hinojosa-Meza et al. (2022) highlighted the need for cost-effective, precise pH monitoring instruments specifically suited to vertical farming, where consistent accuracy is essential for maintaining nutrient stability.

Similarly, managing EC levels poses its own set of challenges, as EC measures the concentration of dissolved salts in nutrient solutions. High EC levels may induce osmotic stress, while low EC can result in insufficient nutrient availability, both affecting plant health. Marschner (2012) discussed the delicate balance required for EC to support nutrient availability, while Hosseini et al. (2021) found that even slight deviations from optimal EC levels could significantly impact the growth and yield of crops like lettuce and basil in vertical systems. Sulaiman et al. (2021) emphasized that temperature variations further complicate EC management, necessitating precise control to maintain stability across growth cycles.

In vertical hydroponic systems, achieving consistent EC adjustments is particularly challenging due to the need for high precision in a densely packed, controlled environment (Van Quy et al., 2018). Resh (2022) underscores the importance of continuously monitoring and adjusting these parameters, noting that even minor inconsistencies can disrupt nutrient absorption and adversely impact plant productivity. Overall, maintaining optimal pH and EC levels remains a persistent challenge in vertical farming, requiring innovative solutions and advanced monitoring tools to overcome these obstacles effectively.

6.1.2. Maintaining Nutrient Balance

Maintaining a balanced supply of macro- and micronutrients is a significant challenge in nutrient solution optimization for vertical farming. Imbalances in nutrient levels can cause competitive inhibition, where an excess of one nutrient interferes with the uptake of others, potentially leading to deficiencies or toxicities (Savvas & Gruda, 2018). Precise nutrient formulation and continuous monitoring are essential to manage these nutrient interactions, particularly in recirculating systems where nutrient levels fluctuate over time, posing additional challenges for stability.

To address these issues, real-time monitoring technologies offer potential solutions by enabling continuous tracking of nutrient levels. For example, Luna Juncal et al. (2020) highlighted that mobile nitrate monitoring supports frequent data collection, making nutrient management more responsive. Fan et al. (2022) and Swathy et al. (2024) underscored the importance of real-time monitoring, particularly for nitrogen, in enhancing nutrient use efficiency and preventing excess buildup, which supports a balanced nutrient environment. Silva et al. (2024) expanded on this by reviewing sensing technologies for nitrogen, phosphorus, and potassium, emphasizing their role in maintaining precise nutrient balance and preventing competitive inhibition.

Together, these studies reveal that ensuring nutrient balance in vertical farming is not only technically complex but also requires advanced, responsive monitoring systems to avoid imbalances that could compromise plant health and productivity.

6.2. Disease and Contamination Management

Disease and contamination control is a significant challenge in vertical farming, where the closed and controlled environments can sometimes favor the proliferation of pathogens if not managed properly.

Microbial contamination, including bacteria, fungi, and viruses, threatens crop health in high-density and recirculating systems by facilitating the rapid spread of pathogens. Bittsanszky et al. (2016) highlighted ammonium toxicity as a factor that weakens plant resistance, increasing susceptibility to microbial threats. Effective microbial control strategies in vertical farming include using biocontrol agents, monitoring microbial populations, and implementing strict hygiene protocols (Sharma et al., 2019). Advanced technologies also support early disease detection; Jayasekara et al. (2021) proposed an automated system for growth and disease monitoring, while Anubhove et al. (2020) and Bakar and Audah (2021) demonstrated the potential of machine learning and image processing for detecting microbial infections in real-time.

Sterilization of equipment and nutrient solutions is essential to prevent pathogen introduction and spread. Techniques such as UV sterilization, ozonation, and chemical disinfection are widely used to maintain a pathogen-free environment. UV radiation, in particular, has shown effective results for disinfecting recirculating water and nutrient solutions in hydroponic systems, helping to inactivate pathogens (Runia & Boogert, 2005; Sutton et al., 2000). Pantanella et al. (2010) explored UV sterilization in aquaponics, demonstrating its effectiveness in reducing total coliforms and enhancing food safety in integrated systems, while Moriarty et al. (2018) further highlighted UV's reliability as a microbial control method by successfully controlling coliforms and Escherichia coli in aquaponic lettuce. Tsunedomi et al. (2018) and Kim et al. (2020) highlighted the energy-efficient potential of UV LED technology for microbial control. Similarly, ozonation has been shown to reduce microbial loads in hydroponic setups, thus enhancing crop resilience (Zheng et al., 2020). However, these sterilization methods may also impact beneficial microorganisms, requiring a balanced approach to maintain a healthy microbial community (Savvas & Gruda, 2018).

6.3. Cost and Resource Efficiency

The high costs of establishing and operating vertical farming systems present significant challenges, as advanced technology, infrastructure, and maintenance demands create financial barriers, particularly for small-scale farmers and new entrants (AlShrouf, 2017). Initial capital investments required for LED lighting, HVAC systems, and automation technology are substantial, with added logistical and financial challenges in urban environments, making broader accessibility difficult (Kalantari et al., 2017; Graamans et al., 2017).

In addition to startup costs, operational expenses pose ongoing challenges. While technologies like LED lighting and climate control are critical for maintaining optimal growth conditions, they also increase recurring expenses, particularly in urban settings with high energy costs (Kozai, 2018). As such, cost-effective solutions for energy and resource use are essential for economic sustainability. Graamans et al. (2017) and Kozai et al. (2019) noted that minimizing costs associated with specialized lighting and climate control could improve the financial viability of vertical farming, particularly in high-density urban areas.

Mir et al. (2022) pointed out that both high initial and operational costs restrict vertical farming's accessibility, though the system's potential to meet future agricultural demands remains promising. Reducing infrastructure and resource-related expenses is therefore key, as highlighted by Benke and Tomkins (2017) and Panotra et al. (2024), to making vertical farming a sustainable and scalable solution for the future. Moreover, while monitoring and sensor systems contribute to growth optimization, their costs can impact profitability, underscoring the need for balanced investment in technology to support long-term sustainability (Morella et al., 2023).

6.4. Scalability and Commercial Applications

Scaling vertical farming operations and ensuring their commercial viability are critical challenges that need to be addressed for the widespread adoption of this farming method.

6.4.1. Managing Large-Scale Systems

Managing large-scale vertical farming systems involves complexities in maintaining uniform environmental conditions, nutrient distribution, and disease control across all levels of the farm. Kalantari et al. (2017) reviewed the opportunities and challenges in scaling vertical farming for sustainability, highlighting the difficulties in achieving consistent environmental control and efficient resource use in larger systems. They noted that as scale increases, maintaining system efficiency and sustainability becomes more complex. The integration of automation and advanced monitoring systems can help, but they also add to the complexity and cost of scaling operations. Jensen and Malter (1995) discussed similar challenges in protected agriculture globally, pointing out that managing large-scale systems requires significant investment in technology and infrastructure, which may be challenging for widespread adoption.

6.4.2. Market and Supply Chain Issues

Vertical farming products need to compete with conventionally grown produce in terms of price and quality. Establishing efficient supply chains and market access is essential for the commercial success of vertical farming. Al-Kodmany (2018) discussed the challenges of integrating vertical farms into urban environments, noting that streamlined supply chains are vital to making vertically farmed products accessible and competitively priced within city markets. However, the current market for vertically farmed products is still limited, and consumer awareness and acceptance are crucial for expanding this market. Benke and Tomkins (2017) emphasized that while vertical farming has potential, its success depends on public acceptance and creating a reliable market for these products, which may require educational efforts and strategic marketing to build consumer trust and demand.

6.5. Technological Limitations and Adaptation

Technological advancements have enabled the growth of vertical farming, but there are still limitations and challenges in adapting these technologies.

6.5.1. Technology Integration

Integrating various technologies, such as automation, IoT, and AI, into a cohesive vertical farming system can be challenging. Ensuring that these technologies work seamlessly together and are easily managed by farm operators requires significant expertise and ongoing maintenance. Kumar et al. (2020) developed an IoT-based automated hydroponic system using Arduino, illustrating how IoT can optimize nutrient delivery but also highlighting the technical knowledge required for successful operation. Van Delden et al. (2021) reviewed the current state and future challenges of scaling vertical farming systems, emphasizing the complexities involved in integrating multiple advanced technologies and the expertise needed to maintain system efficiency at larger scales. Moreover, technological failures or incompatibilities can lead to significant disruptions in production. Kabir et al. (2023) discussed emerging technological trends and engineering challenges, pointing out that inconsistencies between systems can hamper smooth operations and cause costly downtimes.

6.5.2. Lack of Training and Expertise

The rapid development of vertical farming technologies has created a knowledge gap, where many farmers and operators lack the necessary skills and expertise to effectively manage these systems. Sharma et al. (2019) provided an overview of hydroponics, highlighting that as advanced cultivation techniques become more widespread, there is an increasing need for specialized training to bridge the skill gap in managing these systems. Providing adequate training and education is essential for the successful adoption and operation of vertical farming systems. Bradley and Marulanda (2000) argued that simplified hydroponics training can reduce global hunger by empowering individuals with the skills to grow food in limited spaces. Van Henten et al. (2006) emphasized the complexity of managing artificial lighting in horticultural environments, noting that adaptive control requires technical knowledge that is often lacking among new adopters of vertical farming. Nugroho (2019) demonstrated that introductory training on hydroponic systems helps participants gain foundational skills necessary for managing hydroponic plants effectively. Lubna et al. (2022) discussed how the lack of awareness and expertise about vertical farming systems can hinder its adoption and efficiency, suggesting that structured education programs are essential. Pambudi et al. (2022) conducted hydroponic training programs aimed at improving food security, community economy, and environmental quality, underscoring the role of hands-on training in building community knowledge. Safeyah et al. (2023) focused on verticulture hydroponics, illustrating how knowledge and skill development in vertical farming can be enhanced through targeted training initiatives.

7. SUCCESS STORIES AND APPLICATIONS

7.1. International Success Stories

Vertical farming has seen remarkable success in various parts of the world, with several projects standing out for their innovation, scalability, and impact. One of the most prominent examples is the Singapore-based company Sky Greens, which operates the world's first low-carbon, hydraulic-driven vertical farm. This project has significantly contributed to Singapore's food security by producing fresh vegetables within the city-state, reducing reliance on imports (SkyGreens Canada 2022; SkyGreens, 2024;). Another noteworthy project is AeroFarms in the United States, which has pioneered the use of aeroponic technology to grow leafy greens in an urban setting. AeroFarms' patented technology uses 95% less water than traditional farming, making it a model of sustainable urban agriculture (Despommier, 2010; Aerofarms, 2024;).

In Japan, the Mirai Plant Factory has become a global leader in vertical farming, using advanced LED lighting and climate control technologies to produce high-quality crops year-round. This project has been particularly successful in addressing food supply challenges in disaster-prone regions, demonstrating the resilience and adaptability of vertical farming systems (Kozai et al., 2015; Mirai Plant Factory, 2024). These international projects highlight the potential of vertical farming to address global food security challenges through innovative, sustainable practices.

7.2. Local and Regional Success Stories

In addition to international examples, there are numerous local and regional success stories that demonstrate the versatility of vertical farming across different contexts. In the Middle East, where arable land and water resources are scarce, companies like Badia Farms in Dubai have successfully implemented vertical farming to produce fresh greens using minimal water and space. This project has not only provided a local source of fresh produce but also contributed to the region's food security and sustainability goals (AlShrouf, 2017; Badia Farms, 2024;).

In Europe, the Nordic Harvest vertical farm in Denmark is one of the largest of its kind, utilizing renewable energy sources to power its operations. The farm's commitment to sustainability and efficiency has made it a leading example of how vertical farming can be integrated into a region's broader environmental strategy (Al-Kodmany, 2018). Similarly, in the Netherlands, the Urban Farmers project in The Hague has successfully combined aquaponics and vertical farming to produce fresh vegetables and fish in an urban environment, showcasing the potential of integrated farming systems (Goddek et al., 2019; YesHealthGroup, 2024).

7.3. Analysis of Best Practices

The success of these projects can be attributed to several best practices that have been identified across different vertical farming operations. First, the use of advanced technologies, such as LED lighting and automated nutrient delivery systems, has been crucial in optimizing crop growth and reducing resource use (Kozai, 2018; Kozai et al., 2019). Second, the integration of sustainable practices, such as water recycling and the use of renewable energy, has helped to reduce the environmental footprint of vertical farms while improving their economic viability (Benke & Tomkins, 2017).

Another key factor in the success of these projects is their ability to adapt to local conditions and market demands. For instance, vertical farms in arid regions have focused on water-efficient practices, while those in urban areas have prioritized space optimization and local food production (Kalantari et al., 2017). Furthermore, successful vertical farms often engage in continuous innovation and improvement, regularly updating their technologies and practices to stay competitive and meet the evolving needs of consumers (Graamans et al., 2017).

8. FUTURE PERSPECTIVES AND RESEARCH NEEDS

8.1. Emerging Technological Developments

The future of vertical farming is closely tied to advancements in technology, which are expected to drive improvements in efficiency, productivity, and sustainability. Emerging technologies such as advanced robotics, artificial intelligence (AI), and machine learning are poised to revolutionize nutrient management, plant monitoring, and automation within vertical farms. For instance, AI-driven systems can analyze vast amounts of data to optimize growing conditions and predict crop needs in real-time, leading to more precise and efficient farming practices (Cai et al., 2019; Chatterjee et al., 2020; Van Delden et al. 2021, Siregar, 2022; Siropyan, 2022; Bhamare & Bansal, 2024; Rathor et al., 2024; Suganob, 2024). Additionally, innovations in lighting technology, such as the development of tunable LEDs that can adjust the light spectrum according to the plant's growth stage, are expected to further enhance productivity (Massa et al., 2008).

Research is also needed to explore the integration of these technologies into existing vertical farming systems and to address the challenges of scalability and cost-effectiveness. As these technologies evolve, it will be essential to ensure that they are accessible and affordable for a broader range of users, including small-scale farmers and startups (Van Henten et al., 2006).

8.2. Sustainability and Environmental Impacts

Sustainability remains a central concern in the development of vertical farming systems. While vertical farming has the potential to reduce land and water use compared to traditional agriculture, there are ongoing challenges related to energy consumption and waste management (Graamans et al., 2017). Future research should focus on enhancing the sustainability of vertical farming by developing energy-efficient systems, exploring renewable energy sources, and improving nutrient recycling processes (Savvas & Gruda, 2018).

Additionally, the environmental impact of vertical farming on urban ecosystems should be carefully assessed. Studies are needed to evaluate the long-term effects of large-scale vertical farms on local biodiversity, air quality, and resource use (Benke & Tomkins, 2017). Addressing these concerns will be critical for ensuring that vertical farming contributes positively to both food security and environmental sustainability.

8.3. The Role of Policy and Regulations

The expansion of vertical farming will require supportive policies and regulations that encourage innovation while ensuring safety and sustainability. Governments and regulatory bodies have a crucial role to play in establishing standards for vertical farming practices, including guidelines for food safety, environmental protection, and resource use (Kalantari et al., 2017; Van Delden et al. 2021, Akintuyi, 2024).

Future research should explore the development of policy frameworks that support the growth of vertical farming, particularly in urban areas. This includes examining the potential for incentives, such as tax breaks or subsidies, to encourage investment in vertical farming technologies (Al-Kodmany, 2018). Additionally, the role of international cooperation in sharing best practices and knowledge across borders should be considered, as vertical farming has the potential to address global food security challenges (Despommier, 2010).

8.4. Multidisciplinary Approaches and Collaborations

The complex nature of vertical farming necessitates a multidisciplinary approach, involving experts from agriculture, engineering, environmental science, economics, and urban planning. Collaborative research efforts are essential to address the diverse challenges facing vertical farming and to develop holistic solutions that consider the social, economic, and environmental aspects of the practice (Kozai, 2018; Kozai et al. 2019).

Future research should focus on fostering collaborations between academia, industry, and government to drive innovation and knowledge sharing in vertical farming. Partnerships with technology companies can help integrate cutting-edge tools into vertical farming systems, while collaboration with policymakers can ensure that regulations keep pace with technological advancements (Goddek et al., 2019). Additionally, engaging with local communities and stakeholders is crucial for ensuring that vertical farming initiatives are aligned with the needs and values of the populations they serve.

9. CONCLUSION

The integration of advanced technologies into vertical farming has greatly enhanced the precision and efficiency of nutrient management. Innovations such as automated nutrient delivery systems, sensor technologies, and AI-driven optimization have allowed for more accurate control over nutrient concentrations, ensuring that plants receive the precise amounts of nutrients they need at each growth stage. These advancements have not only improved crop yields and quality but also contributed to the sustainability of vertical farming by reducing resource use and minimizing waste. The development of energy-efficient systems, such as LED lighting and advanced HVAC systems, has played a key role in reducing operational costs, making vertical farming more economically viable. Additionally, the ability to recycle and reuse nutrient solutions has minimized the environmental impact of vertical farming operations.

However, several challenges remain in nutrient management. Optimizing nutrient solutions to maintain a balanced supply of macro and micronutrients while preventing the buildup of unwanted compounds is still an issue. Ongoing research is needed to develop more sophisticated nutrient formulations and real-time monitoring systems that can adjust nutrient delivery based on the specific needs of plants. Furthermore, managing disease and contamination in the controlled environments of vertical farms presents another challenge. Advanced sterilization techniques and the integration of biocontrol agents can help, but further improvements are necessary to develop more effective and sustainable solutions. Additionally, reducing the high initial capital investments and operational costs remains critical for the wider adoption of vertical farming. Innovations in automation, renewable energy integration, and resource management will be essential in overcoming these financial barriers.

As vertical farming continues to evolve, nutrient management will remain a critical factor in its success. The future of vertical farming is likely to see even greater integration of technology, with AI and IoT optimizing every aspect of the farming process. Precise control over nutrient delivery and environmental conditions will enable vertical farms to produce high-quality crops year-round, regardless of external factors. With the growing global population and the increasing demand for sustainable food production, vertical farming will play an essential role in ensuring food security. Effective nutrient management will be central to this effort, allowing vertical farms to maximize productivity while minimizing their environmental footprint. Continued advancements in nutrient management practices will be crucial for the future of vertical farming, ensuring that it meets the challenges of feeding a growing global population in a sustainable manner.

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