Numerical Investigation of Fourth-Order Boundary Value Problems Using the Finite Difference Method

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ABSTRACT

In this work, the finite difference method (FDM) is applied to derive numerical approximations for fourth-order boundary value problems (BVPs) governed by linear ordinary differential equations (LODEs). To assess the effectiveness of the proposed approach, the numerical results are compared with known exact solutions. The computations are carried out using various step sizes, and the findings demonstrate that the method provides highly accurate results. Enhanced accuracy is achieved by adopting sufficiently small step sizes. Furthermore, the numerical errors corresponding to different step sizes are thoroughly analyzed. Several examples are included to effectively demonstrate the accuracy and performance of the proposed finite difference method (FDM).

Keywords: Finite difference method, boundary value problem, mathematical discretization, convergence analysis.

1.0 INTRODUCTION

The finite difference method (FDM) has emerged as an effective numerical approach for solving boundary value problems (BVPs) involving linear and nonlinear ordinary differential equations (ODEs), which frequently arise in science and engineering. Many fundamental principles in physics, chemistry, economics, and statistics can be formulated as boundary value problems. These problems are also widely used in engineering and materials science to describe complex systems and processes. In practical applications, finding exact solutions to BVPs is often difficult due to the complexity of the equations involved. While a few boundary value problems allow for analytical solutions, most require numerical techniques to obtain approximate results. Among these methods, the finite difference method is known for its simplicity, accuracy, and ease of implementation. Over the past several decades, finite difference, finite element, and integral equation methods have been the most commonly used approaches for numerically solving differential equations. Of these, the finite difference method remains particularly popular for its efficiency and suitability for a wide range of problems. This study introduces the formulation and implementation of the finite difference method as a numerical approach for solving fourth order boundary value problems. To demonstrate its effectiveness, two illustrative examples are provided. The method's accuracy is supported by numerical results, error estimates, and graphical representations. Several studies have addressed similar problems using different numerical techniques. Variational iteration, Adomian decomposition, homotopy perturbation, and B-spline methods have been applied to obtain approximate solutions for higher-order BVPs.

Numerous researchers have made significant contributions to the development of numerical methods for solving fourth-order boundary value problems. Notable works include those by Noor and Mohyud-Din (2007), Hashim (2006), Pandey (2013), Salama and Mansour (2005), Wang and Guo (2008), Dang and Luan (2010), Momani and Moadi (2006), Mohyud-Din and Noor (2007), Liang and Jeffrey (2009), Momani and Noor (2007), Xu (2009), and Al-Hayani and Casasús (2005). Further advancements in the field are reflected in subsequent studies by Inc and Cherruault (2005), Noor and Mohyud-Din (2009), Ertürk and Momani (2007), Wazwaz (2002), and Bai et al. (2020), as well as recent contributions by Rao and Jonnalagadda (2024), Dimitrov and Jonnalagadda (2024), Mehrpouya et al. (2024), and Zhang et al. (2022), which employ innovative analytical and numerical techniques to enhance the accuracy and applicability of solutions in increasingly complex scenarios. In this study, the finite difference method is used to solve linear BVPs and is validated through practical examples. The numerical results demonstrate high accuracy and convergence, especially as the step size becomes smaller. The findings confirm that the method is a powerful tool for solving fourth-order linear boundary value problems in scientific and engineering contexts.

This paper is organized to ensure clarity and logical flow. Section 2.0 outlines the mathematical formulation and discretization of the boundary value problem (BVP) using the finite difference method. Section 3.0 presents a comprehensive convergence analysis of the proposed numerical approach. Section 4.0 presents numerical examples that serve to confirm the precision and effectiveness of the proposed method. In Section 5.0, the outcomes are analyzed and their significance is explored. The paper concludes in Section 6.0 with a concise overview of the key results and insights gained from the study.

1.1 Mathematical discretization of the BVP

The primary objective of this paper is to investigate linear ordinary differential equations subject to boundary conditions. Finite difference methods serve as effective numerical tools for solving such boundary value problems by replacing the differential equations with discrete difference equations through mathematical discretization. To demonstrate the fundamental concepts and application of the finite difference technique, we focus on a general fourth-order linear boundary value problem (BVP) expressed in the form:

$$p(x)y^{(iv)} + q(x)y''' + r(x)y'' + s(x)y' + t(x)y = f\,(x) \quad (1)$$

with boundary conditions:

$$y(a) = \alpha_0, y(b) = \beta_0, y'(a) = \alpha_1, y'(b) = \beta_1$$

or,

$$y(a) = \alpha_0, y(b) = \beta_0, y''(a) = \alpha_2, y''(b) = \beta_2$$

Let f be a continuous function on the interval $[a, b]$ and let α_i and β_i,(for $i = 0, 1, 2$) be real constants. Consider a regular partition of the interval $[a, b]$ such that $a = x_0 \le x_1 \le x_3 \ldots \le x_{n-1} \le x_n = b$ where $x_i = a + ih$; $i = 0, 1, 2, \ldots, n$ and $h = \frac{b-a}{n}$. The points $x_1 = a + h,\ x_2 = x_1 + h \ldots, x_n = x_{n-1} + h$ are referred to as the interior mesh points of the interval $a \le x \le b$. To obtain numerical approximations, we define

$$y_i = y(x_i); p_i = p(x_i);\ q_i = q(x_i);\ r_i = r(x_i); s_i = s(x_i); t_i = t(x_i);\ f_i = f(x_i)$$

We now apply second-order central difference formulas to approximate the first four derivatives of $y(x)$, as described below:

$$y'(x) \approx \frac{y_{i+1} - y_{i-1}}{2h}, y'' \approx \frac{y_{i+1} - 2y_i + y_{i-1}}{h^2}$$

$$y''' \approx \frac{y_{i+2} - 2y_{i+1} + 2y_{i-1} - y_{i-2}}{2h^3}$$

$$y'''' \approx \frac{y_{i+2} + 4y_{i+1} + 6y_i - 4y_{i-1} + y_{i-2}}{h^4}$$

In this method, the derivatives appearing in the differential equation and boundary conditions are approximated using finite difference schemes. This process transforms the original problem into a system of linear algebraic equations, which is then solved using standard numerical techniques. The computed solutions provide approximate values of the unknown function at the selected discrete grid points within the domain.

2.0 CONVERGENCE ANALYSIS

The accuracy of a numerical solution can be enhanced by choosing a sufficiently small step size h. In the finite difference method, the precision of solving boundary value problems is highly dependent on this step size. A numerical solution $y(x_n)$ is said to converge to the exact solution y_n if, for any given $\delta > 0$, there exists a sufficiently large positive integer N such that, $|\ y(x_n) - y_n\ | < \delta$ for all for all $n \ge N$. In this study, two linear boundary value problems are examined to evaluate the accuracy of the proposed finite challenges despite the material's strong electrochemical properties and ease of synthesis. Furthermore, LCO faces issues with structural instability and poor interface compatibility, particularly as the energy density of LIBs increases, and undergoes irreversible phase transitions at high potentials. Recent studies have focused on doping or coating LCO to enhance its stability at intense potential, with some works enhancing the discharge capacity of LCO to over 200 mAh/g. Numerous metals such as Al, Cr, Mn, and Fe have been used as dopants or partial substitutes for cobalt, demonstrating improved performance but still with limitations. Coating LCO with metal oxides has shown promise in stabilizing the material during deep cycling by reducing structural changes and minimizing side reactions with the electrolyte. These coatings are generally chosen for their low toxicity and cost-effectiveness. Lithium Nickel Oxide ($LiNiO_2$), with a similar structure to LCO, is an alternative cathode material where cobalt (Co^{3+}) is replaced by nickel (Ni^{3+}). $LiNiO_2$ operates at an average voltage of 4 V, with a specific capacity of 250 mAh/g and an electrode density of at least 3.3 g/cm³. It boasts an outstanding rate capability and is less prone to oxygen evolution(Li et al., 2020). On the other hand, pure $LiNiO_2$ is not a desirable cathode material due to Ni^{2+} ions that tend to replace Li^+ sites during fabrication and delithiation, which hinders lithium diffusion. Additionally, $LiNiO_2$ is thermally less stable than LCO, as Ni^{3+} is more easily reduced than Co^{3+}. The effective use of pure $LiNiO_2$ is limited because factors like restricted voltage cut-offs, incomplete rhombohedral phase reversibility, poor thermal stability, and lithium deficiency degrade its electrochemical performance. While $LiNiO_2$ was initially considered a promising alternative to LCO, its poor cycle life and stability problems prevent it from being suitable for current applications. Efforts have been made to address these issues by partially substituting other metals, in particular nickel, manganese, and aluminum, in $LiNiO_2$ to improve its electrochemical properties and overall performance (Jyoti et al., 2021).

5.1.2 Lithium Nickel Oxide (LNO)

Dyer et al. were the first to report using LNO as a cathode material, which was seen as a more favorable alternative to LCO due to its lower toxicity and cost (Liu et al., 2025). $LiNiO_2$ has a structure similar to LCO, with cobalt (Co^{3+}) replaced by nickel (Ni^{3+}). As a cathode material, $LiNiO_2$ operates at an average voltage of 4 V, has a specific capacity of 250 mAh/g, and an electrode density of at least 3.3 g/cm³(Assat & Tarascon, 2018). The $LiNiO_2$ cathode in LIBs has rhombohedral layered structures, with the basic formula $Li_{1-x}Ni_{1+x}O_2$, where x ranges from 0.05 to 0.20. $LiNiO_2$ displays remarkable rate capability and is less prone to oxygen evolution. Though pure $LiNiO_2$ is not ideal due to Ni^{2+} ions that tend to replace Li^+ sites during fabrication and delithiation, hindering lithium diffusion. Additionally, $LiNiO_2$ is thermally less stable than LCO because Ni^{3+} is more easily reduced than Co^{3+}. The workable use of pure $LiNiO_2$ is limited by multiple factors, including restrictive cut-off voltages, irreversible rhombohedral phase transition, and poor thermal stability. Furthermore, pure $LiNiO_2$ suffers from significant lithium deficiency and cation disorder, which deteriorates its electrochemical performance. These issues, particularly safety concerns due to the breakdown of cathode materials after exothermic oxidation of the electrolyte, prevent the exclusive commercialization of pure $LiNiO_2$ cathodes. Although $LiNiO_2$ was initially considered a more effective substitute for $LiCoO_2$, its short cycle life and stability issues remain major challenges. As a result, $LiNiO_2$ is not currently a compatible cathode material for LIBs. Efforts to conquer these problems include partially substituting other metals, such as nickel, manganese, and aluminum, for cobalt to increase the electrochemical performance of $LiNiO_2$.

5.1.3 Lithium Manganese Oxides (LMO)

Other layered oxide materials, such as $LiMnO_2$, have been widely studied owing to manganese's lower cost and toxicity compared to other materials. The structure of LMO is more intricate than that of $LiCoO_2$ and $LiNiO_2$. LMO can be synthesized in various forms, with the primary structures being a zigzag-type orthorhombic LMO with Pmnm symmetry and a monoclinic LMO with C/2m symmetry. These structures are electrochemically active and have a theoretical capacity of 285 mAh/g(Nitta et al., 2015). Over the past two decades, efforts have focused on synthesizing anhydrous and stoichiometric LMO to improve properties such as structural instability during cycling, low crystallinity, and stoichiometric variations. However, pure $LiMnO_2$ and $LiNiO_2$ are challenging to synthesize, and their structures are less stable than $LiCoO_2$ during the charging process. The cycling performance of LMO is still suboptimal because of issues such as (i) the tendency of the layered structure to transform into a spinel structure during Li^+-ion extraction, and (ii) the leaching of Mn from LMO during cycling. Although the theoretical capacity of LMO is 285 mAh/g, the practical capacity is only around 200 mAh/g, with a voltage range of 2.5 to 4.3 V. A main disadvantage of LMO is its fast capacity fading, as the material transforms from the spinel structure. This conversion reduces the electrochemical activity of the cathode, as the specific capacity is divided into two voltage domains around 3 V and 4 V vs. Li/Li^+, with phase transitions occurring between these domains. Efforts to stabilize LMO through cationic doping have been attempted both theoretically and experimentally, but these have not significantly improved cycle stability at elevated temperatures. As a result, the widespread commercialization of LMO has been hindered. Recent research has shifted towards exploring other transition metal oxide materials for use in LIBs, such as $LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ (NCM), $LiNi_{0.94}Co_{0.06}O_2$, tungsten-doped $LiNiO_2$, and Ni-enriched layered oxide cathodes.

6.0 TERNARY LITHIUM TRANSITION METAL OXIDES WITH LAYERED STRUCTURES

Ternary cathode materials have been widely studied because of their simple processing, robust operating voltage, excellent energy density, and potential for large-scale commercial manufacturing.

difference method. The approximate solutions are generated using Maple software across various step sizes. When the exact solution is available, the numerical error is quantified by the expression $|\, y(x_n) - y_n \,|$.

3.0 NUMERICAL APPLICATION EXAMPLES

In this study, we examine two linear boundary value problems to validate the effectiveness of the proposed finite difference method. The corresponding numerical results are computed and the associated errors are illustrated through graphical representations.

Example 01: We investigate the fourth order linear boundary value problem $y^{iv}(x) + 10x = 0$ defined on the interval $0 \le x \le 1$ subject to the boundary conditions $y(0) = 2, y(1) = 2, y'(0) = 2, y'(1) = 2$. The exact solution to this problem is $y(x) = -\frac{1}{12}x^5 + \frac{17}{4}x^3 - \frac{37}{6}x^2 + 2x + 2$.

Numerical results obtained using the finite difference method are presented in Table 01, while the corresponding error graphs of the numerical solutions are shown in Figure 01.

Table 01: Computed numerical results for Example 1.

x_n	step size $h = 0.1$	step size $h = 0.05$	y_n
	$y(x_n)$	$y(x_n)$	
0.1	2.139502206	2.141802219	2.142582500
0.2	2.183032941	2.186224622	2.187306667
0.3	2.155516324	2.158527790	2.159547500
0.4	2.081676471	2.083772307	2.084480000
0.5	1.985937500	1.986718748	1.986979166
0.6	1.892323529	1.891727691	1.891520000
0.7	1.824358676	1.822659709	1.822077500
0.8	1.804967059	1.802775382	1.802026666
0.9	1.856372794	1.854635283	1.854042500
1.0	2.000000000	2.000000000	2.000000000

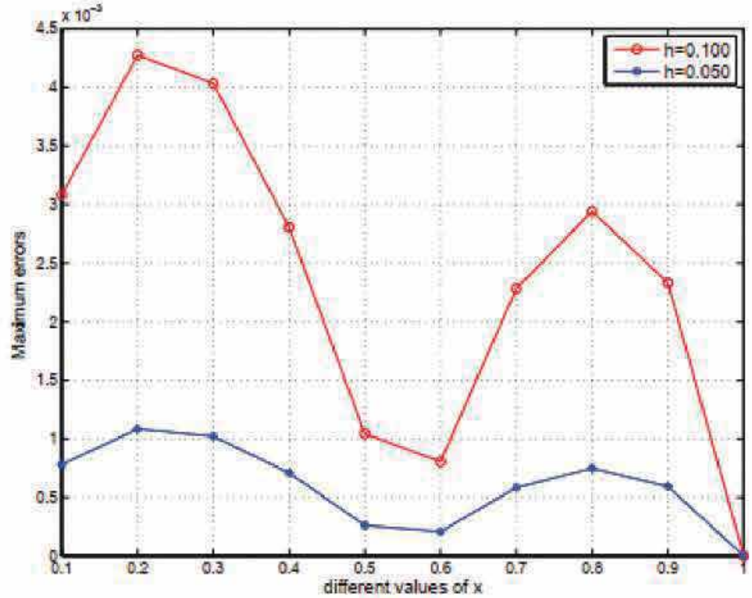

Figure 01: Errors for different step sizes of h.

From Figure 01, the graph illustrates the variation of maximum errors at different values of x using the Finite Difference Method (FDM) for two step sizes, $h = 0.100$ and $h = 0.050$. It clearly shows that the numerical solution becomes more accurate as the step size decreases, with the error significantly reduced for $h = 0.050$ compared to $h = 0.100$. This behavior confirms the convergence property of the FDM, where a finer discretization leads to improved accuracy. The fluctuations in error across the domain indicate that certain regions may be more sensitive to discretization, possibly due to higher curvature or boundary effects. Overall, Fig. 1 demonstrates that FDM provides reliable approximations, and reducing the step size enhances the precision of the solution.

Example 02: We investigate the fourth order linear boundary value problem $y^{iv}(x) + y''(x) = x$ defined on the interval $0 \leq x \leq 1$ subject to the boundary conditions $y(0) = 1, y(1) = 1, y''(0) = 1, y''(1) = 1$. The exact solution is $y(x) = sin(x)cot(1) - cos(x) + \frac{1}{6}x^3 - \frac{7}{6}x^3 + \frac{7}{6}x + 2$.

Numerical results obtained using the finite difference method are presented in Table 02, while the corresponding error graphs of the numerical solutions are shown in Figure 02.

Table 02: Computed numerical results for Example 2.

x_n	step size $h = 0.1$	step size $h = 0.05$	y_n
	$y(x_n)$	$y(x_n)$	
0.1	0.9525701011	0.9525912493	0.9525981347
0.2	0.9154495023	0.9154857614	0.9154975324
0.3	0.8888544123	0.8889000715	0.8889148536
0.4	0.8729157842	0.8729655687	0.8729816482
0.5	0.8676880060	0.8677371801	0.8677530363
0.6	0.8731583569	0.8732028221	0.8732171479
0.7	0.8892571326	0.8892935148	0.8893052331
0.8	0.9158683436	0.9158940575	0.9159023401
0.9	0.9528408757	0.9528541728	0.9528584566
1.0	1.0000000000	1.0000000000	1.0000000000

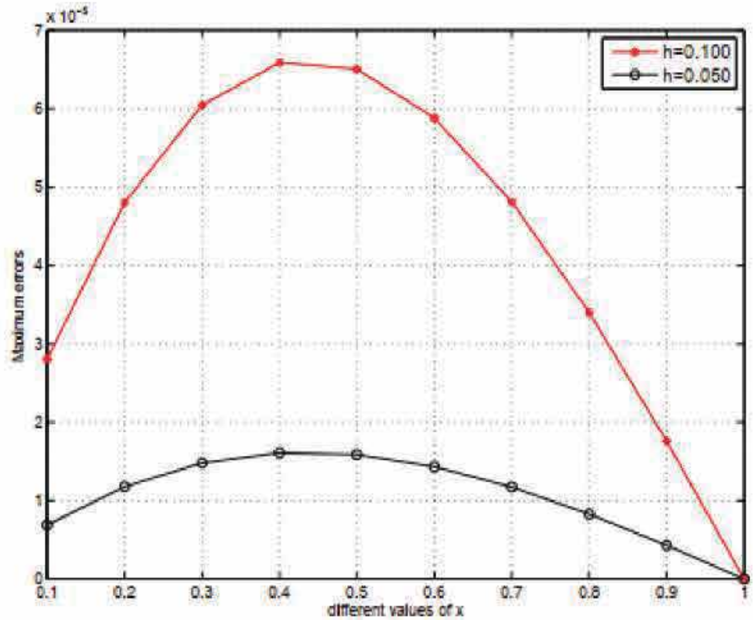

Figure 02: Errors for different step sizes of h.

From Fig. 2, the graph presents the maximum errors at various values of x for two different step sizes, $h = 0.100$ and $h = 0.050$, using the Finite Difference Method (FDM). The red curve, corresponding to the coarser step size $h = 0.100$, exhibits significantly higher errors than the black curve for $h = 0.050$, confirming that smaller step sizes yield more accurate results. The error for $h = 0.100$ peaks around the midpoint of the domain, while for $h = 0.050$, the error remains relatively low and smooth throughout. This figure clearly demonstrates the convergence behavior of FDM reducing the step size improves the numerical approximation by minimizing the discretization error.

4.0 DISCUSSION OF RESULTS

The results of the proposed method are presented in Table 01 and Table 02, with corresponding graphical illustrations in Figures 01 and 02. The approximate solutions were computed using step sizes of 0.10 and 0.05, and the maximum errors were evaluated for each case. It is evident that achieving more accurate approximations requires a greater number of smaller step sizes. The proposed finite difference method demonstrates strong agreement with the exact solution, indicating its effectiveness. As the step size h approaches zero, the numerical solution obtained through the developed algorithm converges closely to the exact solution.

5.0 CONCLUSION

In this study, we have developed and implemented the finite difference method (FDM) to solve boundary value problems involving linear ordinary differential equations. The effectiveness and reliability of the proposed numerical approach are illustrated through several example problems. The obtained results confirm both the convergence and stability of the method. As shown in Table 01 and Table 02, the accuracy of the solutions improves as the step size decreases. These findings highlight the finite difference method as a robust and efficient tool for obtaining numerical solutions to fourth-order linear boundary value problems (LBVPs).

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International Labor Migration and Economic Development in Bangladesh: Evidence from an ARDL Analysis

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ABSTRACT

Migration is occurring continuously on a global scale. Numerous individuals migrate to improve their quality of life and seek superior career prospects in the global labor market, thereby impacting a nation's economic growth in various ways. This study employs the ARDL bounds testing methodology to examine the long-term relationship among international labor migration, remittance inflows, and economic development in Bangladesh. The research demonstrates a significant long-term association among GDP, remittances, and gross capital formation, utilizing secondary time series data from 1994 to 2021. The findings indicate that alleviation of poverty and economic advancement are fundamentally reliant on remittances. The research recommends enhancing labor migration rules and training programs to capitalize on remittance opportunities. This study addresses a significant gap in the existing literature and offers policy-relevant insights for the sustainable economic development of Bangladesh.

Keywords: Bangladesh Economic Development; ARDL Approach; GDP; Labor Migration; Remittance

1.0 INTRODUCTION

In 2017, nearly 258 million international migrants were anticipated (Rubinskaya, 2023), indicating that international labour migration is a growing global phenomenon. Globalisation, demographic shifts, and economic disparities all contribute to this trend (Fayzullayev & Khalid, 2024). In 2020, international migrants constituted 3.6% of the global population, the highest proportion in three decades (Tomoiagă, 2024). In 2018, remittances totalled $689 billion, with $518 billion directed to developing countries, indicating significant economic impacts of migration (Rubinskaya, 2023). The ongoing refugee crisis in the Middle East and North Africa exacerbates migration pressures. Policymakers grapple with managing the intricacies of migration as it continually shapes global economies and societies. A comprehensive approach is necessary to tackle the complex nature of international labour migration (Fayzullayev & Khalid, 2024), and destination countries must enact policies that promote migrant integration and regulate the labour market (Tomoiagă, 2024).

The fundamental motivation behind international migration, whether temporary or permanent, is to enhance the quality of life. In low- and middle-income countries, remittances sent by migrant workers have become a critical economic lifeline. As Plaza et al. (2019) note, remittances now surpass official development assistance (ODA) and portfolio investments as the largest source of foreign currency earnings in these nations. According to the World Bank (2024), the number of people living outside their country of origin rose significantly from 173 million in 2000 to approximately 281 million in 2023. Correspondingly, remittance flows surged to an estimated $656 billion in 2023, underscoring their importance as a major external financing source.

Surpassing official development assistance and portfolio investments, remittances have emerged as a crucial source of external funding for developing countries (Čakajac et al., 2024). Variations in GDP growth rates between origin and destination countries, educational attainment, and trade openness (Yoshino et al., 2020) influence remittance flows. While remittances primarily alleviate poverty, "green remittances" directed towards renewable energy and climate resilience initiatives could align them with sustainability goals (Mills, 2023). Remittances significantly contribute to financial development, as evidenced by a long-run equilibrium relationship with various financial development indicators (Bhattacharya et al., 2018). Remittances exert a greater influence on financial development in developed nations compared to developing ones, highlighting the necessity of enhancing institutional frameworks to augment remittance inflows and, consequently, financial development across countries (Bhattacharya et al., 2018).

In Bangladesh, remittances play a vital role in the national economy. In 2023, the country received over $23 billion in remittances, ranking seventh globally and third in South Asia (IOM, 2024). These inflows have significantly contributed to increasing foreign exchange reserves, boosting national savings, and alleviating poverty. Despite these benefits, remittances also present complex economic implications. While they can contribute to physical and human capital accumulation and enhance total factor productivity (Ratha, 2010), studies suggest they may also reduce labor force participation by acting as a substitute for earned income (Murakami et al., 2021).

Upadhyay (2022) highlights the paradox of labor migration in liberal global economies, where migration is seen less as a path to collective national progress and more as an individual pursuit of economic relief. The consumption-oriented use of remittances, rather than investment in productive assets, limits their developmental impact. Without effective institutional frameworks to channel remittances into income-generating activities, labor migration risks fostering economic dependency and unsustainable consumer behavior.

Empirical evidence on Bangladesh suggests a nuanced relationship between migration, remittances, and economic growth. Using a Vector Error Correction Model (VECM), Laskar et al. (2025) found a significant long-run relationship between remittances and gross domestic product (GDP), confirming the positive contribution of remittances to economic development. However, the study also reported a negative long-run correlation between migration and GDP, indicating potential drawbacks of excessive labor outflow (Rahman, 2023). These findings underline the need for targeted policy interventions to enhance the productive utilization of remittance income and reduce dependency on foreign labor markets.

This study contributes to the ongoing discourse by empirically analyzing the impact of international labor migration and remittance inflows on the economic development of Bangladesh. Utilizing the Autoregressive Distributed Lag (ARDL) bounds testing approach and time series data from 1994 to 2021, the study explores the long-term relationships among GDP, remittances, gross capital formation (GCF), and economic growth. It further disaggregates the impact by analyzing four categories of labor migration—Professional Labor Migration (PLM), Skilled Workforce Migration (SWM), Semi-Skilled Workforce Migration (SSWM), and Unskilled Workforce Migration (USWM)—to offer a comprehensive understanding of how different migrant profiles contribute to or constrain national development.

The general objective is to examine the role of international labor migration in Bangladesh's economic development. Specific objectives are: (a) to give an overview of the international migrants from Bangladesh over a certain period, and; (b) to find out the impact of international labor migration on Bangladesh's economic development.

2.0 LITERATURE REVIEW

Remittances remain a major determinant of the cash flows imported into underdeveloped nations by foreign labor migration, therefore supporting the economy of these countries. Remittances have been a regular source of support for Bangladesh's foreign currency reserves and household incomes. The fact that remittances amounted to around $21.9 billion in 2023 underlines their importance for the national economy.

Remittances, however, have a complicated and many effect on the growth of the economy. While some research point to possible negative effects, others imply that remittances have a favorable correlation with GDP growth. One instance of this would be the discovery via an ARDL model analysis that remittances favorably affect GDP growth in Bangladesh. Conversely, another study applying the ARDL approach found that remittances have a negative effect on economic development; this result reflects the complex character of their influence. Furthermore, raising questions is the use of remittances. Remittance income limits its capacity to assist sustainable economic development since it is more often used for consumption than for investment. Usually, a lot of remittance money is directed towards consumption. This approach, which emphasizes consumption, might not be able to effectively promote long-term development.

Furthermore, exposed by the COVID-19 pandemic were flaws in systems reliant on outgoing remittances. Withers et al. (2022) claim that global crises can significantly affect nations like Bangladesh's remittance flows, therefore affecting their development. This underlines in economic planning the need of diversification and resilience. Government actions must be carried out if we are to fully use remittances' possibilities. Investments in skill development, certification programs, and financial literacy help migrant workers and their families to become more efficient remittance users. If such programs are carried out, remittances might become the engine behind steady economic growth.

This study aims to analyze the intricate effects that international labor migration and remittance inflows have had on Bangladesh's economic development in order to add to the already body of information. By means of the Autoregressive Distributed Lag (ARDL) bounds testing method and time series data covering 1994 to 2021, the study aims to uncover the long-term relationships among gross domestic product (GDP), remittances, gross capital creation (GCF), and economic growth. This study aims to give a thorough knowledge of the ways in which many migrant characteristics affect national growth. Data will be broken out into groups including Professional Labor Migration (PLM), Skilled Workforce Migration (SWM), Semi-Skilled Workforce Migration (SSWM), and Unskilled Workforce Migration (USWM).

3.0 RESEARCH METHODOLOGY

A quantitative research approach was used to conduct the study where secondary data were used to find out the results based on the objectives of the study. EViews 12 Student Version, IBM SPSS Statistics 20 was used to analyze the data. The Augmented Dickey-Fuller (ADF) stationarity test assessed the stationarity of the variables. The ARDL and Bounds test were used for best estimation. VAR Model was adopted with slight changes from Ejaz et al. (2002) and LAWAL et al. (2022) to develop both the aggregated model and disaggregated model.

3.1 Data and Sampling

The study relied on secondary data that covered the period of 28 years from 1994 to 2021, with the bulk of these time series data. In this study the remittance inflows data has been collected from the annual reports of the Bangladesh Bank (the Central Bank of Bangladesh); data related to international labor migration has been collected from the annual reports of the Bureau of Manpower, Employment and Training (BMET); and GDP data has been retrieved from the World Development Indicators. EViews 12 Student Version, and Microsoft Excel was used to analyze the data.

3.2 Methods and Approaches

As the study adopted the data from 1994 to 2021, it is necessary to test the stationarity of the data. So, the Augmented Dickey-Fuller (ADF) stationarity test was used to assess the stationarity of the variables indicated in the research to attain the goal. Pesaran et al. (2001) established the Autoregressive Distributed Lag (ARDL) model which was used to determine the optimal estimation. All the tests and approaches were found to be applied by several researchers to find the co-integration and relationship among such data sets.

3.3 ARDL Model Specification

According to Pesaran et al. (2001), if the dataset's stationarity test shows I(0) and I(1) variables, ARDL and Bounds test would be the best estimate methods. The study specifies ARDL Model as follows:

$$GDPPC_t = \beta_0 + \beta_1 REMIN_t + \beta_2 GCF_t + \beta_3 GDPG_t + \mu_t \quad (1)$$

Here,

GDPPC = Gross Domestic Product per capita which indicates the economic output of the country in million dollars

REMIN = Remittance Inflows in million dollars

GCF = Gross fixed capital formation that indicates the domestic investment in physical capital

GDPG = Growth rate of the Gross Domestic Product in percentage (%).

B_0 = Intercept; β_1, β_2 and β_3 = Elasticity parameters; and μ_t= error term

3.4 VAR Model Specification

This research utilizes a Vector Autoregressive (VAR) model to examine the short-term and dynamic interrelationships among the variables, treating all variables as endogenous. The VAR model illustrates the influence of each variable on itself and on the past values of other variables.

The fundamental framework of the VAR model comprising four variables is delineated as follows:

$$Y_t = A_0 + \sum_{i=1}^{p} A_i y_{t-i} + \mu_t \tag{2}$$

Where,

Y_t = (4×1) vector consisting of [GDPPC, REMIN, GCF, GDPG]

A_0 = a vector of intercept terms

A_i = the coefficient matrices corresponding to each lag i

p = the optimal duration of the lag

μ_t = a vector of white noise error components

Each equation in the VAR model (Equations III–VI) is intended to clarify one variable as a function of the lagged values of all four variables. The GDPPC equation is structured as follows:

$$\text{GDPPC}_t = \beta_0 + \sum_{i=1}^{p} \beta_1^i \text{ GDPPC}_{t-i} + \sum_{i=1}^{p} \beta_2^i \text{ REMIN}_{t-i} + \sum_{i=0}^{p} \beta_3^i \text{ GCF}_{t-i} + \sum_{i=0}^{p} \beta_4^i \text{ GDPG}_{t-i} + \mu_{1t} \tag{3}$$

Similarly,

$$\text{REMIN}_t = \beta_0 + \sum_{i=0}^{p} \beta_1^i \text{ REMIN}_{t-i} + \sum_{i=0}^{p} \beta_2^i \text{ GCF}_{t-i} + \sum_{i=0}^{p} \beta_3^i \text{ GDPPC}_{t-i} + \sum_{i=0}^{p} \beta_4 \text{ GDPG}_{t-i} + \mu_{2t} \tag{4}$$

$$\text{GCF}_t = \beta_0 + \sum_{i=0}^{p} \beta_1^i \text{ GCF}_{t-i} + \sum_{i=0}^{p} \beta_2^i \text{ REMIN}_{t-i} + \sum_{i=0}^{p} \beta_3^i \text{ GDPPC}_{t-i} + \sum_{i=0}^{p} \beta_4^i \text{ GDPG}_{t-1} + \mu_{3t} \tag{5}$$

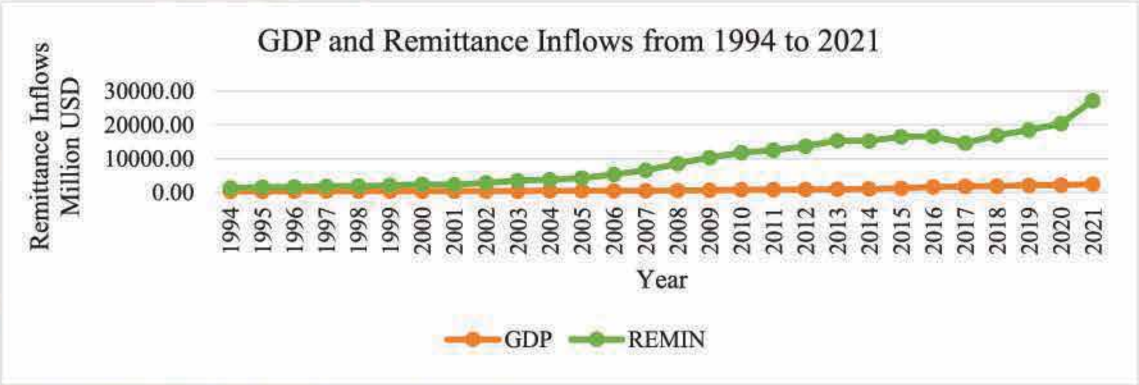
$$\text{GDPG}_t = \beta_0 + \sum_{i=0}^{p} \beta_1^i \text{ GDPG}_{t-i} + \sum_{i=0}^{p} \beta_2^i \text{ REMIN}_{t-i} + \sum_{i=0}^{p} \beta_3^i \text{ GDPPC}_{t-i} + \sum_{i=0}^{p} \beta_4^i \text{ GCF}_{t-i} + \mu_{4t} \tag{6}$$

3.5 Variables

The research is primarily focused on migration remittances inflows, GDP per capita, Gross Capital Formation, and growth rate as its primary variables. The study divided the Workforce Migration into four categories as was also done by Ejaz et al. (2002) and LAWAL et al. (2022) (i) Professional Labor Migration (PLM), (ii) Skilled Workforce Migration (SWM), (iii) Semi-Skilled Workforce Migration (SSWM), and (iv) Unskilled Workforce Migration (USWM) which have been used for descriptive analysis.

4.0 RESULTS AND DISCUSSIONS

Descriptive statistics show a significant growth of remittance in 2020 and 2021, a significant fluctuation of GDP growth over the period of 28 years, and a massive growth of remittance in 2021 which is 36.1% (Figure



1). **Figure 01: GDP and Remittance Inflows from 1994 to 2021**

Source: Author's computation from Bangladesh Bank Data (Annual Reports)

A 28-year log summary of remittances, growth rate, GDP per capita, and gross fixed capital creation. Empirical analysis pre-estimates variables using descriptive statistics. Thus, Log RI (Remittance Inflows Million USD), which measures Bangladeshi migrant remittance from 1994 to 2021, averages $13,678.31 where in 2021 it was a maximum value of $24,777.71 and the lowest one i.e., $1,088.72 in 1994. See Figure 1 to have a clear picture of the Remittance Inflows in Million USD from 1994 to 2021.

The trend of workforce migration shows that the number of Professional workforce and skilled workforce is proportionately lower than the number of semi-skilled and unskilled workers which implies that if the number of professional and skilled workforce can be increased, remittance inflows will also be increased and the GDP will be increased (see Figure 02).

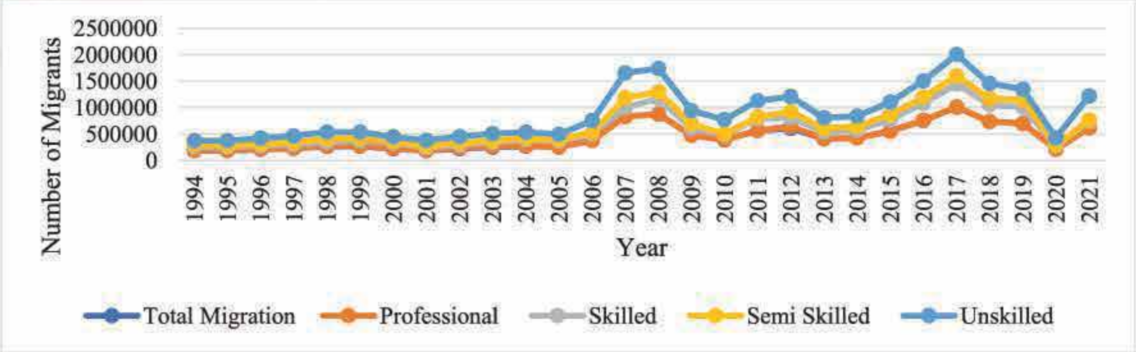


Figure 02: Four categories of Workforce Migration (Professional, Skilled, Semi-skilled, and Unskilled)

Source*: Author's computation based on BMET Data*

Due to COVID-19, in 2020, the flow of overseas remittances on which many South Asian countries rely has hampered significantly (Withers et al., 2022). But the remittance inflows go higher in 2021. However, time series empirical analysis must handle unit roots which bias empirical results. If unresolved, this may affect research outcomes. So, the study validated data stationarity using the Augmented Dickey-Fuller (ADF) test shown in the following table 1.

Tables 01: Unit Root Test: Augmented Dickey-Fuller (ADF)

Unit Root Test: Augmented Dickey-Fuller (ADF)					
Variables	**Level**		**1st Difference**		**Comment**
	a*	**a & c****	**a**	**a & c**	
GDP Per Capita (GDPPC)	1.000	1.000	0.139	0.011	I(1)
GDP Growth Rate (GDPG)	0.029	0.109			I(0)
Gross Capital Formation (GCF)	0.143	0.033			I(0)
Remittance inflows (REMIN)	1.000	0.484	0.513	0.045	I(1)

*a = Intercept, **c = Trend
Source: Author's computation

The Augmented Dickey-Fuller (ADF) test results shows that the GDP Per Capita data are stationary at the first difference; GDP Growth Rate data are stationary at level; Gross Capital Formation data are stationary at level; and finally, remittance inflows data are stationary at first differencing. After the first differencing, all variables except the economic growth rate (GDPG) and Gross Capital Formation (GCF) are stationary at first difference i.e., I (1) and I (0). So, ARDL bound test is appropriate for the study to identify the objectives of the study.

According to Pesaran et al. (2001), if the dataset's stationarity test shows I(0) and I(1) variables, ARDL and Bounds test (Table 01) would be the best estimate methods. The same was done by LAWAL et al. (2022) and Ejaz et al. (2002).

Table 01: ARDL Bound Test

Sample: 1994-2021

Observations: 28

F-Bound Test | Null Hypothesis: No levels relationship exists

Test Statistics	Value	Signif.	I(0)	I(1)
			Asymptotic: n=1000	
F-statistics	17.3807	10%	2.37	3.2
k	3	5%	2.79	3.67
		2.50%	3.15	4.08
		1%	3.65	4.66
Actual Sample Size	23		Finite Sample: n=35	
		10%	2.618	3.532
		5%	3.164	4.194
		1%	4.428	5.816
			Finite Sample: n=30	
		10%	2.676	3.586
		5%	3.272	4.306
		1%	4.614	5.966

Source: Author's computation

A long-term association between migrant remittances and other macroeconomic indicators in Bangladesh was investigated in this research. Since the F-Statistic has a value (F=17.38) that is higher than the value of the upper Critical Value i.e., I(0) = 3.67 and lower Critical Value I(1) = 2.79, Bounds at the 5% significant level, it is possible to conclude that there is a long-run relationship between Bangladesh's GDP, migrant remittances, growth, and GCF. Now, the study examines the Error Correction of the above model in Table 02.

Table 02: ARDL Error Correction Regression

ARDL Error Correction Regression
Dependent Variable: D(GDP)
Selected Model: ARDL (3,2, 4, 4)
Case 2: Restricted Constant and No Trend
Sample: 1994-2021
Included Observations: 23

ECM Regression
Case 2: Restricted Constant and No Trend

Variable	Coefficient	Std. Error	t-Statistic	Prob.
D(GDP(-1))	-1.375225	0.206657	-6.654619	0.0006
D(GDP(-2))	-1.194151	0.15381	-7.763801	0.0002
D(GCF)	-110.61008	11.1483	-9.921766	0.0001
D(GCF(-1))	21.65873	5.302139	4.0848837	0.0065
D(REMIN)	-0.059887	0.005501	-10.88566	0.0000
D(REMIN(-1))	-0.027349	0.004054	-6.746414	0.0005
D(REMIN(-2))	-0.013541	0.003122	-4.336713	0.0049
D(REMIN(-3))	0.100755	0.008473	11.89127	0.0000
D(GDPG)	13.02369	0.43107	30.21691	0.0000
D(GDPG(-1))	-9.382269	1.321755	-7.098343	0.0004
D(GDPG(-2))	-2.241821	0.402574	-5.568724	0.0014
D(GDPG(-3))	-2.402387	0.394854	-6.084238	0.0009
CointEq(-1)*	0.544273	0.045225	12.03491	0.0000

R-squared	0.997066	Mean dependent var	89.38955
Adjusted R-squared	0.993546	S.D. dependent var	95.93505
S.E of regression	7.707038	Akaike info criterion	7.219671
Sum squared resid	593.9844	Schwarz criterion	7.861472
Log-likelihood	-70.02621	Hannan-Quinn criter.	7.381082
Durbin-Watson stat	2.935989		

*p-value incompatible with t-Bounds distribution.

Source: Author's computation

Table 02 shows that for the years 1994 to 2021 in Bangladesh, the ARDL Error Correction Regression results indicate a strong long-term relationship between GDP, remittances, gross capital formation (GCF), and GDP growth. The error correction term (CointEq (-1)) is positive and very significant (0.544, $p < 0.01$), meaning that about 54.4% of the differences from the long-term balance are fixed each year. The error correction term (CointEq (-1)) is positive and very important (0.544, $p < 0.01$), which means that about 54.4% of the differences from the long-term balance are fixed each year, showing a fast adjustment. Short-term changes in GCF and remittances indicate mixed effects: whereas initial changes in GCF severely affect GDP, the lagged value becomes greatly positive, implying delayed investment advantages. Likewise, current remittance inflows have a short-term contractionary effect; nevertheless, their third lag reveals a large positive impact on GDP, suggesting delayed productive use of remittances. Short-term GDP growth helps to increase GDP, although its lagged terms have less effect. The model is robust and well-fitted, with an R-squared value of 0.997 and no hint of autocorrelation (Durbin-Watson stat = 2.93). These results draw attention to the complex and time-dependent contribution remittances and capital building make to Bangladesh's economic growth.

5.0 POLICY IMPLICATIONS

With the strong long-term link between labor migration, remittances, and GDP growth, Bangladesh's government should implement more strategic initiatives to maximize the economic possibilities of labor migration—akin to Thailand's "Thailand 4.0" project meant to change its workforce and economy (Tipayalai, 2020). Coordinating with the Ministry of Labour and Employment, the Ministry of Expatriate Welfare and Overseas Employment should improve the execution and monitoring of the National Policy on Labour Migration. Establishing a dedicated implementation committee and a secretariat to organize events and document advancement using quantifiable criteria helps to enable this. Such projects can be funded from the national budget, overseas development partners, and ILO-style entities. Building on the achievements of past initiatives including the Bangladesh Skills for Employment and Productivity (B-SEP) Project (2013–2019)—a cooperation between the Government of Bangladesh, the Government of Canada, and the ILO—future programs should concentrate on increasing access to quality skill training, especially for aspirant migrant workers. Globally recognized certificates and job-ready competencies will empower the workforce and increase migrant productivity as well as the developmental effect of remittances.

6.0 LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

Although this study provides important insights into the long-term relationship between international labor migration, remittances, and economic development in Bangladesh, several limitations must be considered and opportunities for future research. First, the study only uses secondary time series data from 1994 to 2021. This means that it may not reflect all of the most recent structural changes or the real-time effects of global economic disruptions such as the COVID-19 pandemic, geopolitical shifts, or labor market changes caused by new technologies. Subsequent research may include more recent data or panel datasets that allow for cross-national comparisons, improving the generalizability of the findings. Second, while the ARDL bounds testing method is useful for identifying long-term relationships between variables, it fails to account for the possibility of endogeneity or nonlinear interactions between migration, remittances, and economic development. Advanced econometric models such as vector error correction models (VECM), nonlinear ARDL, and dynamic panel models may help us better understand the situation.

This study focuses primarily on macroeconomic indicators such as GDP and gross capital formation, potentially overlooking the microeconomic effects of remittances on households, such as education, health, and consumption patterns. To investigate the overall welfare implications of remittances, future research should take a mixed-methods approach or use micro-level data analysis. Furthermore, migration is influenced by a variety of social, political, and institutional factors that were not fully explored in this study. Examining the impact of governance quality, diaspora engagement policies, and international labor agreements can help us better understand how policy frameworks influence the remittance-growth relationship.

Finally, while the study suggests changes to migration rules and training programs, it does not test the effectiveness of Bangladesh's current migration management systems. Future research should focus on assessing institutional capacity, identifying implementation gaps, and investigating the roles of private and public stakeholders in promoting safe and productive migration. To summarize, broadening the scope of analysis, using stronger methods, and considering both macro and micro levels will strengthen future research and assist policymakers in making evidence-based decisions to maximize the potential for labor migration and remittances in Bangladesh.

7.0 CONCLUSION

This paper confirms that remittances are a major driver of economic development by establishing a notable long-term link between Bangladesh's GDP, remittances, economic growth, and gross capital creation (GCF). From Bangladesh, approximately 127,000 highly qualified professionals moved overseas in 2021 alone, significantly driving up remittance inflows. Labor migration policies have to be flexible and in line with the needs of the world labor market if we are to maintain and increase this effect. Strategic migration plans can simultaneously solve unemployment and improve foreign exchange reserves considering the sizable unemployed population of the nation. The government should so give migration facilitation tools and skill development top priority. The results of this study provide insightful analysis for legislators trying to maximize the social advantages of labor migration and remittances for the development agenda of Bangladesh.

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