



Engineering Journal IJOER
VOLUME-12, ISSUE-4,
APRIL 2026

DOWNLOAD NOW

Contact us



+91-7665235235



www.ijoer.com



info@ijoer.com

Preface

We would like to present, with great pleasure, the volume-12, Issue-3, March 2026, of a scholarly journal, *International Journal of Engineering Research & Science*. This journal is part of the AD Publications series in the field of Engineering, Mathematics, Physics, Chemistry and science Research Development, and is devoted to the gamut of Engineering and Science issues, from theoretical aspects to application-dependent studies and the validation of emerging technologies.

This journal was envisioned and founded to represent the growing needs of Engineering and Science as an emerging and increasingly vital field, now widely recognized as an integral part of scientific and technical investigations. Its mission is to become a voice of the Engineering and Science community, addressing researchers and practitioners in below areas:

Chemical Engineering	
Biomolecular Engineering	Materials Engineering
Molecular Engineering	Process Engineering
Corrosion Engineering	
Civil Engineering	
Environmental Engineering	Geotechnical Engineering
Structural Engineering	Mining Engineering
Transport Engineering	Water resources Engineering
Electrical Engineering	
Power System Engineering	Optical Engineering
Mechanical Engineering	
Acoustical Engineering	Manufacturing Engineering
Optomechanical Engineering	Thermal Engineering
Power plant Engineering	Energy Engineering
Sports Engineering	Vehicle Engineering
Software Engineering	
Computer-aided Engineering	Cryptographic Engineering
Teletraffic Engineering	Web Engineering
System Engineering	
Mathematics	
Arithmetic	Algebra
Number theory	Field theory and polynomials
Analysis	Combinatorics
Geometry and topology	Topology
Probability and Statistics	Computational Science
Physical Science	Operational Research
Physics	
Nuclear and particle physics	Atomic, molecular, and optical physics
Condensed matter physics	Astrophysics
Applied Physics	Modern physics
Philosophy	Core theories

Chemistry	
Analytical chemistry	Biochemistry
Inorganic chemistry	Materials chemistry
Neurochemistry	Nuclear chemistry
Organic chemistry	Physical chemistry
Other Engineering Areas	
Aerospace Engineering	Agricultural Engineering
Applied Engineering	Biomedical Engineering
Biological Engineering	Building services Engineering
Energy Engineering	Railway Engineering
Industrial Engineering	Mechatronics Engineering
Management Engineering	Military Engineering
Petroleum Engineering	Nuclear Engineering
Textile Engineering	Nano Engineering
Algorithm and Computational Complexity	Artificial Intelligence
Electronics & Communication Engineering	Image Processing
Information Retrieval	Low Power VLSI Design
Neural Networks	Plastic Engineering

Each article in this issue provides an example of a concrete industrial application or a case study of the presented methodology to amplify the impact of the contribution. We are very thankful to everybody within that community who supported the idea of creating a new Research with IJOER. We are certain that this issue will be followed by many others, reporting new developments in the Engineering and Science field. This issue would not have been possible without the great support of the Reviewer, Editorial Board members and also with our Advisory Board Members, and we would like to express our sincere thanks to all of them. We would also like to express our gratitude to the editorial staff of AD Publications, who supported us at every stage of the project. It is our hope that this fine collection of articles will be a valuable resource for *IJOER* readers and will stimulate further research into the vibrant area of Engineering and Science Research.



Mukesh Arora
(Chief Editor)

Board Members

Mr. Mukesh Arora (Editor-in-Chief)

BE (Electronics & Communication), M.Tech (Digital Communication), currently serving as Assistant Professor in the Department of ECE.

Prof. Dr. Fabricio Moraes de Almeida

Professor of Doctoral and Master of Regional Development and Environment - Federal University of Rondonia.

Dr. Parveen Sharma

Dr Parveen Sharma is working as an Assistant Professor in the School of Mechanical Engineering at Lovely Professional University, Phagwara, Punjab.

Prof. S. Balamurugan

Department of Information Technology, Kalaignar Karunanidhi Institute of Technology, Coimbatore, Tamilnadu, India.

Dr. Omar Abed Elkareem Abu Arqub

Department of Mathematics, Faculty of Science, Al Balqa Applied University, Salt Campus, Salt, Jordan, He received PhD and Msc. in Applied Mathematics, The University of Jordan, Jordan.

Dr. AKPOJARO Jackson

Associate Professor/HOD, Department of Mathematical and Physical Sciences, Samuel Adegboyega University, Ogwa, Edo State.

Dr. Ajoy Chakraborty

Ph.D.(IIT Kharagpur) working as Professor in the department of Electronics & Electrical Communication Engineering in IIT Kharagpur since 1977.

Dr. Ukar W. Soelistijo

Ph D, Mineral and Energy Resource Economics, West Virginia State University, USA, 1984, retired from the post of Senior Researcher, Mineral and Coal Technology R&D Center, Agency for Energy and Mineral Research, Ministry of Energy and Mineral Resources, Indonesia.

Dr. Samy Khalaf Allah Ibrahim

PhD of Irrigation &Hydraulics Engineering, 01/2012 under the title of: "Groundwater Management under Different Development Plans in Farafra Oasis, Western Desert, Egypt".

Dr. Ahmet ÇİFCİ

Ph.D. in Electrical Engineering, Currently Serving as Head of Department, Burdur Mehmet Akif Ersoy University, Faculty of Engineering and Architecture, Department of Electrical Engineering.

Dr. M. Varatha Vijayan

Annauniversity Rank Holder, Commissioned Officer Indian Navy, Ncc Navy Officer (Ex-Serviceman Navy), Best Researcher Awardee, Best Publication Awardee, Tamilnadu Best Innovation & Social Service Awardee From Lions Club.

Dr. Mohamed Abdel Fatah Ashabrawy Moustafa

PhD. in Computer Science - Faculty of Science - Suez Canal University University, 2010, Egypt.

Assistant Professor Computer Science, Prince Sattam bin AbdulAziz University ALkharj, KSA.

Prof.S.Balamurugan

Dr S. Balamurugan is the Head of Research and Development, Quants IS & CS, India. He has authored/co-authored 35 books, 200+ publications in various international journals and conferences and 6 patents to his credit. He was awarded with Three Post-Doctoral Degrees - Doctor of Science (D.Sc.) degree and Two Doctor of Letters (D.Litt) degrees for his significant contribution to research and development in Engineering.

Dr. Mahdi Hosseini

Dr. Mahdi did his Pre-University (12th) in Mathematical Science. Later he received his Bachelor of Engineering with Distinction in Civil Engineering and later he Received both M.Tech. and Ph.D. Degree in Structural Engineering with Grade "A" First Class with Distinction.

Dr. Anil Lamba

Practice Head – Cyber Security, EXL Services Inc., New Jersey USA.

Dr. Anil Lamba is a researcher, an innovator, and an influencer with proven success in spearheading Strategic Information Security Initiatives and Large-scale IT Infrastructure projects across industry verticals. He has helped bring about a profound shift in cybersecurity defense. Throughout his career, he has parlayed his extensive background in security and a deep knowledge to help organizations build and implement strategic cybersecurity solutions. His published researches and conference papers has led to many thought provoking examples for augmenting better security.

Dr. Ali İhsan KAYA

Currently working as Associate Professor in Mehmet Akif Ersoy University, Turkey.

Research Area: Civil Engineering - Building Material - Insulation Materials Applications, Chemistry - Physical Chemistry – Composites.

Dr. Parsa Heydarpour

Ph.D. in Structural Engineering from George Washington University (Jan 2018), GPA=4.00.

Dr. Heba Mahmoud Mohamed Afify

Ph.D degree of philosophy in Biomedical Engineering, Cairo University, Egypt worked as Assistant Professor at MTI University.

Dr. Kalpesh Sunil Kamble (Ph.D., P.Eng., M.Tech, B.E. (Mechanical))

A distinguished academic with a Ph.D. in Mechanical Engineering and 13 Years of extensive teaching and research experience. He is currently a Assistant professor at the SSPM's COE, Kankavli and contributes to several undergraduate and masters programs across Maharashtra, India.

Dr. Aurora Angela Pisano

Ph.D. in Civil Engineering, Currently Serving as Associate Professor of Solid and Structural Mechanics (scientific discipline area nationally denoted as ICAR/08"-"Scienza delle Costruzioni"), University Mediterranea of Reggio Calabria, Italy.

Dr. Faizullah Mahar

Associate Professor in Department of Electrical Engineering, Balochistan University Engineering & Technology Khuzdar. He is PhD (Electronic Engineering) from IQRA University, Defense View, Karachi, Pakistan.

Prof. Viviane Barrozo da Silva

Graduated in Physics from the Federal University of Paraná (1997), graduated in Electrical Engineering from the Federal University of Rio Grande do Sul - UFRGS (2008), and master's degree in Physics from the Federal University of Rio Grande do Sul (2001).

Dr. S. Kannadhasan

Ph.D (Smart Antennas), M.E (Communication Systems), M.B.A (Human Resources).

Dr. Christo Ananth

Ph.D. Co-operative Networks, M.E. Applied Electronics, B.E Electronics & Communication Engineering Working as Associate Professor, Lecturer and Faculty Advisor/ Department of Electronics & Communication Engineering in Francis Xavier Engineering College, Tirunelveli.

Dr. S.R.Boselin Prabhu

Ph.D, Wireless Sensor Networks, M.E. Network Engineering, Excellent Professional Achievement Award Winner from Society of Professional Engineers Biography Included in Marquis Who's Who in the World (Academic Year 2015 and 2016). Currently Serving as Assistant Professor in the department of ECE in SVS College of Engineering, Coimbatore.

Dr. Balasubramanyam, N

Dr.Balasubramanyam, N working as Faculty in the Department of Mechanical Engineering at S.V.University College of Engineering Tirupati, Andhra Pradesh.

Dr. PAUL P MATHAI

Dr. Paul P Mathai received his Bachelor's degree in Computer Science and Engineering from University of Madras, India. Then he obtained his Master's degree in Computer and Information Technology from Manonmanium Sundaranar University, India. In 2018, he received his Doctor of Philosophy in Computer Science and Engineering from Noorul Islam Centre for Higher Education, Kanyakumari, India.

Dr. M. Ramesh Kumar

Ph.D (Computer Science and Engineering), M.E (Computer Science and Engineering).

Currently working as Associate Professor in VSB College of Engineering Technical Campus, Coimbatore.

Dr. Maheshwar Shrestha

Postdoctoral Research Fellow in DEPT. OF ELE ENGG & COMP SCI, SDSU, Brookings, SD Ph.D, M.Sc. in Electrical Engineering from SOUTH DAKOTA STATE UNIVERSITY, Brookings, SD.

Dr. D. Amaranatha Reddy

Ph.D. (Postdoctoral Fellow, Pusan National University, South Korea), M.Sc., B.Sc. : Physics.

Dr. Dibya Prakash Rai

Post Doctoral Fellow (PDF), M.Sc., B.Sc., Working as Assistant Professor in Department of Physics in Pachhungga University College, Mizoram, India.

Dr. Pankaj Kumar Pal

Ph.D R/S, ECE Deptt., IIT-Roorkee.

Dr. P. Thangam

PhD in Information & Communication Engineering, ME (CSE), BE (Computer Hardware & Software), currently serving as Associate Professor in the Department of Computer Science and Engineering of Coimbatore Institute of Engineering and Technology.

Dr. Pradeep K. Sharma

PhD., M.Phil, M.Sc, B.Sc, in Physics, MBA in System Management, Presently working as Provost and Associate Professor & Head of Department for Physics in University of Engineering & Management, Jaipur.

Dr. R. Devi Priya

Ph.D (CSE), Anna University Chennai in 2013, M.E, B.E (CSE) from Kongu Engineering College, currently working in the Department of Computer Science and Engineering in Kongu Engineering College, Tamil Nadu, India.

Dr. Sandeep

Post-doctoral fellow, Principal Investigator, Young Scientist Scheme Project (DST-SERB), Department of Physics, Mizoram University, Aizawl Mizoram, India- 796001.

Dr. Roberto Volpe

Faculty of Engineering and Architecture, Università degli Studi di Enna "Kore", Cittadella Universitaria, 94100 – Enna (IT).

Dr. S. Kannadhasan

Ph.D (Smart Antennas), M.E (Communication Systems), M.B.A (Human Resources).

Research Area: Engineering Physics, Electromagnetic Field Theory, Electronic Material and Processes, Wireless Communications.

Mr. Bhavinbhai G. Lakhani

An expert in Environmental Technology and Sustainability, with an M.S. from NYIT. Their specialization includes Construction Project Management and Green Building. Currently a Project Controls Specialist Lead at DACK Consulting Solutions, they manage project schedules, resolve delays, and handle claim negotiations. Prior roles as Senior Project Manager at FCS Group and Senior Project Engineer at KUNJ Construction Corp highlight their extensive experience in project estimation, resource management, and on-site supervision.

Mr. Omar Muhammed Neda

Department of Electrical Power Engineering, Sunni Diwan Endowment, Iraq.

Mr. Amit Kumar

Amit Kumar is associated as a Researcher with the Department of Computer Science, College of Information Science and Technology, Nanjing Forestry University, Nanjing, China since 2009. He is working as a State Representative (HP), Spoken Tutorial Project, IIT Bombay promoting and integrating ICT in Literacy through Free and Open Source Software under National Mission on Education through ICT (NMEICT) of MHRD, Govt. of India; in the state of Himachal Pradesh, India.

Mr. Tanvir Singh

Tanvir Singh is acting as Outreach Officer (Punjab and J&K) for MHRD Govt. of India Project: Spoken Tutorial - IIT Bombay fostering IT Literacy through Open Source Technology under National Mission on Education through ICT (NMEICT). He is also acting as Research Associate since 2010 with Nanjing Forestry University, Nanjing, Jiangsu, China in the field of Social and Environmental Sustainability.

Mr. Abilash

M.Tech in VLSI, B.Tech in Electronics & Telecommunication engineering through A.M.I.E.T.E from Central Electronics Engineering Research Institute (C.E.E.R.I) Pilani, Industrial Electronics from ATI-EPI Hyderabad, IEEE course in Mechatronics, CSHAM from Birla Institute Of Professional Studies.

Mr. Varun Shukla

M.Tech in ECE from RGPV (Awarded with silver Medal By President of India), Assistant Professor, Dept. of ECE, PSIT, Kanpur.

Mr. Shrikant Harle

Presently working as a Assistant Professor in Civil Engineering field of Prof. Ram Meghe College of Engineering and Management, Amravati. He was Senior Design Engineer (Larsen & Toubro Limited, India).

Mr. Zairi Ismael Rizman

Senior Lecturer, Faculty of Electrical Engineering, Universiti Teknologi MARA (UiTM) (Terengganu) Malaysia Master (Science) in Microelectronics (2005), Universiti Kebangsaan Malaysia (UKM), Malaysia. Bachelor (Hons.) and Diploma in Electrical Engineering (Communication) (2002), UiTM Shah Alam, Malaysia.

Mr. Ronak

Qualification: M.Tech. in Mechanical Engineering (CAD/CAM), B.E.

Presently working as a Assistant Professor in Mechanical Engineering in ITM Vocational University, Vadodara. Mr. Ronak also worked as Design Engineer at Finstern Engineering Private Limited, Makarpura, Vadodara.

Table of Contents

Volume-12, Issue-3, March 2026

S. No	Title	Page No.
1	Interdependent Networks with Higher-Order Structures Authors: Heng Zhao  DOI: https://dx.doi.org/10.25125/ijoer-mar-2026-1  DIN Digital Identification Number: IJOER-MAR-2026-1	01-10
2	The Impact of Implicit Guarantees and Market-Based Guarantees on the Issuance Spreads of Urban Investment Bonds Authors: Qiu Liu  DOI: https://dx.doi.org/10.25125/ijoer-mar-2026-2  DIN Digital Identification Number: IJOER-MAR-2026-2	11-23
3	Review of Processing and Manufacturing Challenges in the Fabrication of Ceramic Matrix Composites Authors: Dr. Balasubramanyam. N; D. Jyosthna; A.V.N.S. Kiran  DOI: https://dx.doi.org/10.25125/ijoer-mar-2026-9  DIN Digital Identification Number: IJOER-MAR-2026-9	24-29
4	Research on Interpretable Loan Approval Identification Using Multi-Dimensional Features Authors: Tiantian Lu  DOI: https://dx.doi.org/10.25125/ijoer-mar-2026-12  DIN Digital Identification Number: IJOER-MAR-2026-12	30-44

Transplanting Machinery and Key Components: A Comprehensive Review

Herui Dong¹; Guibin Wang²; Jijia He³; Tingbo Xu⁴; Maile Zhou^{5*}

¹⁻⁵School of Agricultural Engineering, Jiangsu University, Zhenjiang 212013, China

^{*5}Key Laboratory of Modern Agricultural Equipment and Technology, Jiangsu University, Zhenjiang 212013, China

*Corresponding Author

Received: 01 April 2026/ Revised: 10 April 2026/ Accepted: 17 April 2026/ Published: 30-04-2026

Copyright © 2026 International Journal of Engineering Research and Science

This is an Open-Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (<https://creativecommons.org/licenses/by-nc/4.0>) which permits unrestricted Non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

Abstract— As demand for agricultural products continues to grow, mechanized transplanting technologies and equipment are constantly evolving. Transplanting is one of the primary cultivation methods for crops such as grains, oilseeds, and vegetables, and it represents a critical technical step in crop production, playing a significant role in increasing crop yields. This paper outlines the current state of research on transplanters and their key components. It categorizes and summarizes the research and development of existing transplanters based on their driving modes, classifies transplanting mechanisms according to different seedling retrieval methods and analyzes their working principles, and analyzes and summarizes the existing issues with current transplanters and transplanting mechanisms. Based on these issues, the paper proposes recommendations for future development. High-efficiency, low-damage transplanting technology is key to increasing crop yields, and strengthening the integration of agricultural machinery and agronomy is an important method for reducing crop production costs. Intelligence, full automation, and green, low-carbon operations represent important future research directions for transplanters.

Keywords— Transplanting machine, transplanting mechanism, intelligent, fully automated, eco-friendly and low-carbo.

I. INTRODUCTION

Crops come in diverse varieties, and their cultivation methods are equally varied. Transplanting is one such method, primarily suited for crops like rice, corn, peppers, tomatoes, cotton, and rapeseed [1]. Rice is a primary staple crop for humanity and ranks among the world's three most significant food crops, with global annual production reaching approximately 450 million tons [2-8]. Vegetables are indispensable in daily diets and constitute a vital component of food consumption. In recent years, the vegetable industry has experienced rapid growth, accompanied by a continuous expansion of vegetable cultivation areas worldwide [9]. The agricultural workforce is currently experiencing a pronounced aging trend, leading to a sharp decline in labor availability and creating a labor shortage in agriculture [10-11]. Faced with the contradiction between growing demand for agricultural products and the rapid depletion of agricultural resources and labor, as well as the challenge of meeting increasing demands for sustainable food production, it is imperative to enhance crop yields per unit area of farmland. Agricultural mechanization and automation play a crucial role in effectively reducing labor intensity and enhancing agricultural productivity [12-14]. To address this contradiction, the mechanization and automation of rice and vegetable transplanting are of significant importance, representing an inevitable trend that improves planting efficiency, reduces labor intensity, and increases crop yields [15]. To further boost agricultural output, research on seedling cultivation and transplanting techniques has been proposed, as this technology can extend the crop growth period [16]. Compared to traditional seedling cultivation methods, greenhouse seedling production offers several advantages, including higher seedling survival rates, stronger stress resistance, shorter cultivation cycles, and reduced pest and disease incidence [17-18]. The transplanting process involves removing seedlings from seedling trays and planting them in the field soil. Mechanized transplanting has become the mainstream method for large-scale vegetable and rice cultivation [19-20]. Transplanting is categorized into manual and

mechanized methods. Manual transplanting requires bending or squatting postures, involving monotonous and labor-intensive work. Mechanized transplanting can replace agricultural workers in performing repetitive tasks, reducing labor intensity [21-22]. Mechanized transplanting is further divided into semi-automatic and fully automatic systems [23]. Semi-automatic transplanters lack seedling tray conveyors, requiring manual intervention for seedling retrieval [24]. Compared to semi-automatic and manual methods, fully automatic transplanters operate without human interference. They achieve full automation throughout the entire process—from removing seedlings from trays to conveying and depositing them into planting holes—maintaining high-speed operation. Consequently, they impose stringent requirements on seedling quality [25-27].

Research on transplanters primarily encompasses studies on the main body of transplanters and transplanting mechanisms. Current transplanters primarily include walk-behind transplanters, ride-on transplanters, and unmanned transplanters. Walk-behind and ride-on transplanters are more commonly used in field transplanting operations, while unmanned transplanters are mostly in the experimental stage. Compared to ride-on transplanters, unmanned transplanters utilize autonomous navigation systems and automated control technologies to enable self-propulsion. Navigation systems currently used in agriculture mainly include satellite navigation systems and machine vision systems [28]. The transplanting device is a critical component of transplanters [29-30], responsible for seedling retrieval, transport, and planting. Numerous device types exist, primarily categorized by retrieval method into gripper-type, push-out-type, pneumatic-type, insertion-type, and combination-type. By drive method, they are primarily categorized into mechanical, pneumatic, and mechatronic types. Among mechanical transplanting devices, common designs include planetary gear systems, multi-link mechanisms, and cam-link mechanisms [31].

This paper provides a review of research on crop transplanters. The research framework is illustrated in Figure 1. Specifically, the study systematically summarizes the current research progress and status of various types of transplanters, analyzes the working principles, technologies employed, and operational performance of different types of transplanters, and summarizes various types of transplanting devices, describing their structural composition, working principles, and seedling transplanting performance. Building on this foundation, the paper analyzes the existing issues in the research on transplanters and transplanting devices and discusses the future development prospects of transplanters. It aims to provide a reference for research on crop transplanters and their key components, as well as offer suggestions for the future development direction of transplanters.

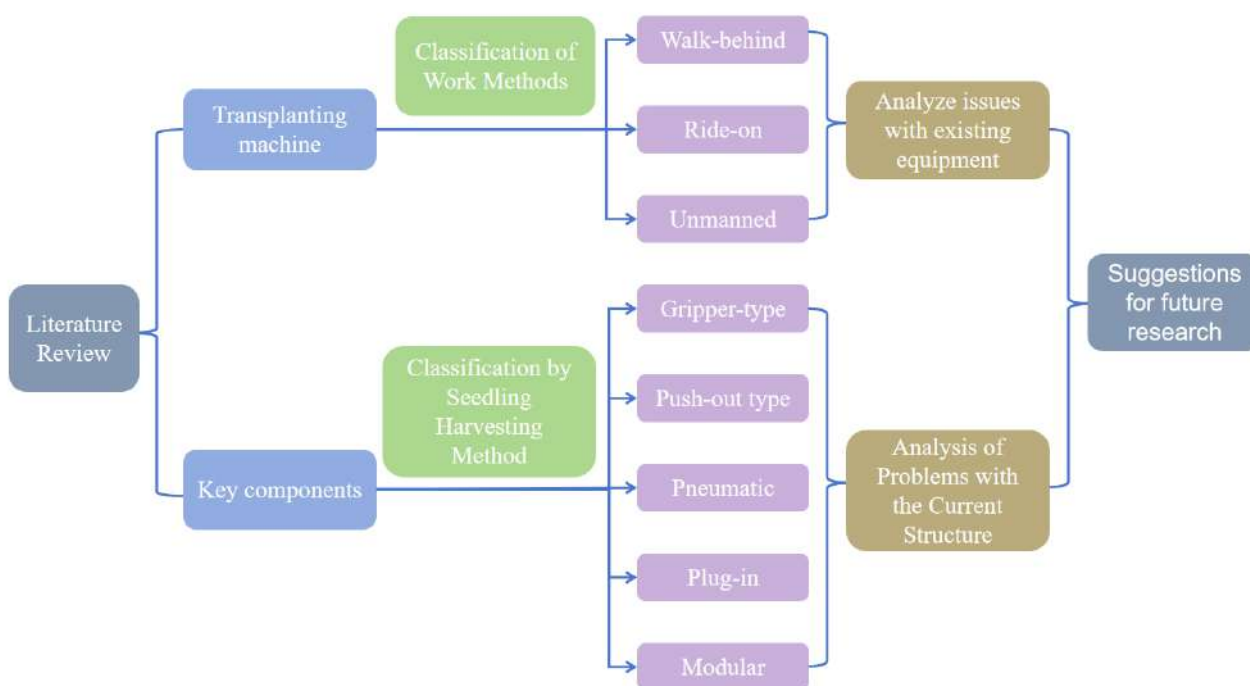


FIGURE 1: Structure of this article

II. CURRENT RESEARCH STATUS OF TRANSPLANTING MACHINES





The transplanting machine is a complex mechanical system primarily comprising drive and control units, chassis, and transplanting working units [32]. Research on transplanters has progressed from walk-behind models to rider-type machines and unmanned transplanters, progressively reducing labor intensity while continuously enhancing operational efficiency to achieve comprehensive automation in seedling transplantation. Currently, widely adopted are high-speed rider-type transplanters, which require an operator to control the machine's movement [33]. Unmanned transplanters, fully autonomous mobile field transplanters, remain largely experimental but have seen partial adoption in agricultural production [34]. Meanwhile, walk-behind transplanters remain prevalent for small-plot transplanting or for replanting seedlings in previously transplanted fields.

2.1 Research on Walk-Behind Transplanters

Research on walk-behind transplanters has enabled the transition from manual to mechanized transplanting, reducing labor intensity and improving operational efficiency. These transplanters feature simple structures and flexible operation, making them suitable for small plots in various terrains. However, despite these advantages, labor intensity remains high during large-scale transplanting, and their efficiency is lower than that of self-propelled transplanters, which limits their suitability for large-scale production.

Currently, numerous simple walk-behind transplanters based on lever mechanisms have been developed. While these designs are low-cost, they require substantial manual effort. As shown in Table 1, which compares four representative simple walk-behind transplanter designs, a common characteristic is that their operation relies entirely on human labor without any auxiliary power source.

TABLE 1
POLE-BASED MANUAL WALKING TRANSPLANTER WITHOUT ADDITIONAL POWER

Machine Type	Developer/ Organization	Features	Machine Images
4-row manual rice transplanter	Bangladesh Rice Research Institute [35]	This transplanting machine features a pull-back design, allowing adjustment of plant spacing during transplanting, with an operational efficiency of 0.033 hectares per hour.	
Artificial Rice Transplanter Based on a Four-Bar Mechanism	Vibhakar C. et al[36].	This compact machine is designed to meet the operational needs of small-scale farmers.	
Reconfigurable Four-Bar Linkage Transplanter	Felezi M.E. et al[37].	Adjustable planting row spacing and planting depth	
Manual Two-Row Vegetable Transplanter	Thorat P. V. et al[38].	Four seedlings can be planted at once, achieving an operational efficiency of 463 plants per hour.	

The use of external power significantly reduces manual labor intensity, as the transplanting operations of such machines no longer rely on human strength, thereby greatly enhancing transplanting efficiency. Yuan Xinbin et al. innovatively designed a lever-based ejection-type ordered transplanting machine [39], as shown in Figure 2(a). This machine features an innovative gear-driven automatic tray feeding mechanism. Operated by an operator walking alongside to control its movement, it achieves the required plant spacing for seedling transplantation. Yanmar Agricultural Machinery developed the Yanmar AP4 hand-guided step-type transplanting machine [40], as shown in Figure 2(b). This machine is manually guided and driven, employing a crank-rocker transplanting mechanism. It features four working rows with four adjustable planting row spacings. Both the longitudinal seedling feed rate and planting depth are adjustable. Its relatively simple mechanism makes it suitable for small field operations.



(a)



(b)





FIGURE 2: (a) Ejector ordered transplanter [39]; (b) Yanmar AP4 walk-behind stepper transplanter [40]

2.2 Research on Ride-on High-Speed Transplanter

Currently, ride-on high-speed transplanters are widely used for transplanting operations. These machines feature high automation levels and enable large-scale transplanting. They require manual operation for transplanting seedlings. Some models incorporate automated navigation technology, which substantially reduces operator workload [41]. By adopting a human-machine collaboration model and high-speed operation, these machines significantly enhance the efficiency and quality of large-scale transplanting. The shift to seated operation for transplanters greatly reduces operator fatigue, enabling extended working hours during transplanting operations.




In the development of ride-on transplanters, various methods have been employed to continuously enhance the efficiency and quality of crop transplanting. Progress has been made from manual seedling feeding and transplanting to mechanized automatic seedling delivery and transplanting, progressively reducing the labor intensity of transplanting operations. As shown in Table 2, four representative ride-on transplanters are presented, all of which effectively meet the agronomic requirements for crop transplanting.

TABLE 2
RIDE-ON HIGH-SPEED TRANSPLANTER

Machine Type	Developer / Organization	Features	Operational Performance	Machine Images
Semi-Automatic Seedling Transplanter for Vegetables[42].	Xin Jin et al.	Manual operation is required to complete seedling removal and feeding.	Two rows can operate simultaneously; transplanting frequency reaches 50-70 plants per minute; seedling upright rate is 93% to 91.1%; planting depth compliance rate is 96% to 92%.	
PF2R Automatic Transplanter[43].	Yanmar Company.	Adjustable planting spacing and planting depth	Capable of transplanting two rows simultaneously, with a transplanting efficiency of 2.55 mu per hour, and featuring automatic seedling delivery.	
Ride-on Fully Automatic Vegetable Seedling Transplanter[44].	Han Luhua et al.	Capable of automatically conveying seedling trays, it fully utilizes integrated electromechanical, pneumatic, and hydraulic system engineering to achieve automated seedling transplanting.	Capable of simultaneous operation on two rows; transplanting frequency reaches 40-60 plants per minute; both seedling retrieval success rate and planting qualification rate exceed 90%.	 <ol style="list-style-type: none"> 1. Air compressor; 2. Engine; 3. Control system; 4. Operating system; 5. Feeding mechanism; 6. Pick-up mechanism; 7. Rotary discharge mechanism; 8. Planting mechanism; 9. Soil covering ring; 10. Hydraulic lifting mechanism; 11. Driving wheel; 12. Frame; 13. Driven wheel; 14. Battery.
Three-Row Precision Synchronous Transplanter[45].	Manuel Perez-Ruiz et al.	Enables precise control of three rows working in sync during seedling transplanting operations, ensuring transplanted seedlings are aligned in a grid-like rectangular pattern.	Three rows transplanted simultaneously, with the machine traveling at 1.6 km/h and a row spacing of 380 mm.	

Some developed ride-on transplanters incorporate additional functions tailored for transplanting operations beyond their core transplanting capability. This enables them to perform other planting tasks concurrently while completing crop transplantation. Multifunctional transplanters reduce the number of machines entering the field, minimize soil disturbance, save planting time, and improve transplanting quality. However, their complex machinery structure and the need for coordinated interaction among multiple components present significant technical challenges in both development and operation. Table 3 lists three representative multifunctional transplanters.



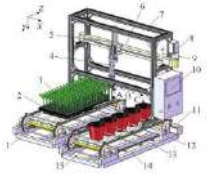
TABLE 3
RIDE-ON MULTI-FUNCTION TRANSPLANTER

Machine Type	Developer	Additional features	Advantages	Operational Performance	Machine Images
2ZY-6 Rapeseed Mat Seedling Transplanter [46].	Wu Jun et al.	Cutting slits, transplanting, and covering with soil while firming down	Improve the efficiency and quality of crop transplanting	In rice stubble fields: The machine's travel speed must be within 1.15 m/s; planting pass rate reached 85.66%. In dry fields: The machine's travel speed must be between 0.8 and 1.2 m/s; planting pass rate reached 87.01%.	 1. Rice transplanter chassis; 2. Power cutting disc; 3. Forming roller; 4. Dryland profiling device; 5. Transplanting device; 6. Counterweight box; 7. Soil covering and suppression mechanism.
Automatic Tray Seedling Transplanter [47].	Han Changjie et al.	The transplanting condition monitoring system has been added, enabling real-time observation of transplanting conditions[48].	Adjust transplanting operations in a timely manner according to transplanting conditions to ensure the quality of transplanting operations.	Transplanting machine operating speed: 1.4–1.7 km/h; Planting frequency: 123 plants/min; Transplanting success rate: 97.07%; Lodging rate: only 1.67%.	
Multi-Function Vegetable Seedling Transplanter [49].	Shao Yuanyuan et al.	Laying drip irrigation tape and covering with plastic film, transplanting seedlings, applying fertilizer, covering with soil, and watering	Effectively reduce the number of times machinery enters the field and minimize repeated soil compaction damage.	Transplanting frequency: 57–88 plants per minute; Average seedling survival rate: 96.4%–98.6%; Qualified planting depth rate: 97.2%–99.0%.	

2.3 Research on Unmanned Transplanting Machines

Due to high labor costs and labor shortages, unmanned transplanters have gradually become a popular research direction for transplanters [50]. The fundamental technologies of unmanned transplanters encompass robotic arm technology, visual recognition systems, autonomous navigation systems, path tracking control technology, and automated control systems [51]. Compared to high-speed rider-type transplanters, unmanned transplanters operate via automated control and can autonomously navigate along pre-planned paths [52]. Eliminating the need for manual operation significantly reduces labor requirements while enhancing transplanting efficiency and quality. Table 4 details three existing unmanned transplanting machines, providing comprehensive specifications for each.

TABLE 4
UNMANNED TRANSPLANTER

Machine Type	Developer	Function	Operational Performance	Machine Images
High-Efficiency Fully Automatic Pot Seedling Transplanter for Greenhouses[53].	Hu Jianping et al.	Features automatic backfilling, hole digging, positioning conveyance, and rapid, smooth planting capabilities.	Movement error ranges from 0.15 to 1.22 mm; Transplanting frequency: 120 plants per minute; Transplanting pass rate reaches 90.23%.	 1. Soil loader; 2. Soil filling device; 3. Hole punching device; 4. Conveying device; 5. Transplanting device;
Electric Self-Propelled Dual-Row Transplanter [54].	Ning Mengjiao et al.	Capable of performing integrated operations including furrow opening, seedling retrieval, soil covering, and plastic mulching.	Machine travel speed: 0.14 km/h; Transplanting success rate: 88%; Seedling survival rate: 86%.	
Lightweight Automatic Transplanter for Greenhouse Seedling Trays[55].	Han Luhua et al.	Capable of performing automated seedling feeding, delivery, and transplanting operations.	For 128-cell and 72-cell seedling trays, transplanting efficiency reached 1,221 plants per hour and 1,025 plants per hour respectively; transplant success rate achieved 90.70% in both cases; seedling pot breakage rate remained below 5%.	 1. Source plate conveying mechanism; 2. Hole disc; 3. Plug seedling tray; 4. Seedling terminal effector; 5. Rodless cylinder; 6. Linear module; 7. Frame; 8, 11. Motor; 9. Photoelectric switch; 10. Control system; 12. Flower pot; 13. Conveyor chain; 14. Beam rod; 15. Target disc conveyor mechanism.

2.4 Comparison of Different Types of Transplanters

Based on the operator's working methods, existing transplanters are categorized into the three types above, each with distinct advantages and disadvantages. A comparative analysis is presented in Table 5.

TABLE 5
COMPARISON OF TRANSPLANTER TYPES

Type	Applicable scenarios	efficiency	peculiarity	How it works	Labor intensity
Walk-behind transplanter	small fields, hilly mountains and seedling replenishment operations	Low	Low cost, simple structure, light and flexible	Walk with the randomizer	Big
Ride-on transplanter	Large-scale plains and large-scale operations	High	High degree of automation, easy operation, balance cost and efficiency, currently widely used	Operate in the cockpit	Small
No one transplanter	Greenhouse planting	Higher	Achieve full automation, high operation accuracy, good quality and high degree of intelligence	The transplanter can be remotely controlled	Basically none

III. CURRENT RESEARCH STATUS OF TRANSPLANTING DEVICES

The transplanting mechanism is a critical component of transplanting machines [56]. Its design must ensure high operational efficiency, minimal seedling damage, and prevent seedling displacement [57]. Addressing these design requirements, current research on transplanting mechanisms encompasses multiple types [58]. Classified by seedling retrieval methods, they primarily include gripping-type [59-60], insertion-type [61], ejection-type [62-63], pneumatic [64], and combined types [65].

3.1 Pinch-Type Transplanting Mechanism

The gripping seedling retrieval method involves directly grasping the seedling stem, seedling pot, or entire seedling with an end-effector to perform seedling retrieval, transport, and planting operations. By designing appropriate motion trajectories, gripper-type transplanting mechanisms can minimize damage to seedlings while enhancing transplanting efficiency. This method imposes higher requirements on seedlings, necessitating thicker stems, and carries a higher risk of stem damage. Based on mechanical structure, these mechanisms can be further categorized into rod-driven transplanting mechanisms and gear-driven transplanting mechanisms.

3.1.1 Transplanting Mechanism of the Rod Mechanism

Research on transplanting mechanisms based on rod mechanisms is extensive, encompassing types such as connecting rod slide mechanisms, multi-link mechanisms, crank-connecting rod mechanisms, and crank-rocker mechanisms. While these mechanisms offer advantages like low cost and simple structure, their transmission stability is poor, making them unsuitable for high-speed transplanting. Vivek P et al. developed a pneumatic automatic vegetable seedling transplanting mechanism [66].

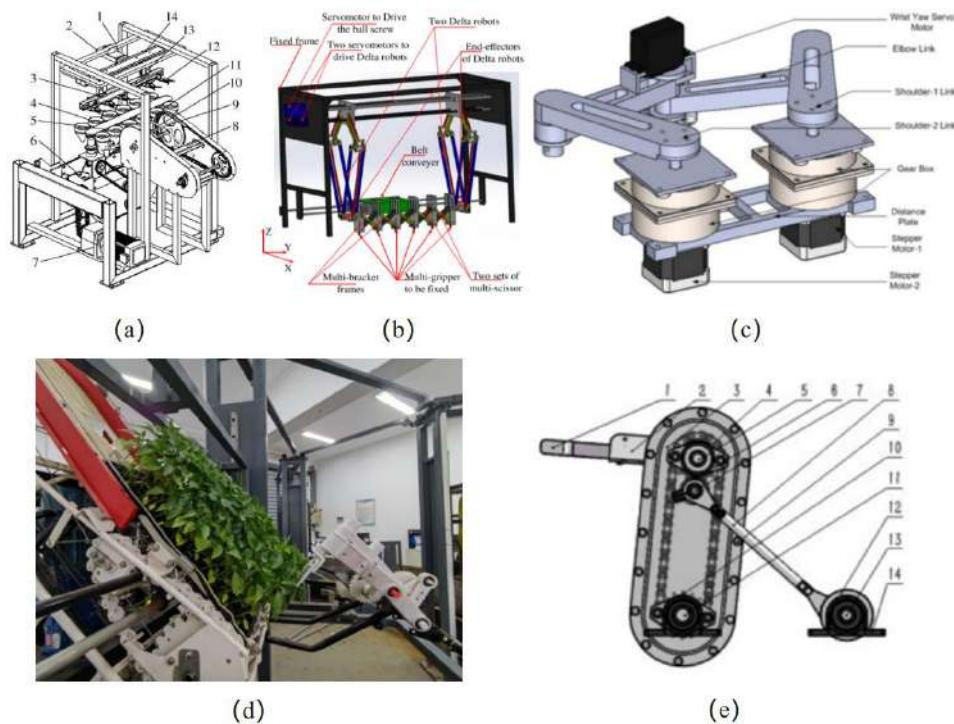


FIGURE 3: Transplanting Mechanism Based on a Rod Mechanism. (a) The whole row of stem seedling picking devices [67]; (b) Three-degree-of-freedom multi-grip potting and transplanting mechanism [68]; (c) 2-degree-of-freedom parallel transplanting mechanism [70]; (d) Clamping stem-type picking and planting integrated automatic transplanting mechanism [71]; (e) Crank Rocker Stem Gripper Potting Device [72]

This mechanism adjusts the opening size of the seedling gripper according to stem thickness, reducing seedling damage. Set at a transplanting speed of 20-25 plants per minute, it achieved an average transplanting success rate of 89.59%. Wang et al. designed a pneumatic stem-gripping automatic seedling picker [67], as shown in Figure 3(a). At a transplanting speed of 75 plants per minute, this mechanism achieved a 97.36% seedling pickup success rate with a substrate breakage rate of 5.07%, meeting transplanting requirements. Assal, S. F. et al. proposed a partially decoupled 3-degree-of-freedom (DOF) multi-claw

pot seedling transplanting mechanism for open agricultural fields [68-69], as shown in Figure 3(b). It can remove seedlings from seedling trays and plant them individually, verifying its safety in terms of force and deformation. K. Rahul et al. designed a 2-DOF parallel transplanting mechanism [70], as shown in Figure 3(c). Employing mechatronic integration, this mechanism achieves automation with a simplified structure, utilizing microcontrollers and sensors to enable precise grasping and placement of seedlings. Hu et al. designed a stem-gripping integrated harvesting and transplanting mechanism [71], as shown in Figure 3(d). This mechanism achieved a seedling retrieval success rate of 91.1%, a transplanting success rate of 78.5%, and an uprightness qualification rate of 94.9%. Cai et al. proposed a novel crank-rocker stem-gripping pot seedling transplanting device [72], as shown in Figure 3(e). This mechanism features a simple structure. At a transplanting speed of 50 transplants per minute, the missed transplant rate and seedling damage rate were 2.14% and 3.57%, respectively, essentially meeting transplanting requirements.

3.1.2 Gear Mechanism Transfer Device

The transplanting mechanism with a gear system utilizes gear transmission to plan the motion trajectory of the end effector, incorporating components such as circular gears, elliptical gears, and non-circular gears. This type of transplanting mechanism can rotate to perform transplanting operations, offering high transplanting efficiency, smooth operation, and high transmission precision. However, its structure is relatively complex, gear manufacturing costs are high, and its design requires optimization of structural parameters to meet transplanting requirements, presenting significant design challenges. Xin et al. proposed an elliptical gear-based double-crank five-bar transplanting mechanism [73], as shown in Figure 4(a). This mechanism sequentially performs seedling pickup, seedling delivery, and planting actions, forming a figure-eight trajectory. It features a simple structure and low cost, achieving a 98% seedling pickup success rate at 100 rpm. The team also developed a non-circular gear-linkage combination transplanting mechanism [74], as shown in Figure 4(b), enabling coordinated execution of four processes: seedling pickup, seedling delivery, film perforation and hole digging, and planting. Bench tests yielded a 94% seedling pickup success rate and 92% transplanting success rate, meeting the requirements for mechanized integrated rice seedling tray film transplanting. Ye et al. designed a planetary gear-based tray seedling transplanting mechanism utilizing incomplete eccentric circular gears and non-circular gear transmission [75], as shown in Figure 4(c). This mechanism can perform two operations per rotation cycle, achieving a transplanting efficiency of 200 seedlings per minute.

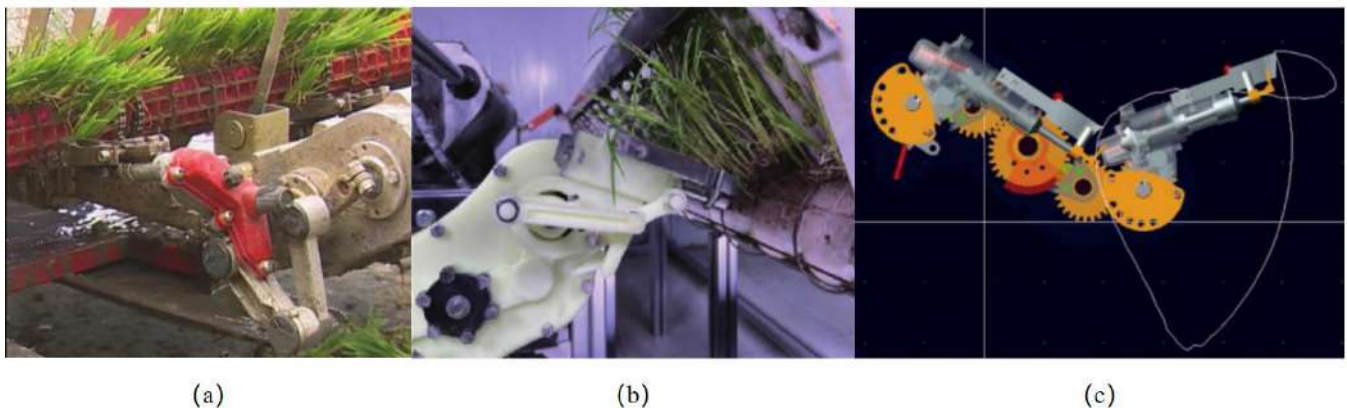


FIGURE 4: Gear-driven transplanting mechanism. (a) Elliptical Gear-Double Crank Five-Bar Transplanting Mechanisms [73]; (b) Non-circular gear-linkage combination transplanting mechanism [74]; (c) Planetary wheel system hole tray seedling transplanting mechanism [75]

3.2 Plug-in Transplanting Mechanism

The insert-type transplanting mechanism directly inserts the seedling-picking needle or end-effector gripper into the seedling pot. Through mechanical transmission, it performs insertion and withdrawal actions, transplanting seedlings along a predetermined trajectory. Based on mechanical structure, it is primarily divided into slide-type and gear-type transplanting mechanisms. This type of transplanting mechanism features a simple structure and high operational efficiency, making it a widely adopted seedling retrieval method. However, it can cause damage to the seedling roots, necessitating the cultivation of high-quality seedling substrates during the nursery stage.

3.2.1 Transfer Mechanism for Slide Structures

The slide-guided insertion transplanting mechanism constrains the movement trajectory of the planting arm or end effector via a slide, coordinating with the transplanting mechanism to complete transplanting operations. This type of mechanism offers high seedling retrieval stability and minimal damage to seedlings. However, its transplanting efficiency is low, necessitating auxiliary control systems or multiple seedling retrieval mechanisms to enhance efficiency. Choi et al. from South Korea developed a five-bar slider transplanting mechanism [76], as shown in Figure 5(a). Its structure is simple and exhibits high seedling pickup success rates, but its pickup efficiency is low, reaching only 30 plants/(min-row). Yue et al. designed a fully pneumatic reciprocating seedling pickup device [77], as shown in Figure 5(b), achieving transplanting frequencies of 120 plants/min and 144 plants/min. Its average seedling pickup success rate reached 97.9%, with a planting success rate of 95.3%. The team also developed a dual-row seedling picker and its control system [78], as shown in Figure 5(c). This device achieves a picking efficiency of 180 plants/min with a transplant success rate of 97.3%, significantly enhancing transplant efficiency. Its flexible pneumatic end-effector design effectively reduces damage to seedling roots. Han's team proposed a novel pre-bending transplanting method, employing a mechanism combination innovation approach to design a side-entry horizontal-transplanting manipulator [79], as shown in Figure 5(d). This device effectively retrieves seedlings with minimal damage, achieving an automatic transplanting success rate of 97.57%. A simplified automatic transplanting device was also designed [80], as shown in Figure 5(e), featuring a straightforward structure that achieves efficient, low-consumption seedling transplantation at a rate of 15 plants/min/grip with a 95.47% success rate. Shi et al. designed an eight-row duckbill-type planting mechanism driven by an electric motor and pneumatic cylinder [81], as shown in Figure 5(f). This mechanism achieved a qualified transplanting rate of 96.62% and a transplanting efficiency of 7,135 plants per hour, meeting the agronomic requirements for dense planting with small plant spacing and row spacing.

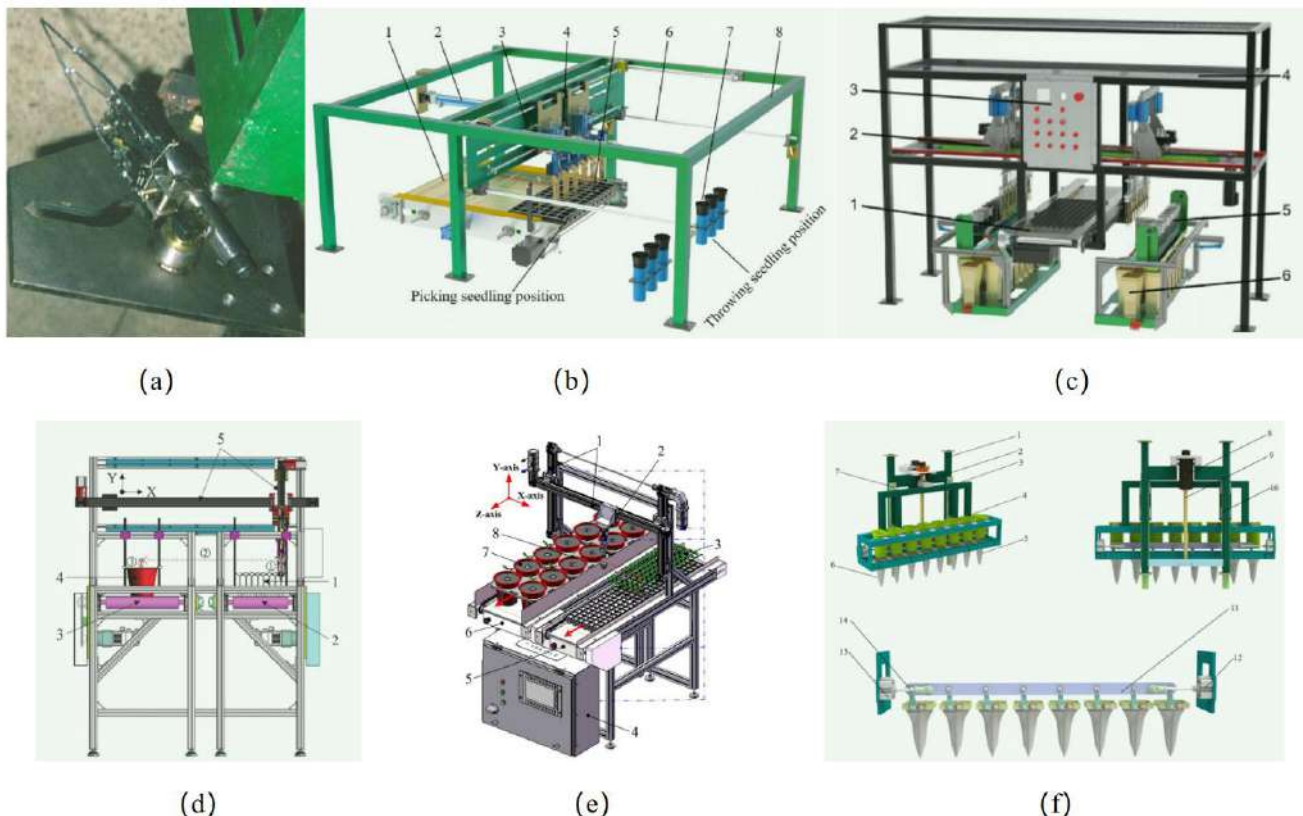


FIGURE 5: Insertion Transplanting Mechanism with Slide Structure. (a) Five-link chute transplanting mechanism [76]; (b) Reciprocating seedling picker with full pneumatic drive [77]; (c) Double-row seedling pick-up device [78]; (d) New pre-bent seedling transplanting robot [79]; (e) Simplified greenhouse transplanting robot cell [80]; (f) Eight rows of duckbill planting mechanism [81]

3.2.2 Gear-Based Transfer Mechanism

The gear-driven insertion transplanting mechanism is similar to the gripping transplanting mechanism described in Section 3.1.2. Both share the same advantages and disadvantages, providing stable transmission while posing significant challenges in planning the end-effector's motion trajectory. These challenges include strong coupling and numerous parameters in the mechanism's optimization. ISLAM et al. proposed a novel long-needle multi-gripping automatic transplanting mechanism [82], as shown in Figure 6(a). This mechanism is suitable for small transplanters, employing a gear-driven crank-slider system to achieve a linear seedling retrieval trajectory. Zhou et al. developed a fully automatic rotary transplanting mechanism for vegetable seedling pots [83], as shown in Figure 6(b). This mechanism performs a series of operations including seedling picking, transportation, plastic film penetration, shaping, and planting, achieving a seedling picking success rate of 92.4% [84]. Sun et al. proposed a transplanting mechanism featuring a two-planetary-frame symmetrical structure driven by a cam-epicyclic gear combination mechanism [85], as shown in Figure 6(c). This mechanism utilizes the combination to generate variable-speed oscillation, forming a pointed-nose seedling-picking trajectory. The transplanting mechanism operates at 60 r/min with a seedling-picking success rate of 93%. Xu et al. designed a variable-speed well-type hole-forming transplanting mechanism for hilly terrain transplanters [86], as shown in Figure 6(d). This mechanism employs a parallel four-bar linkage based on non-circular gears. The interaction patterns between the hole-forming mechanism and soil were analyzed to optimize the mechanism's parameters. Yu et al. proposed a hybrid six-bar single-degree-of-freedom integrated seedling-picking and planting mechanism constrained by non-circular gears [87], as shown in Figure 6(e). This mechanism achieves an "eagle-beak-shaped" static trajectory for seedling retrieval and an "approximate straight-line" dynamic trajectory for planting. At rotational speeds of 25–45 r/min, it achieves a 96.1% seedling retrieval success rate and a 91.4% planting success rate.

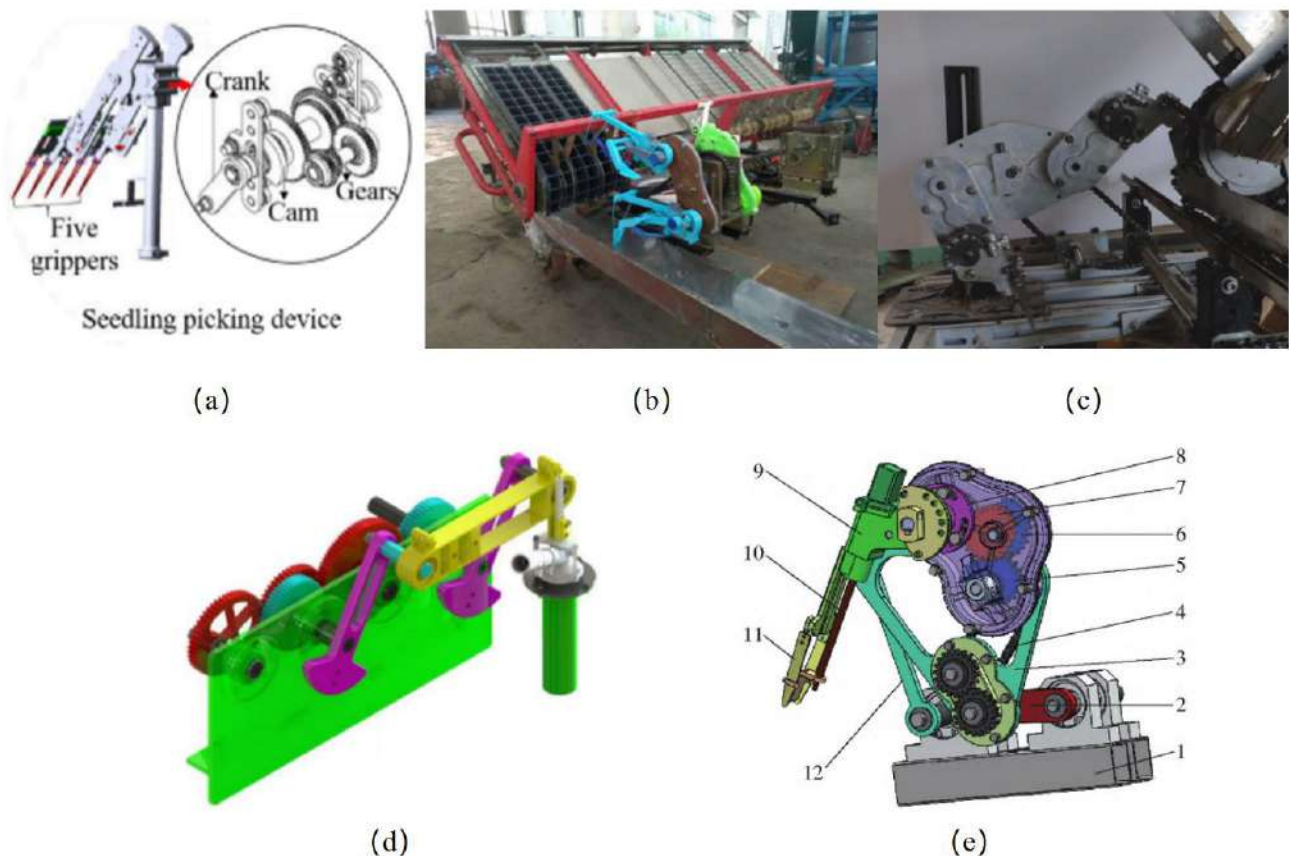


FIGURE 6: Insert-type transplanting mechanism with gear structure. (a) Long-needle multi-clamp automatic transplanting mechanism [82]; (b) Fully automatic rotary transplanting mechanism for vegetable potting plants [83]; (c) Plant-integrated transplanting mechanism [85]; (d) Variable speed well cellar type hole forming transplanting unit [86]; (e) Integral transplanting mechanism for picking and planting [87]

3.3 Ejector-Type Transplanting Mechanism

The push-out seedling removal method employs a push rod that passes through the drainage holes at the bottom of the seedling tray to eject the seedlings. These seedlings are then collected by a conveyor belt or a dedicated seedling removal mechanism. This mechanism features a simple structure and results in low seedling damage rates. However, it requires precise alignment of the drainage holes at the tray bottom, with equal center-to-center distances between adjacent holes [88-89].

SUGGS et al. developed a transplanting mechanism that uses a push rod to eject seedlings and employs a needle-type picker for seedling retrieval, achieving a picking efficiency of 180 plants per minute. However, this method results in partial loss of root soil during seedling extraction [90]. Zhang et al. proposed a rotary-type ordered seedling-throwing device based on a push-rod ejection mechanism [91]. This device uses a push rod to dislodge seedlings from trays, which then fall into the field via guide tubes under gravity to complete transplanting. Wang et al. designed a pneumatic downward-pressure high-speed seedling picker [92], as shown in Figure 7. They developed a high-speed seedling picking sequence and control system, achieving a picking frequency of 120 plants/min with a 100% success rate. The substrate breakage rate was 22.46%, and the stem and leaf damage rate was 3.54%.

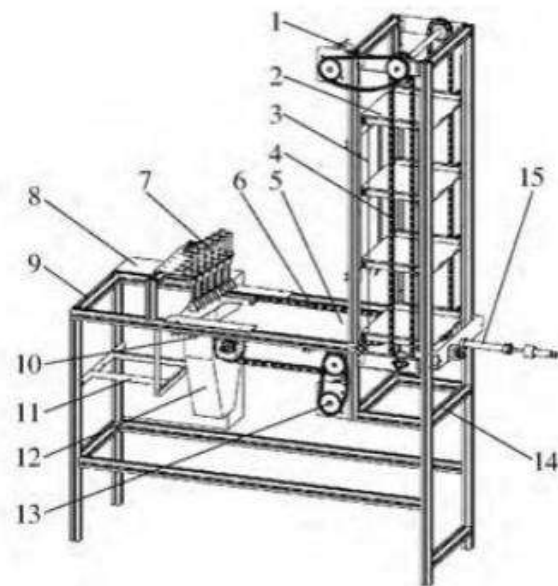


FIGURE 7: Pneumatic downward pressure type high-speed seedling extraction device [92]

Wen et al. designed an insert-and-eject seedling removal device [93], as shown in Figure 8. This device employs a combined mechanical-electrical-pneumatic drive system to achieve automated transplanting operations. When tested with 30-day-old seedlings, it achieved a removal rate of 120 plants per minute, a success rate of 97.22%, and a seedling damage rate of 1.39%.

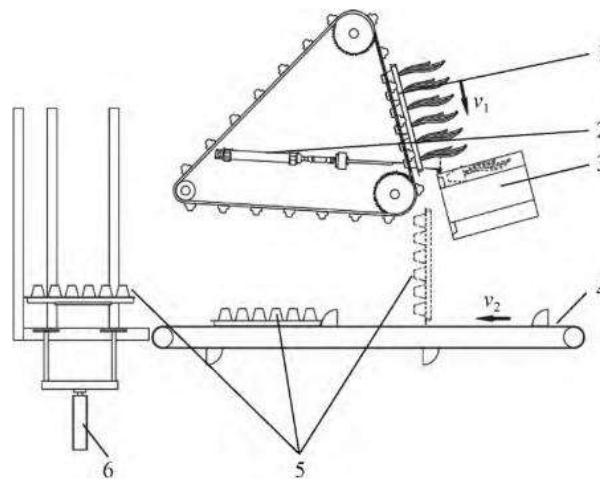


FIGURE 8: Ejector type seedling extraction device [93]

3.4 Pneumatic Transplanting Mechanism

The core of pneumatic transplanting mechanisms lies in utilizing airflow dynamics to extract seedlings from seedling trays, minimizing mechanical contact damage to young plants. However, this type of mechanism consumes relatively high energy and demands precise control over airflow intensity. It primarily employs compressed air to create pressure differentials for seedling handling, and can be categorized into two methods: suction-type and blowing-type seedling extraction.

Bao et al. developed an air-suction transplanting mechanism that utilizes a negative-pressure fan and microcontroller to coordinate control of air pressure within the seedling tube, enabling seedling retrieval and placement through air suction [94].

Luo et al. developed a pneumatic seedling removal device [95-96], which employs a jet airflow generated by an air compressor directed at the bottom of the seedling tray to blow seedlings out into a seedling guide tube, thereby completing the removal process. Yuan et al. designed a composite air-blowing and vibration seedling removal mechanism for vegetable transplanting [97], where a vibration device reduces friction between some seedling pots and the tray, followed by an air-blowing device that blows the seedlings into the guide tube to complete removal. Mao et al. developed an automatic row-based seedling removal device that uses air force to eject seedlings from trays [98]. As shown in Figure 9, it integrates mechatronics with a pneumatic system to achieve automated, high-speed seedling removal and ejection while minimizing damage to seedlings. Tests demonstrated that this device achieves a seedling removal success rate exceeding 95%, with removal efficiency meeting transplanting requirements.

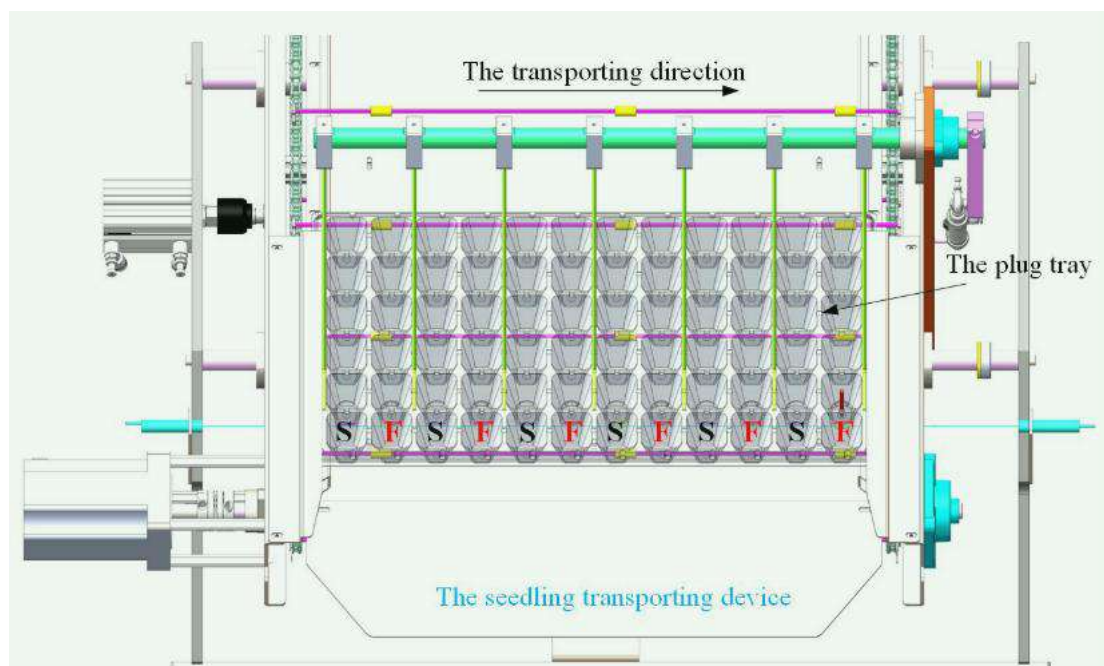


FIGURE 9: Air-blown whole-row automatic seedling pick-up device [98]

3.5 Combination Transplanting Mechanism

A combined transplanting mechanism integrates two or more seedling-picking methods, leveraging the advantages of each to achieve efficient, low-damage seedling retrieval. However, this mechanism features a complex structure and higher production costs.

Han et al. designed and manufactured a novel seedling-picking device [99], as shown in Figure 10. This device integrates mechanical, electrical, and pneumatic technologies to achieve efficient seedling transplantation while minimizing damage to the roots.

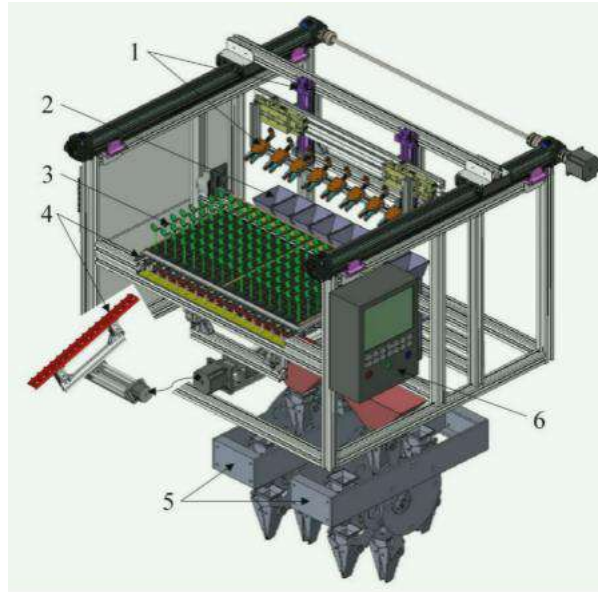


FIGURE 10: New high efficiency transplanting and picking up device [99]

The push-and-grip seedling removal device is currently one of the most extensively researched modular seedling removal systems. Zhang developed a push-pot-grip-stem transplanting mechanism [100], as shown in Figure 11(a). This mechanism combines a push-pot unit with a grip-stem seedling removal and placement unit to achieve both functions. Field trials demonstrated an average seedling removal success rate of 93.05% with a qualified plant spacing rate of 88.17%. Ni et al. designed a similar push-and-grip transplanting mechanism [101], incorporating a PLC-based control system that utilizes pneumatic cylinders and hydraulic motors to execute transplanting operations. Song et al. developed a crank-rocker-type seedling-picking mechanism based on the push-and-grip method. Its gripping force is powered by a return spring, enabling precise control over gripping intensity. However, due to the significant inertial forces of the linkage mechanism, this design exhibits relatively low transplanting efficiency [102]. Zhou et al. developed an automated seedling pickup and placement mechanism integrating electric and pneumatic systems [103], as shown in Figure 11(b). This system employs an electromagnetic ejector pin mechanism coordinated with pneumatic flexible grippers to perform ejection and grasping actions. At a transplanting speed of 72 plants per minute, it achieved a transplant success rate of 91.69%.

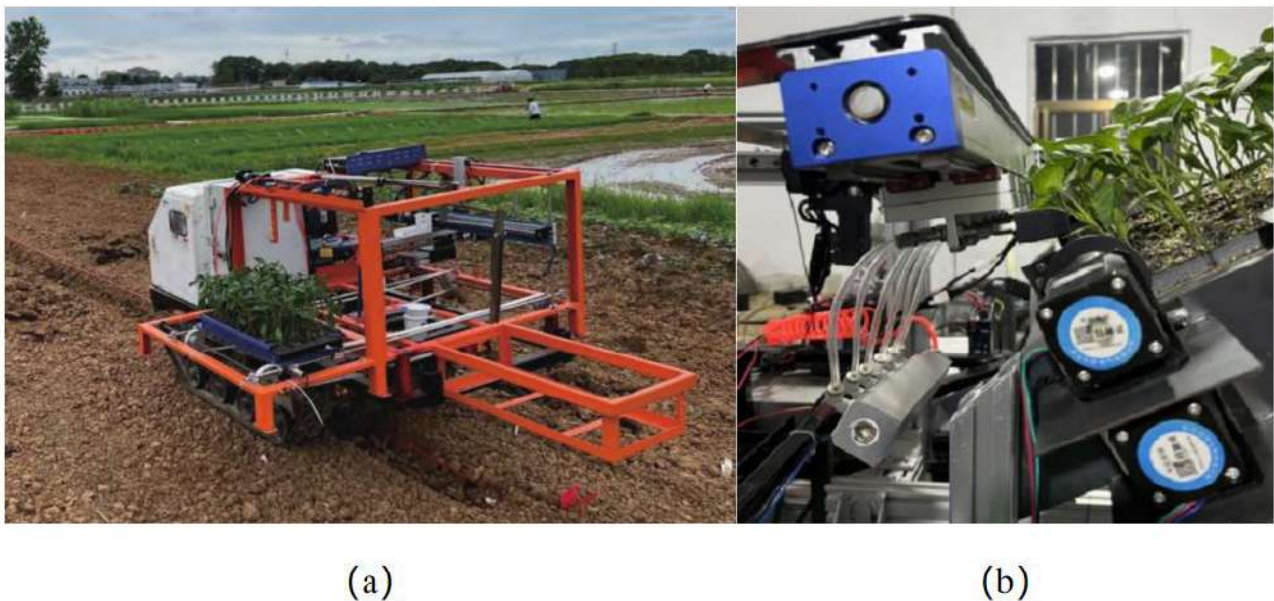


FIGURE 11: Ejector-gripper type seedling removal device. (a) Top Pot - Stem Clamping Transplanting Mechanisms [100]; (b) Automatic transplanting machine with electrical combination [103]

3.6 Comparative Analysis of Transplanting Mechanisms

Transplanting mechanisms are classified into five types based on different seedling retrieval methods: gripping, insertion, pneumatic, ejection, and combination. Each type possesses distinct advantages, disadvantages, and implementation forms, as shown in Table 6.

TABLE 6
COMPARISON OF TRANSPLANTING MECHANISMS FOR DIFFERENT SEEDLING REMOVAL METHODS

Type of transplanting mechanism	Forms of realization	Vantage	Damage to seedlings	Economic evaluation
Clamping type	Seedlings are picked up by clamping the stalks or pots with the seedling clamps.	Capable of adapting to seedlings of different sizes and forms; relatively simple structure, suitable for high-speed operation.	Easily injures young stems.	High requirements for seedling growth conditions, requiring sturdy stems and a long seedling cultivation period.
Inserted type	Insert the needle into the pot and remove the seedling.	It causes little damage to seedlings and can be adapted to a wide range of substrate types.	Easily causes seedling substrate to break apart, damaging seedling root systems.	High requirements for seedling substrate and seedling cultivation techniques.
Pneumatic type	Sucking or blowing seedlings out of seedling trays using air currents.	No contact seedling extraction, no mechanical damage, multiple seedlings can be operated at the same time.	Easily lost seedlings, damaged seedling substrate.	High energy consumption, high costs, highly susceptible to environmental influences, and stringent requirements for controlling air pressure.
Ejector type	Ejecting seedlings from the bottom of the seedling tray using an ejector bar.	No contact with seedling stems and leaves, minimal damage, precise seedling extraction, high stability.	Low damage rate to seedlings, mainly damaging the roots of seedlings.	Requires special seedling trays, which are costly, not very versatile, and have a complex structure.
Combinatorial type	Utilizes two or more structures that work in conjunction with each other to complete the seedling extraction.	More adaptable, with higher seedling extraction efficiency and success rate, able to cope with complex seedling conditions.	Low seedling damage rate.	Complex structure, high cost, difficult to control, requires simultaneous coordination of multiple components.

IV. CURRENT ISSUES

4.1 Problems with Existing Transplanters

- 1) **Limited functionality:** Existing transplanters have limited functionality, with most capable only of transplanting crops. Crop cultivation involves multiple planting processes, each essential for high yields. For instance, field operations often require additional tasks like mulching, irrigation, and fertilization. This necessitates specialized machinery entering the field to perform these functions, thereby reducing the need for multiple machine purchases. However, frequent entry of agricultural equipment into fields can lead to soil compaction and crop damage.

- 2) **Insufficient intelligence:** Existing transplanters lack sufficient intelligence. Although research on unmanned transplanters exists, most remain in the experimental stage or are limited to greenhouse use, unable to operate in the complex field environment. Most ride-on transplanters still require manual assistance for seedling feeding during transplanting, limiting transplanting efficiency. This approach is prone to missed plants and cannot dynamically adjust planting parameters such as spacing and depth. It also fails to provide timely evaluation and feedback on transplanting quality. Overall transplanting operations thus require significant labor costs.
- 3) **Limited versatility:** Existing transplanters have limited versatility, with each model capable of transplanting only one specific crop. Different farmland environments require distinct transplanters for operation. High-speed transplanters designed for large-scale operations prove ineffective in mountainous terrain, hilly landscapes, and small plots. Employing multiple transplanters increases costs. Furthermore, most transplanter designs cater to single crop types, necessitating equipment changes when transplanting different crops—further elevating agricultural production expenses.
- 4) **Environmental concerns:** Existing transplanters are predominantly powered by diesel or gasoline engines. This drive method causes environmental pollution, which is inconsistent with the future trend of green and low-carbon agriculture. Additionally, such transplanters generate significant noise. Research on electric transplanters remains limited, and they are primarily suited for greenhouse transplanting. Their batteries have limited endurance, preventing continuous operation over large areas, and they often suffer from insufficient power.

4.2 Problems with Existing Transplanting Mechanisms

- 1) **Seedling damage:** Existing transplanting mechanisms pose issues of seedling damage. Different seedling retrieval methods cause varying forms of damage due to their distinct operating principles: gripping methods may damage seedling stems, while insertion, pneumatic, and ejection methods may compromise seedling pots. Such damage can lead to slow post-transplant development, reduced seedling survival rates, and ultimately lower crop yields.
- 2) **Instability and complexity:** Existing transplanting mechanisms suffer from instability and complexity. The cam-rod mechanism generates significant vibration during transplanting, leading to unstable operation and reduced precision in seedling pickup and placement. This results in issues such as missed transplants or inconsistent planting depths. While planetary gear mechanisms offer stable transmission, their complex structure incurs higher production costs and requires advanced machining techniques. Maintenance of these mechanisms also incurs substantial expenses. Additionally, some transplanting mechanisms require specialized seedling trays incompatible with standardized trays, further increasing production costs.
- 3) **Limited crop adaptability:** Existing transplanting mechanisms have certain limitations. Most are designed for a single crop type, requiring the use of corresponding mechanisms for different crops. This leads to increased production costs for agricultural crops.
- 4) **Poor integration with agronomy:** The current transplanting mechanisms are poorly integrated with existing seedling cultivation techniques. Existing seedling cultivation practices lack standardization, and the seedling trays used for growing seedlings vary significantly. This necessitates designing transplanting mechanisms tailored to different tray types, which in turn increases agricultural production costs.

V. OUTLOOK FOR FUTURE DEVELOPMENT

5.1 Development Recommendations for Transplanters

- 1) **Multifunctional design:** Given the diversity of crops and the complex, variable conditions of farmland, developing multifunctional transplanters is key to reducing costs in future agricultural production. Research focuses on integrating functions such as mulching, transplanting, watering, and fertilizing into a single machine. This enables the completion of basic crop planting processes with a single pass through the field, eliminating the need to purchase multiple machines and minimizing soil disturbance caused by repeated passes.
- 2) **Universal design:** Enhance the universal design of transplanters to enable a single machine to perform transplanting operations for multiple crops through simple adjustments, thereby further reducing agricultural production costs.

- 3) **Intelligent research:** Enhance intelligent research on transplanting machines by integrating autonomous driving technology. Utilize vision and image processing technologies to monitor transplanting operation quality in real time and adjust operations accordingly, thereby preventing issues such as missed plants.
- 4) **Integrated control system:** The integrated control system dynamically adjusts transplanting operations in real time based on field conditions, ensuring consistent plant spacing and planting depth. This enables the transplanting mechanism to dynamically modify seedling pickup trajectories and instantly adjust seedling orientation, guaranteeing upright growth post-transplanting. The result is highly efficient, low-loss transplanting operations that can be performed unmanned, further reducing labor requirements.
- 5) **Electric transplanters:** Strengthen research on electric transplanters to align with the future green and low-carbon development trends in agriculture. Given that electric transplanters require prolonged operation under harsh environmental conditions, frequent recharging can impair operational efficiency, while battery replacement increases operational costs. Therefore, extending battery runtime and optimizing battery lifespan will be critical challenges to address in electric transplanter research.

5.2 Development Recommendations for Transplanting Mechanisms

- 1) **Damage reduction:** In current agricultural production, damage to seedlings caused by existing transplanting mechanisms remains a key factor limiting transplanting quality and efficiency. Future transplanting mechanism designs must enhance theoretical analysis. For gripper-type transplanters, optimize the gripping force of the seedling picker to prevent damage to seedlings. Design suitable insertion-type transplanting mechanisms to ensure complete seedling retrieval. Control the airflow volume in pneumatic transplanters to maintain seedling pot integrity while ensuring successful seedling extraction.
- 2) **Stability and lightweight design:** To enhance transplanting efficiency, conduct a structural dynamic analysis of the transplanting mechanism to ensure transmission stability during high-speed operation. Simplify the structural design of the transplanting mechanism to achieve lightweight construction.
- 3) **Multi-crop adaptability:** Designed for transplanting multiple types of crops, this system breaks the limitations of transplanting machinery by enabling a single unit to handle transplanting operations for various agricultural crops, thereby reducing agricultural production costs.
- 4) **Integration with agronomy:** Strengthen the integration of agricultural machinery and agronomy practices. Standardize seedling cultivation and transplanting procedures by adopting uniform seedling trays. Design transplanting mechanisms specifically for these standardized trays to better align research with seedling cultivation and transplanting techniques. This approach will standardize trays compatible with transplanting equipment and reduce production costs for seedling trays.

ACKNOWLEDGEMENT

The authors have no acknowledgements to declare.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper

REFERENCES

- [1] Cheema, M. J. M., Nauman, M. H., Ghafoor, A., Farooque, A. A., Haydar, Z., Ashraf, M. U., & Awais, M. (2021). Direct seeding of basmati rice through improved drills: Potential and constraints in Pakistani farm settings. *Applied Engineering in Agriculture*, 37(1), 53–63.
- [2] Song, Q., & Wei, X. (2021). Establishment of rice quality prediction model for intermittent drying. *Transactions of the ASABE*, 64(4), 1355–1363. <https://doi.org/10.13031/trans.14243>
- [3] Gao, S., Yu, S., Wang, M., Meng, J., Tang, S., Ding, J., Li, S., & Miao, Z. (2018). Effect of different controlled irrigation and drainage regimes on crop growth and water use in paddy rice. *International Journal of Agriculture and Biology*, 20(3), 486–492. <https://doi.org/10.17957/ijab/15.0503>
- [4] Xu, X., Zhao, T., Ma, J., Song, Q., Wei, Q., & Sun, W. (2022). Application of two-stage variable temperature drying in hot air-drying of paddy rice. *Foods*, 11(6), Article 888. <https://doi.org/10.3390/foods11060888>

- [5] Liu, S., Tang, Z., Shen, C., Wang, T., & Liang, Y. (2023). Effect of rice stubble on soil compaction properties of a crawler undergoing combine harvester harvesting. *Engenharia Agricola*, 43, e20230057. <https://doi.org/10.1590/1809-4430-eng.agric.v43nepe20230057/2023>
- [6] Ren, H., Tang, Z., Li, X., Li, Y., Liu, X., Zhang, B., & Li, Y. (2021). Method for measuring rice grain internal damage degree undergoing threshing force. *International Journal of Agricultural and Biological Engineering*, 14(1), 63–73. <https://doi.org/10.25165/j.ijabe.20211401.5750>
- [7] Sun, J., Lu, X., Mao, H., Jin, X., & Wu, X. (2017). A method for rapid identification of rice origin by hyperspectral imaging technology. *Journal of Food Process Engineering*, 40(1), e12297. <https://doi.org/10.1111/jfpe.12297>
- [8] Tang, Z., Zhang, B., Wang, B., Wang, M., Chen, H., & Li, Y. (2021). Breaking paths of rice stalks during threshing. *Biosystems Engineering*, 204, 346–357. <https://doi.org/10.1016/j.biosystemseng.2021.02.008>
- [9] Zhang, T., Zhou, J., Liu, W., Yue, R., Yao, M., Shi, J., & Hu, J. (2024). Seedling-YOLO: High-efficiency target detection algorithm for field broccoli seedling transplanting quality based on YOLOv7-tiny. *Agronomy*, 14(5), Article 931. <https://doi.org/10.3390/agronomy14050931>
- [10] Fang, S., Wei, B., & Wu, J. (2017). The spatial spillover effect of agricultural mechanization and its distribution pattern: The perspective of interregional-service of agricultural machinery. *Journal of Management World*, (11), 65–78, 187–188. <https://doi.org/10.19744/j.cnki.11-1235/f.2017.11.006>
- [11] Li, S., Liu, W., & Jiang, J. (2024). Can agricultural mechanization solve the shortage of agricultural labor? *Journal of Chinese Agricultural Mechanization*, 45(7), 316–322, 336. <https://doi.org/10.13733/j.jcam.issn.2095-5553.2024.07.046>
- [12] Cao, R., Li, S., Ji, Y., Zhang, Z., Xu, H., Zhang, M., Li, M., & Li, H. (2021). Task assignment of multiple agricultural machinery cooperation based on improved ant colony algorithm. *Computers and Electronics in Agriculture*, 182, Article 105993. <https://doi.org/10.1016/j.compag.2021.105993>
- [13] Jin, Y., Liu, J., Xu, Z., Yuan, S., Li, P., & Wang, J. (2021). Development status and trend of agricultural robot technology. *International Journal of Agricultural and Biological Engineering*, 14(3), 1–19. <https://doi.org/10.25165/j.ijabe.20211404.6821>
- [14] Xie, Y., Wei, L., Ji, Y., & Li, S. (2022). Seed treatment with iron chlorine E6 enhances germination and seedling growth of rice. *Agriculture*, 12(2), Article 218. <https://doi.org/10.3390/agriculture12020218>
- [15] Wu, P., Lei, X., Zeng, J., Qi, Y., Yuan, Q., Huang, W., Ma, Z., Shen, Q., & Lyu, X. (2024). Research progress in mechanized and intelligentized pollination technologies for fruit and vegetable crops. *International Journal of Agricultural and Biological Engineering*, 17(6), 11–21. <https://doi.org/10.25165/j.ijabe.20241706.9403>
- [16] Zhou, J., Li, P., & Wang, J. (2022). Effects of light intensity and temperature on the photosynthesis characteristics and yield of lettuce. *Horticulturae*, 8(2), Article 178. <https://doi.org/10.3390/horticulturae8020178>
- [17] Tian, Z., Ma, W., Yang, Q., Yao, S., Zhang, M., Duan, F., & Xu, H. (2022). Research status and problem analysis of plug seedling transplanter in greenhouse. *Journal of China Agricultural University*, 27(5), 22–38. <https://doi.org/10.11841/j.issn.1007-4333.2022.05.03>
- [18] Zhang, C., Li, X., Yan, H., Ullah, I., Zuo, Z., Li, L., & Yu, J. (2020). Effects of irrigation quantity and biochar on soil physical properties, growth characteristics, yield and quality of greenhouse tomato. *Agricultural Water Management*, 241, Article 106263. <https://doi.org/10.1016/j.agwat.2020.106263>
- [19] Zhang, T., Zhou, J., Liu, W., Yue, R., Shi, J., Zhou, C., & Hu, J. (2024). SN-CNN: A lightweight and accurate line extraction algorithm for seedling navigation in ridge-planted vegetables. *Agriculture*, 14(9), Article 1446. <https://doi.org/10.3390/agriculture14091446>
- [20] Li, J., Wu, Z., Li, M., & Shang, Z. (2024). Dynamic measurement method for steering wheel angle of autonomous agricultural vehicles. *Agriculture*, 14(9), Article 1602. <https://doi.org/10.3390/agriculture14091602>
- [21] Yao, M., Hu, J., Liu, W., Shi, J., Jin, Y., Lv, J., Sun, Z., & Wang, C. (2024). Precise servo-control system of a dual-axis positioning tray conveying device for automatic transplanting machine. *Agriculture*, 14(8), Article 1431. <https://doi.org/10.3390/agriculture14081431>
- [22] Khadatkar, A., Mathur, S. M., & Gaikwad, B. B. (2018). Automation in transplanting: A smart way of vegetable cultivation. *Current Science*, 115(10), 1884–1892. <https://doi.org/10.18520/cs/v115/i10/1884-1892>
- [23] Bhambota, S., Dixit, A. K., Manes, G. S., Dhatt, A. S., Singh, S. K., & Singh, A. (2018). Field evaluation of a semi-automatic vegetable transplanter for major vegetable crops. *The Indian Journal of Agricultural Sciences*, 88(11), 1755–1762. <https://doi.org/10.56093/ijas.v88i11.84922>
- [24] Ma, G., Shi, Q., Wu, Y., Liu, Y., Han, L., Hu, J., Mao, H., & Zuo, Z. (2024). Effects of biochar on the growth and physiological and mechanical properties of cucumber plug seedlings before and after transplanting. *Agriculture*, 14(11), Article 2012. <https://doi.org/10.3390/agriculture14112012>
- [25] Ma, G., Mao, H., Bu, Q., Han, L., Shabbir, A., & Gao, F. (2020). Effect of compound biochar substrate on the root growth of cucumber plug seedlings. *Agronomy*, 10(8), Article 1080. <https://doi.org/10.3390/agronomy10081080>
- [26] Yang, C., Fang, X., Yang, X., Wang, C., Liu, Z., & Sun, X. (2013). Automatic delivery mechanism of potted-seedling for vegetable transplanter based on PLC. *Transactions of the Chinese Society for Agricultural Machinery*, 44(S1), 19–23, 18. <https://doi.org/10.6041/j.issn.1000-1298.2013.S1.004>
- [27] Sharma, A., & Khar, S. (2024). Design and development of a vegetable plug seedling transplanting mechanism for a semi-automatic transplanter. *Scientia Horticulturae*, 326, Article 112773. <https://doi.org/10.1016/j.scienta.2023.112773>
- [28] Wei, L., Jianping, H., Jiabin, L., Rencai, Y., Tengfei, Z., Mengjiao, Y., & Jing, L. (2024). Method for the navigation line recognition of the ridge without crops via machine vision. *International Journal of Agricultural and Biological Engineering*, 17(2), 230–239. <https://doi.org/10.25165/j.ijabe.20241702.7480>
- [29] Sun, K., Ge, R., Li, T., & Wang, J. (2019). Design and analysis of vegetable transplanter based on five-bar mechanism. *IOP Conference Series: Materials Science and Engineering*, 692(1), Article 012029. <https://doi.org/10.1088/1757-899X/692/1/012029>

- [30] Bai, X., Du, G., Zhang, Z., Qiu, S., Zhao, B., & Tian, S. (2025). Design and experiment of oblique automatic seedling picking and throwing device for vegetable dense transplanting. *Transactions of the Chinese Society for Agricultural Machinery*, 56(5), 300–308. <https://doi.org/10.6041/j.issn.1000-1298.2025.05.028>
- [31] Yu, G., Wang, L., Sun, L., Zhao, X., & Ye, B. (2022). Advancement of mechanized transplanting technology and equipments for field crops. *Transactions of the Chinese Society for Agricultural Machinery*, 53(9), 1–20. <https://doi.org/10.6041/j.issn.1000-1298.2022.09.001>
- [32] Zhang, K., Tao, Y., & Gao, K. (2013). Research advances and characteristics in transplanting mechanism of high-speed transplanter. *Advanced Materials Research*, 834–836, 1516–1522. <https://doi.org/10.4028/www.scientific.net/AMR.834-836.1516>
- [33] Liu, W., Zhou, J., Liu, Y., Zhang, T., Yan, M., Chen, J., Zhou, C., Hu, J., & Chen, X. (2024). An ultrasonic ridge-tracking method based on limiter sliding window filter and fuzzy pure pursuit control for ridge transplanter. *Agriculture*, 14(10), Article 1713. <https://doi.org/10.3390/agriculture14101713>
- [34] Liu, J., Zhao, S., Li, N., Faheem, M., Zhou, T., Cai, W., Zhao, M., Zhu, X., & Li, P. (2019). Development and field test of an autonomous strawberry plug seeding transplanter for use in elevated cultivation. *Applied Engineering in Agriculture*, 35(6), 1067–1078. <https://doi.org/10.13031/aea.13236>
- [35] Rahaman, H., Rahman, M. M., Islam, A. K. M. S., Huda, M. D., & Kamruzzaman, M. (2022). Mechanical rice transplanting in Bangladesh: Current situation, technical challenges, and future approach. *Journal of Biosystems Engineering*, 47(4), 417–427. <https://doi.org/10.1007/s42853-022-00161-x>
- [36] Vibhakar, C. C., Vrushali, R. K., Gokul, K. R., Ajinkya, Y. S., Sumedh, K. T., Nikhil, S. B., Vishal, A. L., & Hemlata, A. N. (2018). Design and fabrication of manually operated rice transplanter. *International Journal of Advance Research and Innovative Ideas in Education*, 4(2), 676–681.
- [37] Felezi, M. E., Vahabi, S., & Nariman-Zadeh, N. (2016). Pareto optimal design of reconfigurable rice seedling transplanting mechanisms using multi-objective genetic algorithm. *Neural Computing and Applications*, 27(7), 1907–1916.
- [38] Thorat, P. V., Jhala, K. B., & Jadhav, M. L. (2017). Design, development and performance evaluation of manually operated two row trolley type vegetable transplanter. *International Journal of Current Microbiology and Applied Sciences*, 6(11), 3577–3589.
- [39] Yuan, X., Zhang, G., Chen, J., & Zhao, Y. (2011). Development on rice plotted-seeding sequential transplanter of ejection type. *Journal of Zhejiang Sci-Tech University (Natural Sciences)*, 28*(5), 749–752.
- [40] Li, Z., Ma, X., Li, X., Chen, L., Li, H., & Yuan, Z. (2018). Research progress of rice transplanting mechanization. *Transactions of the Chinese Society for Agricultural Machinery*, 49(5), 1–20. <https://doi.org/10.6041/j.issn.1000-1298.2018.05.001>
- [41] Sun, J., Wang, Z., Ding, S., Xia, J., & Xing, G. (2024). Adaptive disturbance observer-based fixed time nonsingular terminal sliding mode control for path-tracking of unmanned agricultural tractors. *Biosystems Engineering*, 246, 96–109. <https://doi.org/10.1016/j.biosystemseng.2024.06.013>
- [42] Jin, X., Cheng, Q., Zhao, B., Ji, J., & Li, M. (2020). Design and test of 2ZYM-2 potted vegetable seedlings transplanting machine. *International Journal of Agricultural and Biological Engineering*, 13(1), 101–110. <https://doi.org/10.25165/j.ijabe.20201301.5494>
- [43] Peng, Y., Zheng, W., Chen, X., Zheng, R., Luo, H., Cai, S., & Chen, Z. (2025). Research and progress on transplanters and its key technologies. *Agricultural Equipment and Intelligent Technology*, (1), 1–8.
- [44] Han, L., Mao, H., Hu, J., & Kumi, F. (2019). Development of a riding-type fully automatic transplanter for vegetable plug seedlings. *Spanish Journal of Agricultural Research*, 17(3), e0205. <https://doi.org/10.5424/sjar/2019173-15358>
- [45] Pérez-Ruiz, M., & Slaughter, D. C. (2021). Development of a precision 3-row synchronised transplanter. *Biosystems Engineering*, 206, 67–78. <https://doi.org/10.1016/j.biosystemseng.2021.03.014>
- [46] Wu, J., Yu, W., Zhang, M., Wu, C., Jiang, L., & Tang, Q. (2020). Design and test of 2ZY-6 rapeseed carpet seedling transplanter. *Transactions of the Chinese Society for Agricultural Machinery*, 51(12), 95–102, 275. <https://doi.org/10.6041/j.issn.1000-1298.2020.12.010>
- [47] Han, C., Xiao, L., Xu, Y., Zhang, J., & Li, H. (2021). Design and experiment of the automatic transplanter for chili plug seedlings. *Transactions of the Chinese Society of Agricultural Engineering*, 37(13), 20–29. <https://doi.org/10.11975/j.issn.1002-6819.2021.13.003>
- [48] Han, C., Han, H., You, J., Rui, X., Zhang, J., & Gao, J. (2022). Research and design of operation information monitoring system for automatic transplanter. *Journal of Chinese Agricultural Mechanization*, 43(4), 60–65. <https://doi.org/10.13733/j.jcam.issn.2095-5553.2022.04.010>
- [49] Shao, Y., Liu, Y., Xuan, G., Hu, Z., Han, X., Wang, Y., Chen, B., & Wang, W. (2019). Design and test of multifunctional vegetable transplanting machine. *IFAC-PapersOnLine*, 52*(30), 92–97. <https://doi.org/10.1016/j.ifacol.2019.12.503>
- [50] Li, J., Shang, Z., Li, R., & Cui, B. (2022). Adaptive sliding mode path tracking control of unmanned rice transplanter. *Agriculture*, 12(8), Article 1225. <https://doi.org/10.3390/agriculture12081225>
- [51] Ji, X., Wei, X., Wang, A., Cui, B., & Song, Q. (2022). A novel composite adaptive terminal sliding mode controller for farm vehicles lateral path tracking control. *Nonlinear Dynamics*, 110(3), 2415–2428. <https://doi.org/10.1007/s11071-022-07730-x>
- [52] Cui, B., Cui, X., Wei, X., Zhu, Y., Ma, Z., Zhao, Y., & Liu, Y. (2024). Design and testing of a tractor automatic navigation system based on dynamic path search and a fuzzy Stanley model. *Agriculture*, 14(12), Article 2136. <https://doi.org/10.3390/agriculture14122136>
- [53] Hu, J., Zhang, C., Wang, L., & Han, L. (2016). Design and experiment on automatic greenhouse seedling transplanting machine. *Transactions of the Chinese Society for Agricultural Machinery*, 47(S1), 149–154. <https://doi.org/10.6041/j.issn.1000-1298.2016.S0.023>
- [54] Ning, M., Sun, W., Luo, J., & Zhang, L. (2025). Electric self-propelled double row transplanter for *Angelica sinensis* seedlings. *Computers and Electronics in Agriculture*, 237, Article 110512. <https://doi.org/10.1016/j.compag.2025.110512>
- [55] Han, L., Mao, H., Hu, J., Xu, J., Zhao, Z., & Ma, G. (2016). Design and test of automatic transplanter for greenhouse plug seedlings. *Transactions of the Chinese Society for Agricultural Machinery*, 47(11), 59–67. <https://doi.org/10.6041/j.issn.1000-1298.2016.11.008>

- [56] Yu, X., Zhao, Y., Chen, B., Zhou, M., Zhang, H., & Zhang, Z. (2014). Current situation and prospect of transplanter. *Transactions of the Chinese Society for Agricultural Machinery*, 45(8), 44–53. <https://doi.org/10.6041/j.issn.1000-1298.2014.08.008>
- [57] Zhao, G., & Liu, D. (2015). Design of seedling transplanting machine based on motion controller. *Advances in Computer Science Research*, 556–560. <https://doi.org/10.2991/iccse-15.2015.103>
- [58] Chen, H., Quan, W., Shi, F., Jiang, X., Xiang, Y., & Wu, M. (2025). Design and testing of rotary seedling tray conveying device for oilseed rape seedling transplanting machine. *Transactions of the Chinese Society of Agricultural Engineering*, 41(2), 445–454. <https://doi.org/10.11975/j.issn.1002-6819.202501009>
- [59] Han, C., Zhou, T., You, J., Xu, Y., Mao, H., & Liang, J. (2023). Design and experiments of an arc expansion type automatic seedling taking and throwing device for vegetable plug seedlings. *Transactions of the Chinese Society of Agricultural Engineering*, 39(8), 54–64. <https://doi.org/10.11975/j.issn.1002-6819.202302045>
- [60] Chen, J., Zhang, X., Liu, L., Ma, X., Yao, K., & Cheng, D. (2023). Design and experiments of the clipping-stem type non-circular gear transplanting mechanism for corn pot seedlings. *Transactions of the Chinese Society of Agricultural Engineering*, 39(18), 30–40. <https://doi.org/10.11975/j.issn.1002-6819.202306011>
- [61] Yu, G., Wang, X., Liu, J., Ye, B., Li, X., & Zhao, X. (2023). Design and experiment of multi-row seedling taking mechanism for dense planting and transplanting of vegetable pot seedlings. *Transactions of the Chinese Society for Agricultural Machinery*, 54(1), 94–103. <https://doi.org/10.6041/j.issn.1000-1298.2023.01.010>
- [62] Chen, X., Huang, H., Liao, Z., Yu, J., Xiao, L., Wu, J., & Liu, M. (2025). Design and experiment of the cam progressive ejecting-out seedling-taking device for rice potted seedlings. *Transactions of the Chinese Society of Agricultural Engineering*, 41(1), 65–74. <https://doi.org/10.11975/j.issn.1002-6819.202407169>
- [63] Feng, S., Wu, M., Yan, B., & Quan, W. (2020). Design and test of eject lifting type pot seedling detaching device. *Transactions of the Chinese Society of Agricultural Engineering*, 36(5), 50–58. <https://doi.org/10.11975/j.issn.1002-6819.2020.05.006>
- [64] Guo, J., Huang, Y., Dai, Y., Luo, X., & Gou, H. (2014). Performance experimental study of orderly rows seedlings on a type of seedling-falling device with air blast. *Journal of Chinese Agricultural Mechanization*, 35(2), 136–138. <https://doi.org/10.13733/j.cam.issn.2095-5553.2014.02.033>
- [65] Zhang, X., Liu, L., Ning, Y., Kong, D., Liu, Y., & Wu, H. (2023). Design and experiment of end effector of seedling taking by jacking and clamping of vegetable transplanter. *Transactions of the Chinese Society for Agricultural Machinery*, 54(S1), 115–124, 134. <https://doi.org/10.6041/j.issn.1000-1298.2023.S1.013>
- [66] Vivek, P., Duraisamy, V. M., & Kavitha, R. (2017). Development of an automatic transplanting mechanism for prostrate vegetable seedlings. *International Journal of Science, Engineering and Management*, 401–404. <https://doi.org/10.29321/MAJ.2017.000087>
- [67] Wang, X., Liu, M., Zhai, C., Han, C., Yang, S., & Gao, Y. (2023). Design and experiment of vegetable transplanting clip stem seedling device. *Transactions of the Chinese Society for Agricultural Machinery*, 54(9), 122–132. <https://doi.org/10.6041/j.issn.1000-1298.2023.09.012>
- [68] Assal, S. F., & Ndawula, I. (2019). Optimum design and FEA of a hybrid parallel-deployable structure-based 3-DOF multi-gripper translational robot for field pot seedlings transplanting. In *ICINCO (2)* (pp. 68–77). <https://doi.org/10.5220/0007833500680077>
- [69] Sharma, A., & Khar, S. (2022). Current developments in vegetable transplanters in developing countries: A comprehensive review. *International Journal of Vegetable Science*, 28(5), 417–440. <https://doi.org/10.1080/19315260.2022.2046672>
- [70] Rahul, K., Raheman, H., & Paradkar, V. (2019). Design and development of a 5R 2DOF parallel robot arm for handling paper pot seedlings in a vegetable transplanter. *Computers and Electronics in Agriculture*, 166, Article 105014. <https://doi.org/10.1016/j.compag.2019.105014>
- [71] Hu, S., Hu, M., Yan, W., & Zhang, W. (2022). Design and experiment of an integrated automatic transplanting mechanism for picking and planting pepper hole tray seedlings. *Agriculture*, 12(4), Article 557. <https://doi.org/10.3390/agriculture12040557>
- [72] Cai, J., Liu, M., Lin, J., Xiao, L., Cai, H., Mei, Y., Deng, F., & Liang, Y. (2021). Design and test of rice pot seedling transplanting mechanism. *Acta Agriculturae Universitatis Jiangxiensis*, 43(1), 206–213. <https://doi.org/10.13836/j.jjau.2021024>
- [73] Xin, L., Lv, Z., Wang, W., Zhou, M., & Zhao, Y. (2017). Optimal design and development of a double-crank potted rice seedling transplanting mechanism. *Transactions of the ASABE*, 60(1), 31–40. <https://doi.org/10.13031/trans.11680>
- [74] Xin, L., Wang, M., Zhang, H., Sun, G., Wang, H., & Zhuang, Z. (2024). Optimization design and experiment of non-circular gear-linkage combination type transplanting mechanism of rice pot seedling on film. *Transactions of the Chinese Society for Agricultural Machinery*, 55(8), 63–70. <https://doi.org/10.6041/j.issn.1000-1298.2024.08.005>
- [75] Ye, B., Yi, W., Yu, G., Gao, Y., & Zhao, X. (2017). Optimization design and test of rice plug seedling transplanting mechanism of planetary gear train with incomplete eccentric circular gear and non-circular gears. *International Journal of Agricultural and Biological Engineering*, 10(6), 43–55. <https://doi.org/10.25165/j.ijabe.20171006.2712>
- [76] Choi, W. C., Kim, D. C., Ryu, I. H., & Kim, K. U. (2002). Development of a seedling pick-up device for vegetable transplanters. *Transactions of the ASAE*, 45(1), 13–19. <https://doi.org/10.13031/2013.7864>
- [77] Yue, R., Hu, J., Liu, Y., Yao, M., Zhang, T., & Shi, J. (2022). Design and working parameter optimization of pneumatic reciprocating seedling-picking device of automatic transplanter. *Agriculture*, 12(12), Article 1989. <https://doi.org/10.3390/agriculture12121989>
- [78] Yue, R., Yao, M., Zhang, T., Shi, J., Zhou, J., & Hu, J. (2024). Design and experiment of dual-row seedling pick-up device for high-speed automatic transplanting machine. *Agriculture*, 14(6), Article 942. <https://doi.org/10.3390/agriculture14060942>
- [79] Han, L., Mo, M., Ma, H., Kumi, F., & Mao, H. (2023). Design and test of a lateral-approaching and horizontal-pushing transplanting manipulator for greenhouse seedlings. *Applied Engineering in Agriculture*, 39(3), 325–338. <https://doi.org/10.13031/aea.15420>
- [80] Han, L., Xiang, D., Xu, Q., Du, X., Ma, G., & Mao, H. (2023). Development of simplified seedling transplanting device for supporting efficient production of vegetable raw materials. *Applied Sciences*, 13(18), Article 10022. <https://doi.org/10.3390/app131810022>
- [81] Shi, J., Hu, J., Li, J., Liu, W., Yue, R., Zhang, T., & Yao, M. (2024). Design and experiment of planting mechanism of automatic transplanter for densely planted vegetables. *Agriculture*, 14(8), Article 1357. <https://doi.org/10.3390/agriculture14081357>

- [82] Islam, M. N., Iqbal, M. Z., Ali, M., Chowdhury, M., Kabir, M. S. N., Park, T., Kim, Y.-J., & Chung, S.-O. (2020). Kinematic analysis of a clamp-type picking device for an automatic pepper transplanter. *Agriculture*, 10(12), Article 627. <https://doi.org/10.3390/agriculture10120627>
- [83] Zhou, M., Shan, Y., Xue, X., & Yin, D. (2020). Theoretical analysis and development of a mechanism with punching device for transplanting potted vegetable seedlings. *International Journal of Agricultural and Biological Engineering*, 13(4), 85–92. <https://doi.org/10.25165/ijabe.20201304.5404>
- [84] Xu, G., Fang, H., & Liu, J. (2023). Sustainable improvement of planting quality for a planar 5R parallel transplanting mechanism from the perspective of machine and soil interaction. *Sustainability*, 15(12), Article 9582. <https://doi.org/10.3390/su15129582>
- [85] Sun, L., Xu, H., Zhou, Y., Shen, J., Yu, G., Hu, H., & Miao, Y. (2023). Kinematic synthesis and simulation of a vegetable pot seedling transplanting mechanism with four exact task poses. *International Journal of Agricultural and Biological Engineering*, 16(2), 85–95. <https://doi.org/10.25165/ijabe.20231602.67397>
- [86] Xu, G., Fang, H., Song, Y., & Du, W. (2023). Optimal design and analysis of cavitating law for well-cellular cavitating mechanism based on MBD-DEM bidirectional coupling model. *Agriculture*, 13(1), Article 142. <https://doi.org/10.3390/agriculture13010142>
- [87] Yu, G., Li, X., Xu, Y., Ao, M., Wang, Z., & Wang, L. (2025). Design and experiment of integrated transplanting mechanism for taking and planting vegetable pot seedlings. *Transactions of the Chinese Society for Agricultural Machinery*, 56(6), 341–350. <https://doi.org/10.6041/j.issn.1000-1298.2025.06.032>
- [88] Wen, Y., Zhang, J., Yuan, T., & Tan, Y. (2021). Current situation and analysis of automatic pick-up technology for vegetable plug seedlings. *Journal of China Agricultural University*, 26(4), 128–142. <https://doi.org/10.11841/j.issn.1007-4333.2021.04.12>
- [89] Cheng, B., Wu, H., Zhu, H., Liang, J., Miao, Y., Cui, Y., & Song, W. (2024). Current status and analysis of key technologies in automatic transplanters for vegetables in China. *Agriculture*, 14(12), Article 2168. <https://doi.org/10.3390/agriculture14122168>
- [90] Huang, M., Tang, Q., Song, Z., Liu, H., Wu, Y., & Zhu, T. (2023). Development status and trends of the development of seedling pick-up mechanism of transplanter in dry land. *Journal of Intelligent Agricultural Mechanization*, 4(4), 57–64. <https://doi.org/10.12398/j.issn.2096-7217.2023.04.008>
- [91] Zhang, G., Chen, J., Li, J., & Zhao, Y. (2008). Parameter optimization of ejection mechanism of ordered transplanter for plotted rice-seedling. *Journal of Jiangsu University*, (2), 101–105. <https://doi.org/10.3969/j.issn.1671-7775.2008.02.003>
- [92] Wang, C., Liu, C., Li, Y., Song, J., Wang, J., & Dong, X. (2021). Design and experiment of pneumatic punching high-speed seedling picking device for vegetable transplanter. *Transactions of the Chinese Society for Agricultural Machinery*, 52(5), 35–43, 51. <https://doi.org/10.6041/j.issn.1000-1298.2021.05.004>
- [93] Wen, Y., Zhang, J., Zhang, Y., Tian, J., Yuan, T., Tan, Y., & Li, W. (2020). Development of insertion and ejection type seedling taking device for vegetable plug seedlings. *Transactions of the Chinese Society of Agricultural Engineering*, 36(22), 96–104. <https://doi.org/10.11975/j.issn.1002-6819.2020.22.011>
- [94] Bao, C., Li, B., Bao, W., & Wang, R. (2003). Research on rice potting seedling air rooting air suction type orderly transplanting machine. *Transactions of the Chinese Society of Agricultural Engineering*, (6), 130–134.
- [95] Xiang, W., Luo, X., Wang, Y., Chen, J., & Yang, D. (2004). Finite element simulation analysis and test of airflow field of pneumatic sequential rice planting. *Transactions of the Chinese Society of Agricultural Engineering*, (1), 44–47.
- [96] Wang, Y., Luo, X., Tang, Y., & Chen, J. (2004). Dynamic simulation study on the seedling transporting mechanism of pneumatic sequential rice transplanter. *Transactions of the Chinese Society of Agricultural Engineering*, (2), 109–112.
- [97] Yuan, T., Wang, D., Wen, Y., Zhu, S., Chen, Y., & Tan, Y. (2019). Design and experiment of seedlings unloading mechanism based on methods of air-blowing and vibration for vegetable transplanter. *Transactions of the Chinese Society for Agricultural Machinery*, 50(10), 80–87. <https://doi.org/10.6041/j.issn.1000-1298.2019.10.009>
- [98] Mao, H., Ma, G., Han, L., Hu, J., Gao, F., & Liu, Y. (2020). A whole row automatic pick-up device using air force to blow out vegetable plug seedlings. *Spanish Journal of Agricultural Research*, 18(4), e0211. <https://doi.org/10.5424/sjar/2020184-17003>
- [99] Han, L., Ma, H., Mo, M., Kumi, F., Hu, J., & Mao, H. (2024). Design and test of an efficient seedling pick-up device with a combination of air jet ejection and mechanical action. *Journal of Agricultural Engineering*, 55(3). <https://doi.org/10.4081/jae.2024.1575>
- [100] Zhang, N., Zhang, G., Fu, J., Liu, W., Chen, L., & Tang, N. (2024). Design and experiment of the seedling pick-up device with ejecting pot-clamping stem combination. *Transactions of the Chinese Society of Agricultural Engineering*, 40(3), 50–61. <https://doi.org/10.11975/j.issn.1002-6819.202309091>
- [101] Ni, Y., Jin, C., & Liu, J. (2015). Design and experiment of system for picking up and delivering seedlings in automatic transplanter. *Transactions of the Chinese Society of Agricultural Engineering*, 31(23), 10–19. <https://doi.org/10.11975/j.issn.1002-6819.2015.23.002>
- [102] Wang, M., Song, J., Liu, C., Wang, Y., & Sun, Y. (2015). Design and experiment of crank rocker type clamp seedlings mechanism of vegetable transplanter. *Transactions of the Chinese Society of Agricultural Engineering*, 31(14), 49–57. <https://doi.org/10.11975/j.issn.1002-6819.2015.14.007>
- [103] Zhou, B., Miao, H., Guan, C., Ji, X., & Wang, X. (2024). Design and test of seedling-picking mechanism of fully automatic transplanting machine. *Applied Sciences*, 14(20), Article 9235. <https://doi.org/10.3390/app14209235>.

Effect of Rare-Earth Site Composition Complexity on the Microstructure and Mechanical Properties of High-Entropy RE₃NbO₇ Ceramics

Zongjian Yang^{1*}; Xiaojun Yang²; Hui Li³; Peng Zhang⁴

School of Materials Science and Engineering, Beijing University of Technology, Beijing100124, China

*Corresponding Author

Received: 04 April 2026/ Revised: 13 April 2026/ Accepted: 22 April 2026/ Published: 30-04-2026

Copyright © 2026 International Journal of Engineering Research and Science

This is an Open-Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (<https://creativecommons.org/licenses/by-nc/4.0>) which permits unrestricted Non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

Abstract— High-entropy strategies provide a robust approach for tailoring the microstructural evolution and mechanical properties of ceramics. This study investigates the kinetic influence of rare-earth (RE) site compositional complexity on the phase stability, densification, and grain growth of RE₃NbO₇ ceramics. A series of compositions, from single-component Sm₃NbO₇ to a five-component (5RE) high-entropy system, were synthesized via solid-state reaction. X-ray diffraction confirms the formation of pure orthorhombic phases, characterized by distinct lattice distortions. Despite all compositions achieving high relative densities (>98%) at 1600°C, the increase in RE-site complexity profoundly suppressed grain growth. Notably, the 4RE composition exhibited the most pronounced grain refinement, reaching a minimum average grain size of 3.37μm (a 71% reduction compared to Sm₃NbO₇). This suppression is governed by a competitive mechanism between entropy-driven sluggish diffusion and the intrinsic physicochemical properties of the constituent elements. Mechanical evaluations reveal that the 4RE, 3RE, and 2RE compositions exhibit peak Vickers hardness (7.67GPa), fracture toughness (2.25 MPa·m^{1/2}), and flexural strength (180MPa), respectively. These findings demonstrate that entropy-mediated design effectively decouples densification from grain coarsening and enables the systematic modulation of mechanical performance in niobate ceramics.

Keywords— High Entropy, Rare-earth Niobates, Composition Complexity, Densification, Mechanical Properties.

I. INTRODUCTION

Rare-earth niobates (RE₃NbO₇) have attracted significant research interest due to their structural diversity and exceptional high-temperature stability^[1-5]. Depending on the RE³⁺ ionic radius, these compounds typically crystallize into either cubic defect fluorite or orthorhombic weberite-type structures. To date, the high-entropy strategy has been extensively employed in the RE₃NbO₇ system to optimize various functional properties, such as achieving ultra-low thermal conductivity for thermal barrier coatings or tailoring magnetic behaviors for cryogenic magnetocaloric applications^[6-9].

However, despite the proliferation of performance-oriented studies, the intrinsic kinetic influence of configurational entropy on the sintering process remains insufficiently understood. In the processing of advanced ceramics, achieving high densification often triggers rapid grain coarsening, which may lead to microstructural instability and degraded mechanical reliability. Although the sluggish diffusion effect is considered a hallmark of high-entropy systems, its quantitative impact on grain boundary mobility within the complex orthorhombic lattice of RE₃NbO₇ has not been systematically investigated. Most existing literature focuses on the final physical properties, whereas the fundamental evolution from single-component to multi-component compositions, and how this entropy escalation governs grain refinement is often overshadowed^[10, 11].

In this work, we deliberately shift the focus from functional metrics to the fundamental relationship between RE-site complexity and microstructural evolution. By synthesizing a series of compositions ranging from single-component Sm₃NbO₇ to a five-component (5RE) high-entropy system via a solid-state reaction method, we isolate the effect of chemical disorder on densification behavior and grain growth inhibition. Through X-ray diffraction and scanning electron microscopy, we elucidate

the competitive mechanism between lattice strain and kinetic retardation. This study aims to provide a mechanistic framework for the precision microstructural control of niobate ceramics, establishing a necessary foundation for the future design of high-stability rare-earth niobates independent of specific performance targets.

II. MATERIAL AND METHODS

2.1 Material design and Synthesis

The raw materials used in this study included high-purity oxide powders: La_2O_3 , Nd_2O_3 , Sm_2O_3 , Eu_2O_3 , Gd_2O_3 , and Nb_2O_5 (all with 99.9% purity on a metals basis). A series of niobate ceramics, including Sm_3NbO_7 , $(\text{La}_{0.5}\text{Gd}_{0.5})_3\text{NbO}_7$ (2RE), $(\text{La}_{1/3}\text{Sm}_{1/3}\text{Gd}_{1/3})_3\text{NbO}_7$ (3RE), $(\text{Nd}_{0.25}\text{Sm}_{0.25}\text{Eu}_{0.25}\text{Gd}_{0.25})_3\text{NbO}_7$ (4RE), and $(\text{La}_{1/5}\text{Nd}_{1/5}\text{Sm}_{1/5}\text{Eu}_{1/5}\text{Gd}_{1/5})_3\text{NbO}_7$ (5RE), were synthesized by solid-state reaction. The powders were pre-dried and stoichiometrically weighed and homogenized in anhydrous ethanol via planetary ball milling (zirconia ball, 250 rpm, 400 min). After removing the solvent via rotary evaporation and drying at 100 °C for 1 h, the precursor powders were calcined in a muffle furnace at 900 °C for 5 h. The calcined powders were then crushed, sieved through a 200-mesh screen, and subjected to a second ball-milling step for an extended duration of 800 min under identical conditions.

Following subsequent drying and sieving, the powders were granulated using a 5 wt% polyvinyl alcohol (PVA) aqueous solution (1.4 mL per 10 g of powder) and uniaxially pressed into $\phi 14$ mm green bodies. Binder burnout was conducted at 560 °C for 2 h with a slow heating rate of 1 °C/min. Ultimately, the pellets were sintered in a high-temperature furnace at 1600 °C for 10 h, followed by natural furnace cooling to room temperature.

2.2 Sample Preparation and Characterization

The samples were ground to achieve a flat surface and subsequently cleaned using an ultrasonic cleaner. The phase composition and crystal structure were characterized by X-ray diffraction (XRD). For microstructure observation, the surfaces were polished and thermally etched in a muffle furnace at 50 °C below the sintering temperature for 30 minutes. The surface morphology was then analyzed using scanning electron microscopy (SEM). The porosity of the samples was quantified from SEM images using ImageJ software, from which the relative density was determined.

III. RESULT AND DISCUSSION

3.1 Phase Composition and Crystal Structure Analysis

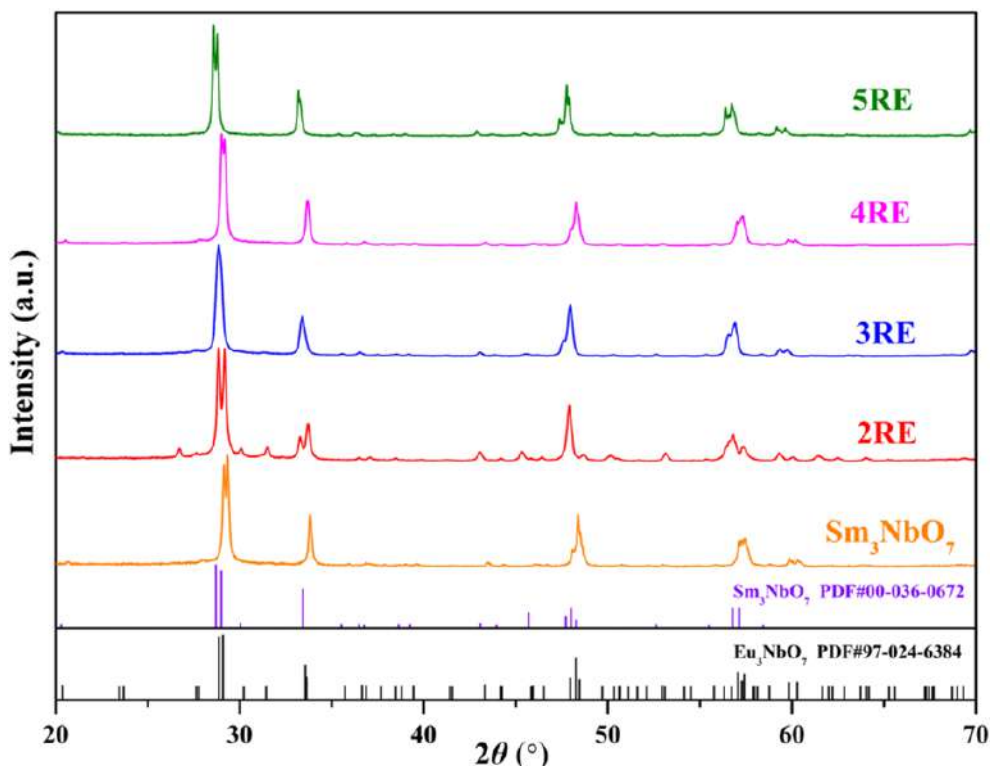
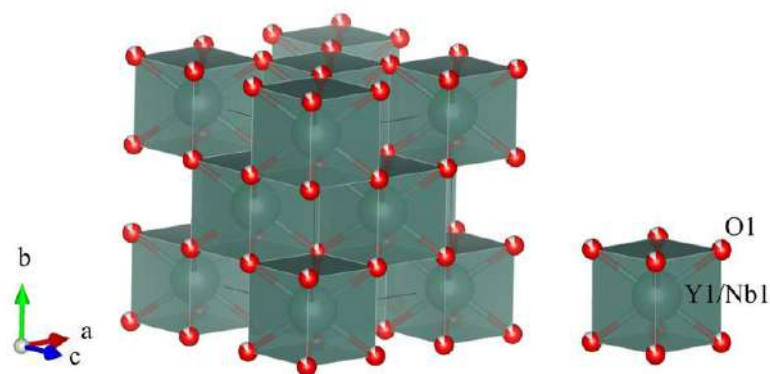


FIGURE 1: The XRD pattern of RE_3NbO_7 ceramics sintered at 1600 °C

The phase composition and crystalline evolution of the synthesized RE_3NbO_7 ceramics, ranging from single-component to five-component high-entropy systems, were characterized via X-ray diffraction (XRD). As illustrated in Figure 1, all samples exhibit well-defined diffraction profiles with high relative intensities, which can be perfectly indexed to a pure orthorhombic phase. No detectable secondary phases or residual precursors were observed, confirming that the rare-earth ions have been successfully incorporated into a single-phase host lattice to form a stabilized crystal structure via the solid-state reaction.

Detailed structural analysis via whole-pattern fitting (WPF) reveals a distinct transition in crystallographic symmetry as a function of RE-site complexity. The Sm_3NbO_7 and multi-component compositions (3RE, 4RE, and 5RE) crystallize into the $C222_1$ space group, while the 2RE composition maintains $Cmcm$ symmetry^[12]. Notably, a characteristic splitting of the diffraction peaks (doublet) at approximately $2\theta \approx 29^\circ$ is clearly observed in the 2RE sample. However, as the configurational entropy increases—accompanied by a decrease in lanthanum (La) content—these doublets gradually attenuate and merge into monolithic reflections. This phenomenon signifies a localized "lattice averaging" effect induced by the high-entropy strategy, where the significant size mismatch and chemical disorder among the multiple RE-site cations intensify the lattice distortion within the weberite framework^[13].

(a) Y_3NbO_7



(b) Eu_3NbO_7

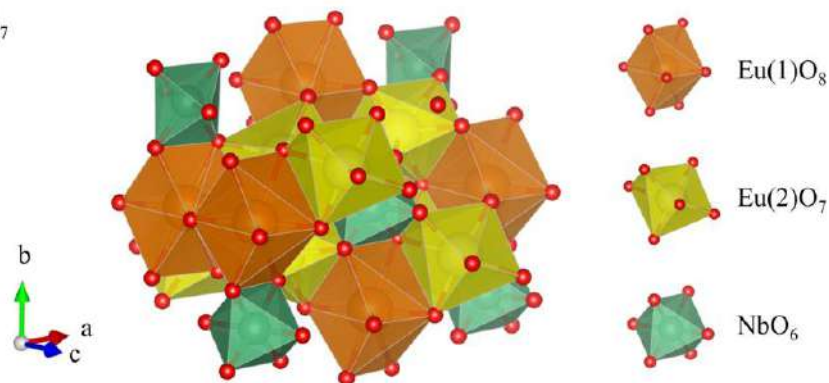


FIGURE 2: Crystal structures of RE_3NbO_7 ceramics crystallizing in (a) defect fluorite and (b) weberite structures

The structural features of the RE_3NbO_7 system are further elucidated by the atomic models presented in Figure 2. Y_3NbO_7 is shown as a representative of the defect fluorite structure for RE_3NbO_7 with smaller RE^{3+} ions. In the high-symmetry defect fluorite structure, cations (Y/Nb) and oxygen vacancies are randomly distributed over their respective crystallographic sites, forming a uniform cubic framework^[14]. Conversely, the orthorhombic weberite structure (Eu_3NbO_7) represents a lower-symmetry variant characterized by the long-range ordering of three distinct cation polyhedra: $Eu(1)O_8$, $Eu(2)O_7$, and NbO_6 ^[15]. The NbO_6 octahedra are predominantly linked via corner-sharing, while the larger rare-earth polyhedra occupy the interstitial sites, connecting to the framework through a combination of edge- and corner-sharing modes.

The crystallographic parameters summarized in Table 1 confirm the orthorhombic nature of these unit cells ($\alpha=\beta=\gamma=90^\circ$). Based on the fitted data, the lattice constants exhibit a geometric relationship of $a \approx 2^{1/2}b$ (e.g., for Sm_3NbO_7 , $10.70/7.54 \approx 1.42$), which is a structural hallmark of weberite-type niobates derived from a parent fluorite lattice^[16]. To quantify the effect of compositional complexity, the systematic evolution of the unit cell volume (V_c) was analyzed. As summarized in Table 1, the

unit cell volume (V_c) exhibits a synergistic fluctuation with the average ionic radius (\bar{r}_{RE}), confirming the successful incorporation of multiple RE^{3+} cations into the weberite lattice.

TABLE 1

THE CELL PARAMETERS, FORMULA UNITS (Z), UNIT CELL VOLUME (V_c), CONFIGURATIONAL ENTROPY (S_{conf}), AVERAGE IONIC RADIUS (\bar{r}_{RE}), RELIABILITY FACTOR (R), LATTICE DISTORTION DEGREE (δ), AND RELATIVE DENSITIES (ρ_r) OF RE_3NbO_7 CERAMICS SINTERED AT 1600 °C

Composition	Sm_3NbO_7	2RE	3RE	4RE	5RE
a (Å)	10.7029	10.8721	10.7448	10.6928	10.7294
b (Å)	7.53901	7.5279	7.5737	7.5445	7.5768
c (Å)	7.6172	7.6551	7.6289	7.6134	7.6562
$\alpha=\beta=\gamma$ (°)	90	90	90	90	90
Z	4	4	4	4	4
V_c (Å ³)	614.6	626.5	620.8	614.2	622.4
S_{conf} (R)	0	0.6931R	1.1065R	1.3863R	1.6094R
\bar{r}_{RE} (Å)	1.079	1.1065	1.0973	1.0768	1.0934
R	16.19%	10.88%	15.41%	9.00%	12.07%
δ	-	4.84%	4.15%	1.93%	3.49%
ρ_r (%)	99.96	99.99	98.9	99.6	99.55

3.2 Sintering Behavior and Microstructural Evolution

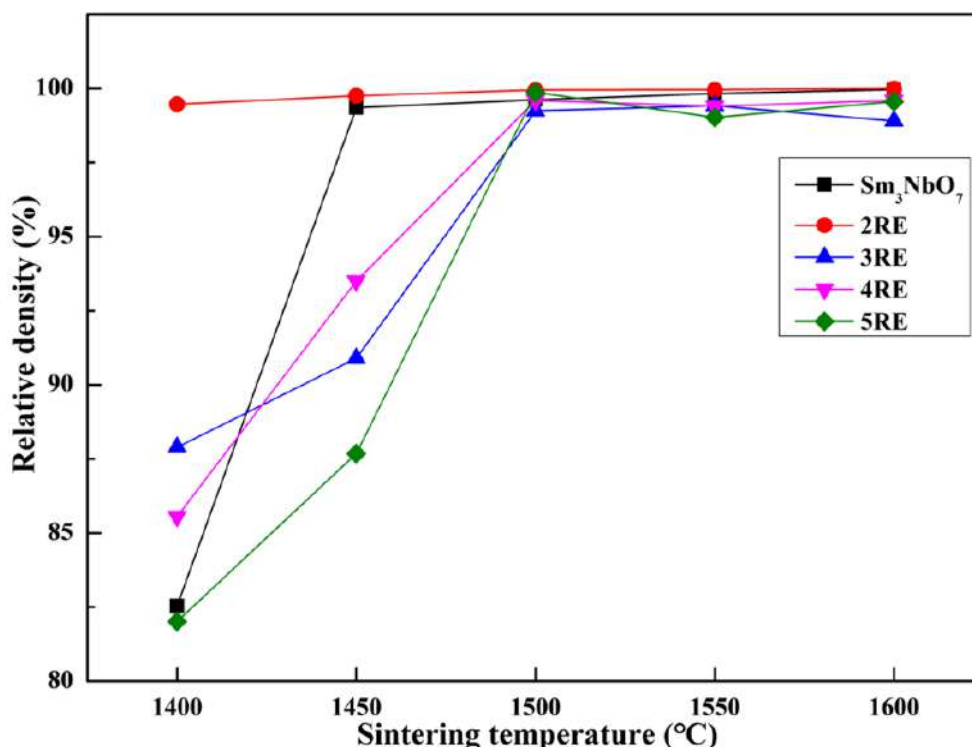


FIGURE 3: The relative density of RE_3NbO_7 ceramics sintered at 1400 °C-1600 °C

The densification behavior of the RE_3NbO_7 ceramics as a function of sintering temperature is depicted in Figure 3. It is evident that the relative density of all compositions increases monotonically as the temperature rises from 1400 °C to 1600 °C, reflecting a progressive elimination of porosity and a clear densification trend. Notably, the 2RE sample maintains a superiority

in densification across all tested temperatures, reaches a maximum relative density of 99.99% at 1600 °C (Table 1). While the 3RE and 5RE samples exhibit relatively lower densification rates at intermediate temperatures, all compositions ultimately achieve a high relative density exceeding 98% upon reaching 1600 °C. This indicates that the high-entropy strategy, despite increasing the chemical complexity, does not significantly impede the final stages of macroscopic densification.

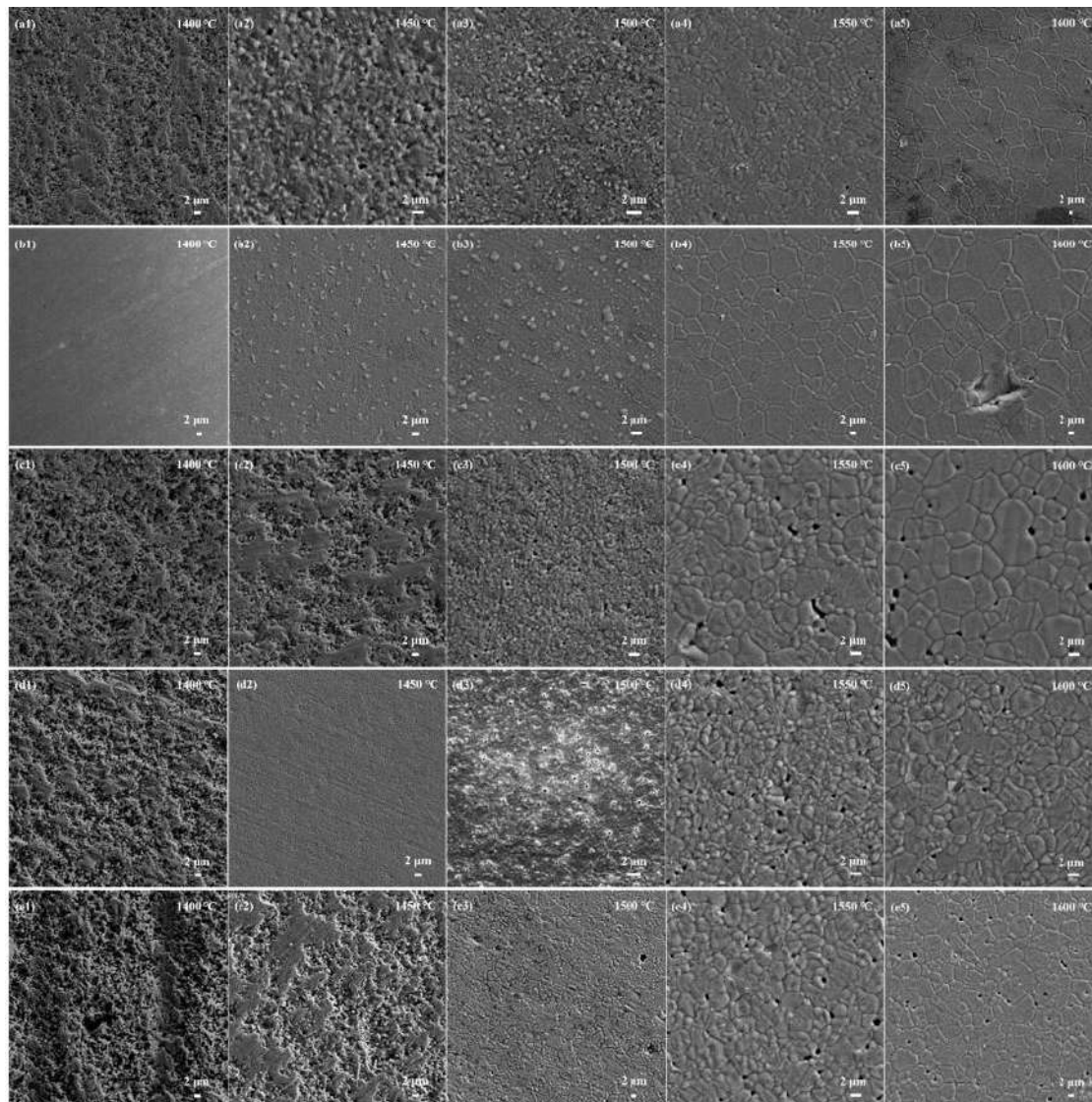


FIGURE 4: The SEM images of RE_3NbO_7 ceramics sintered at 1400 °C-1600 °C: (a1-a5) Sm_3NbO_7 ; (b1-b5) 2RE; (c1-c5) 3RE; (d1-d5) 4RE; (e1-e5) 5RE

The evolution of surface morphology, as captured by SEM in Figure 4, illustrates the transition from a highly porous state to a dense structure with well-defined grain boundaries as the temperature increases. However, a critical observation is the profound impact of RE-site complexity on the grain growth kinetics.

At lower sintering temperatures (1400 °C to 1500 °C), the samples exhibit nascent stages of sintering. These microstructures are characterized by an abundance of interconnected porosity and fine, indistinct particulates. It is evident that at these temperatures, the driving force for mass transport is insufficient to overcome the energy barriers for grain boundary formation, particularly in the multi-component systems. For the 4RE and 5RE compositions, the surfaces at 1450 °C and 1500 °C remain relatively flat or exhibit a "nanocrystalline" appearance, suggesting that high configurational entropy significantly shifts the densification window toward higher temperatures.

As the sintering temperature increases to 1550°C and 1600 °C, the microstructures undergo a dramatic transformation. Porosity is largely eliminated, and the ceramics develop well-defined, equiaxed grains with clearly delineated boundaries. This indicates the completion of the final stage of sintering, where grain growth kinetics become the dominant microstructural process.

A comparative analysis of the samples sintered at 1600 °C highlights the impact of compositional complexity on grain growth. The binary Sm_3NbO_7 and the 2RE ceramics exhibit the coarsest grains, whereas the 4RE sample demonstrates the most pronounced grain refinement. This suppression of grain growth at elevated temperatures further corroborates the sluggish diffusion effect in high-entropy ceramic systems. The multiple rare-earth cations create a complex local environment that hinders long-range diffusion, thereby stabilizing the fine-grained structure even at 1600 °C. However, all compositions achieve a high degree of compactness at this terminal temperature, confirming that 1600 °C is an optimal sintering temperature for achieving dense RE_3NbO_7 high-entropy ceramics with controlled microstructural features.

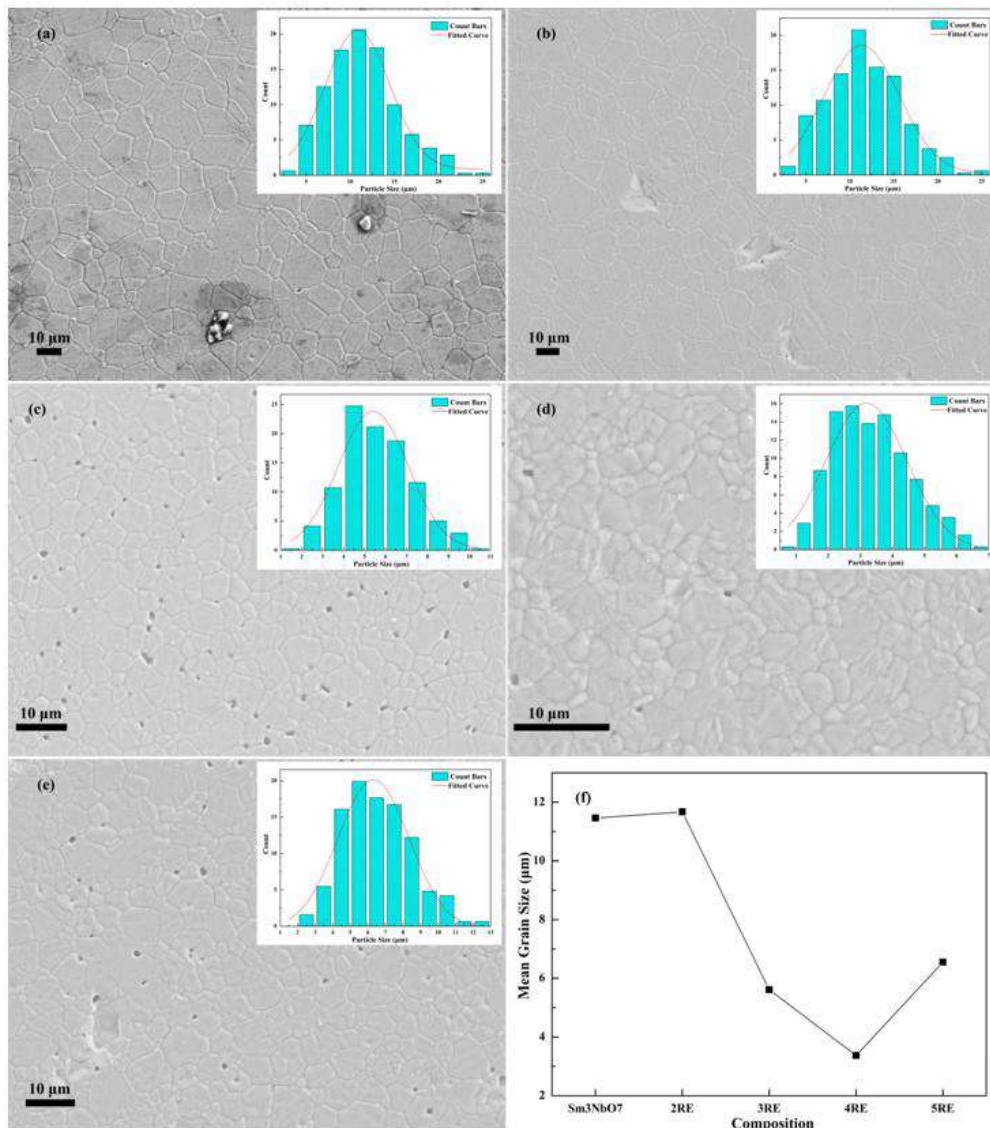


FIGURE 5: Microstructural morphology and grain size analysis of RE_3NbO_7 ceramics: (a–e) SEM images of the samples with corresponding grain size distribution histograms (insets); (f) Variation of the mean grain size as a function of the sample composition.

The surface morphologies and corresponding grain size distributions of the sintered ceramics are illustrated in Figure 5 (a–e). All specimens exhibit a highly densified microstructure characterized by well-defined grain boundaries and predominantly equiaxed grain morphologies. Negligible residual porosity is observed at the triple junctions, indicating that the selected sintering parameters were sufficient for achieving near-theoretical density.

The statistical analysis of grain size, depicted in the inset histograms of Figure 5 (a–e), reveals that the grain populations for all compositions conform well to a Gaussian distribution. For the Sm_3NbO_7 and 2RE samples, the distributions are relatively broad, with grain sizes spanning a wide range from approximately 5 μm to 25 μm. As the configurational entropy increases with the addition of more rare-earth elements, a significant shift in the distribution is observed. In the 3RE and 4RE samples,

the distribution curves markedly narrow and migrate toward the lower end of the scale, representing a high degree of microstructural refinement and homogeneity. However, for the 5RE composition, the distribution breadth slightly increases again, suggesting a moderate variation in grain growth kinetics.

As shown in Figure 5 (f), the average grain size varies significantly with compositional complexity. Compared to the Sm_3NbO_7 reference (11.46 μm), the 2RE composition shows a slight increase, reaching a peak of 11.67 μm . Remarkably, a dramatic non-monotonic reduction in grain size occurs as the system transitions to higher entropy states. The multi-component high-entropy strategy effectively suppresses grain growth compared to the near-single-component references. Among all compositions, the 4RE sample displays the most significant grain refinement, achieving a minimum average grain size of 3.37 μm at 1600 °C. This substantial reduction is a direct manifestation of the sluggish diffusion effect inherent in high-entropy systems. To further elucidate this mechanism, the lattice distortion degree (δ) based on the atomic radii mismatch was considered^[17]. Interestingly, the calculated δ for the 4RE system ($\delta = 1.93\%$) is lower than that of the 2RE system ($\delta = 4.84\%$), yet 4RE exhibits the strongest grain growth inhibition. This anomaly suggests that in the RE_3NbO_7 weberite framework, kinetic retardation is driven less by simple ionic radius mismatch and more by the intense chemical disorder and the cocktail effect of the four equimolar cations (Nd, Sm, Eu, Gd). The uniform distribution of chemically distinct cations maximizes the fluctuation of local bonding energies, thereby significantly elevating the activation energy barrier for grain boundary migration^[18].

In the 5RE composition, the grain size undergoes a moderate recovery to 6.55 μm , although it remains considerably finer than that of the Sm_3NbO_7 reference. This microstructural recovery can be fundamentally ascribed to an intricate interplay between the entropy-induced kinetic retardation and localized perturbations in atomic mobility. The introduction of the larger La^{3+} cation in the 5RE system increases the unit cell volume which may partially alleviate local strain fields or alter the defect chemistry, thereby slightly lowering the energy barrier for atomic diffusion compared to the more compactly disordered 4RE lattice^[19]. Furthermore, this phenomenon underscores that microstructural evolution during high-temperature sintering is not exclusively dictated by macroscopic configurational entropy. The intrinsic physicochemical properties of the constituent elements, such as variations in metal-oxygen bond strength, intrinsic atomic diffusivity, and surface energy among the diverse RE^{3+} cations, play a critical role in governing local mass transport. Consequently, the specific elemental characteristics within the 5RE system may introduce localized diffusion pathways that partially offset the entropy-driven kinetic retardation. These results demonstrate the efficacy of the high-entropy effect in suppressing grain coarsening while maintaining high density, providing critical insights for the microstructural engineering of advanced rare-earth niobate ceramics.

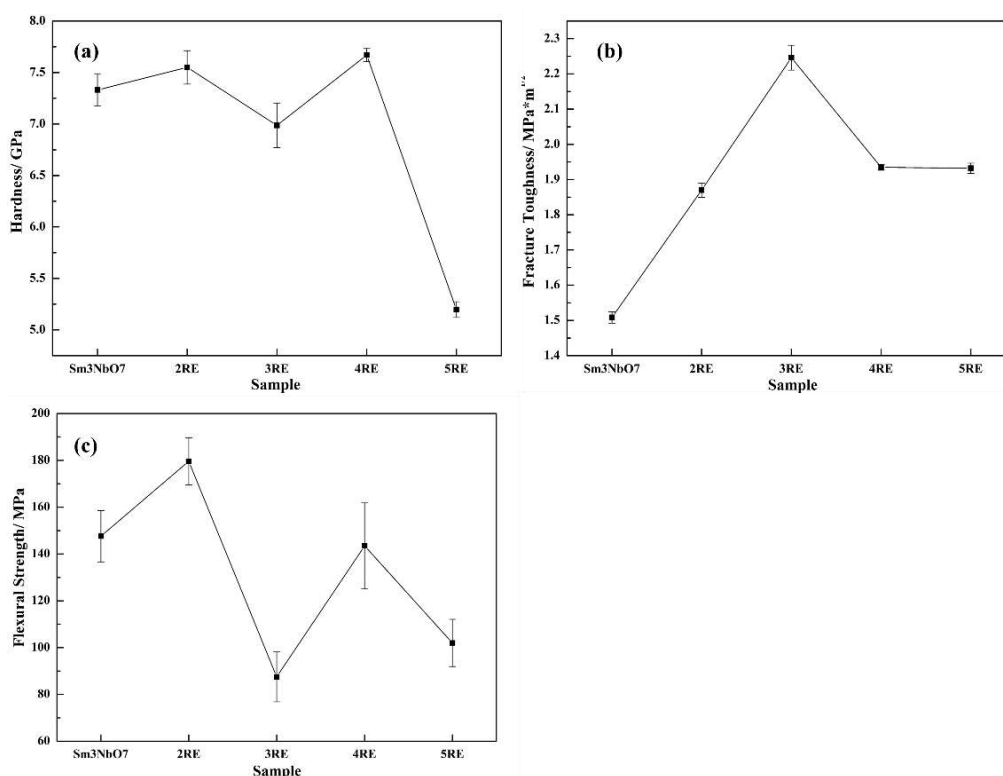


FIGURE 6: Mechanical properties of the RE_3NbO_7 ceramics sintered at 1600 °C as a function of the sample composition: (a) Vickers hardness; (b) Flexural strength; and (c) Fracture toughness

The mechanical properties of the sintered RE₃NbO₇ ceramics, including Vickers hardness, fracture toughness, and flexural strength, are illustrated in Figure 6. The results demonstrate a complex dependence of mechanical performance on the configurational entropy and compositional complexity of the rare-earth sublattice.

The Vickers hardness of the specimens as a function of composition is presented in Figure 6 (a). The hardness of the base Sm₃NbO₇ sample is 7.33 ± 0.15 GPa. With the initial substitution of rare-earth elements, the hardness increases to a peak value of 7.67 ± 0.05 GPa for the 4RE composition. This enhancement is primarily attributed to solid solution strengthening and the high-entropy effect, where the significant atomic size mismatch between the various rare-earth cations induces localized lattice strain, effectively pinning dislocations and resisting plastic deformation during indentation. Notably, a precipitous decline to 5.20 ± 0.06 GPa is observed for the 5RE sample. Such a sharp decrease suggests that excessive lattice distortion or a potential transition in the chemical bonding environment may lead to a reduction in the cohesive energy of the lattice, thereby compromising the intrinsic hardness^[20, 21].

The variation in fracture toughness is shown in Figure 6 (b). A clear upward trend is observed from the Sm₃NbO₇ sample (1.51 ± 0.02 MPa·m^{1/2}) to the 3RE sample, which achieves a maximum toughness of 2.25 ± 0.03 MPa·m^{1/2}. This represents a substantial enhancement of approximately 49% compared to the binary counterpart. This toughening behavior is closely correlated with the microstructural refinement observed in the SEM analysis; the significantly reduced grain size in the multi-component systems increases the grain boundary density, promoting energy-dissipating mechanisms such as crack deflection and crack branching^[22]. For the 4RE and 5RE samples, the toughness stabilizes at approximately 1.93 MPa·m^{1/2}, indicating that the toughening effect reaches a plateau as the grain size and lattice strain reach a critical balance.

Figure 6 (c) depicts the flexural strength of the ceramics. The strength exhibits a non-monotonic evolution, reaching its maximum in the 2RE composition (180 ± 10 MPa). A distinct dip is observed for the 3RE sample (87 ± 11 MPa), followed by a recovery in the 4RE sample (144 ± 18 MPa). The fluctuations in flexural strength are likely a result of the competition between grain refinement strengthening and the accumulation of internal residual stresses caused by the multi-component substitution^[23]. While the 4RE sample exhibits the finest grain size, the 2RE system appears to maintain a superior balance between microstructural homogeneity and minimized lattice-induced micro-strains, resulting in the highest load-bearing capacity before catastrophic failure. The relatively small error bars across the measurements confirm the high densification and phase uniformity achieved during the sintering process.

IV. CONCLUSION

In summary, this study systematically investigated the influence of rare-earth (RE) site compositional complexity on the phase stability and microstructural evolution of RE₃NbO₇ ceramics

1. All synthesized compositions formed phase-pure orthorhombic structures and achieved high relative densities exceeding 98% at 1600 °C, with the 2RE sample exhibiting the highest densification rate.
2. Increasing the configurational entropy exerted a profound, non-monotonic suppression on grain growth. The 4RE composition exhibited the most significant grain refinement, achieving a minimum average grain size of $3.37 \mu\text{m}$, a substantial reduction compared to the Sm₃NbO₇ ($11.46 \mu\text{m}$)
3. This deep suppression is attributed to the sluggish diffusion effect and chemical disorder induced by the multi-cation framework. Although a moderate size recovery ($6.55 \mu\text{m}$) was observed in the 5RE system due to competitive lattice strain, it remained considerably finer than the low-entropy reference.
4. The mechanical properties of RE₃NbO₇ ceramics are significantly modulated by compositional complexity. Specifically, the 4RE composition maximizes Vickers hardness at 7.67 GPa through solid solution strengthening, while the 3RE sample achieves peak fracture toughness (2.25 MPa·m^{1/2}, a 49% increase) via grain refinement and crack deflection. Conversely, the 2RE system exhibits the highest flexural strength (180 MPa), attributed to an optimal balance between microstructural homogeneity and minimized lattice micro-strain.

These findings demonstrate that strategically tailoring RE-site complexity is a highly effective approach for decoupling densification from grain growth, offering a robust kinetic framework for the microstructural engineering of advanced niobate ceramics.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

- [1] Chen, L., Hu, M., Wu, P., & Feng, J. (2019). Thermo-mechanical properties of fluorite Yb_3TaO_7 and Yb_3NbO_7 ceramics with glass-like thermal conductivity.
- [2] Hinatsu, Y., & Doi, Y. (2017). Studies on phase transition temperature of rare earth niobates Ln_3NbO_7 ($\text{Ln} = \text{Pr}, \text{Sm}, \text{Eu}$) with orthorhombic fluorite-related structure.
- [3] Chen, L., Hu, M., Wu, P., & Feng, J. (2020). Features of crystal structures and thermo-mechanical properties of weberites RE_3NbO_7 ($\text{RE} = \text{La}, \text{Nd}, \text{Sm}, \text{Eu}, \text{Gd}$) ceramics.
- [4] Chen, L., Song, P., & Feng, J. (2018). Potential thermal barrier coating materials: RE_3NbO_7 ($\text{RE} = \text{La}, \text{Nd}, \text{Sm}, \text{Eu}, \text{Gd}, \text{Dy}$) ceramics.
- [5] Yang, J., Qian, X., Pan, W., & Wan, C. (2019). Mechanical properties, oxygen barrier property, and chemical stability of RE_3NbO_7 for thermal barrier coating.
- [6] Xiang, H., Xing, Y., Dai, F., Wang, H., Su, L., Miao, L., Zhang, G., Wang, Y., Qi, X., Yao, L., & Zhou, Y. (2021). High-entropy ceramics: Present status, challenges, and a look forward.
- [7] Zhu, J., Meng, X., Xu, J., Ma, Y., & Zhang, P. (2021). Ultra-low thermal conductivity and enhanced mechanical properties of high-entropy rare earth niobates (RE_3NbO_7 , $\text{RE} = \text{Dy}, \text{Y}, \text{Ho}, \text{Er}, \text{Yb}$).
- [8] Ma, X., Liu, Y., & Wen, W. (2025). Thermophysical properties and CMAS corrosion behavior of high-entropy RE_3NbO_7 -type rare-earth niobate ceramic.
- [9] Chen, F., Wang, H., Li, Y., & Liu, Y. (2025). Structural and magnetic characterization of weberite-type RE_3NbO_7 ($\text{RE} = \text{Gd}, \text{Dy}, \text{Ho}$, and Er) ceramics with notable cryogenic magnetocaloric responses.
- [10] Cao, J., Liu, X., Wang, Y., & Chen, L. (2024). Synthesis and thermal behavior of rare-earth-niobate ceramics with fluorite structure.
- [11] Xiang, S., Li, Z., Zhao, Y., & Zhang, H. (2026). Thermophysical and mechanical modulation of RE_3NbO_7 ceramics via compositional entropy design.
- [12] Bao, J., Zhang, Z., Li, E., & Yue, Z. (2022). Crystal structures, bond characteristics, and dielectric properties of novel middle- ϵ_r Ln_3NbO_7 ($\text{Ln} = \text{Nd}, \text{Sm}$) microwave dielectric ceramics with opposite temperature coefficients.
- [13] Yang, X., Liu, B., & Wang, H. (2025). Preparation and properties of high-entropy rare earth niobate LnNbO_4 microwave dielectric ceramics.
- [14] Imer, M. R., Suescun, L., & Rabuffetti, F. A. (2023). A small-box approach to the local crystal structure of Y_3NbO_7 .
- [15] Liu, L., Xu, D., Zhang, H., & Li, E. (2021). Eu_3NbO_7 : Novel middle-dielectric constant microwave dielectric ceramic with monoclinic structure.
- [16] Qin, M., Gild, J., Wang, H., & Luo, J. (2022). 21-Component compositionally complex ceramics: Discovery of ultrahigh-entropy weberite and fergusonite phases and a pyrochlore-weberite transition.
- [17] Zhu, J., Gao, S., Liu, J., & Yang, G. (2021). Enhanced mechanical and thermal properties of ferroelastic high-entropy rare-earth-niobates.
- [18] Zhang, W., Chen, L., & Xu, C. (2022). Grain growth kinetics and densification mechanism of $(\text{TiZrHfVNbTa})\text{C}$ high-entropy ceramic under pressureless sintering.
- [19] Zhou, L., Li, F., Liu, J. X., & Zhang, G. J. (2023). Fast grain growth phenomenon in high-entropy ceramics: A case study in rare-earth hexaaluminates.
- [20] Brewer, L. (1977). The cohesive energies of the elements.
- [21] Yao, G., Liu, J. X., Xu, Q., & Zhang, G. J. (2022). Local orders, lattice distortions, and electronic structure dominated mechanical properties of $(\text{ZrHfTaM}_1\text{M}_2)\text{C}$ ($\text{M} = \text{Nb}, \text{Ti}, \text{V}$).
- [22] Han, Y., Liang, B., Lu, Y., & Wang, Y. (2022). In-situ synthesis of gadolinium niobate quasi-binary composites with balanced mechanical and thermal properties for thermal barrier coatings.
- [23] Hassan, R., & [Additional authors if available]. (2025). Flexural strength of $(\text{Hf}, \text{Nb}, \text{Ta}, \text{Ti}, \text{Zr})\text{B}_2$ - $(\text{Hf}, \text{Nb}, \text{Ta}, \text{Ti}, \text{Zr})\text{C}$ high-entropy dual-phase ceramics.



IJOER
ENGINEERING JOURNAL

International Journal of Engineering Research and Science



Published by
AD Publications

Contact us



+91-7665235235



www.ijoer.com



info@ijoer.com