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ON A DISTINCT FAMILY OF ITERATIVE SCHEMES FOR WEAK CONTRACTIONS

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Abstract. This article introduces a distinct collection of fixed point iteration schemes. For this collection, a strong convergence result is established involving weak contractions. Additionally, a comparison result is obtained to compare the speed of convergence of different iterations in the collection. Furthermore, a result comparing some iterations from the collection with several notable and recent iterative schemes from the literature is procured. Finally, these comparisons are elucidated by a non-trivial exemplification, which is represented graphically as well. This family of iterations is conjectured to be the fastest in literature for steps more than three.

Keywords: Weak contractions, O_r-iterations, fixed points, speed of convergence.

AMS Subject Classification: 47H09, 47H10.

1. Introduction

Fixed point theory relies on iterations or algorithms to approximate to the fixed point. A point $c \in \mathcal{V}$ is called a fixed point of a mapping $\mathcal{G} : \mathcal{V} \to \mathcal{V}$ if $\mathcal{G}c = c$. Once this point of a mapping is established to exist, the next step is the approximation of the fixed point. This procedure is followed to approximate solutions of various non-linear problems, [1, 6, 12, 13], for which analytical methods serve to be extremely complex or lead to complete dead ends. Now, in the domain of iterations, it is essential to look for an efficient algorithm to approximate the fixed point of a mapping. The factors that determine an iteration to be efficient are stability, speed of convergence, data dependence and some other related notions.

Over the decades of progress in the field, these factors have been studied for almost every iteration. One may go through [1, 5, 7, 13] and the references therein for literature on stability and data dependence. The remaining factor which is the focus of every iteration is how fast it converges to the fixed point. In other words, with introduction of many other iterations, the main concern is how a particular iteration fares in the speed of convergence

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when compared with other iterations. This concern is one of the reasons that has driven the progress of the field from one stepped iterations to recent four stepped iterations [1, 5, 7, 8, 10, 13].

Addressing this issue of speed of convergence, we propose a family of iterations as follows

$$\begin{cases} s_n^1 = & \mathcal{G}^n((1-\sigma_n^1)\mathcal{G}^n t_n + \sigma_n^1 \mathcal{G}^{n+1} t_n) \\ s_n^2 = & \mathcal{G}^{n+1}((1-\sigma_n^2)\mathcal{G}^{n+1} s_n^1 + \sigma_n^2 \mathcal{G}^{n+2} s_n^1) \\ & \vdots \\ s_n^r = & \mathcal{G}^{n+r-1}((1-\sigma_n^r)\mathcal{G}^{n+r-1} s_n^{r-1} + \sigma_n^r \mathcal{G}^{n+r} s_n^{r-1}) = t_{n+1} \end{cases} \tag{1}$$

where (σ_n^j) are control sequences in $(0,1)$ for $1 \le j \le r$. We refer to this as the O_r family of iterations, so that for each $1 \le m \le r$, O_m denotes an m-stepped iteration derived from (1). We provide a few essential results pertaining to this O_r family. The results, in sequence, are regarding the strong convergence, theoretical comparison of convergence speed within the O_r family and with other notable iterations existing in the literature. Thereafter, we provide numerical experimentation verifying these comparisons in table and graph. Given the structure of the O_r family, it is conjectured to be the fastest iteration scheme in literature for steps more than three.

2. Preliminaries

Throughout the article, $\mathbb{N}$ and $\mathbb{R}$, respectively, have been used as notations for the sets of natural and real numbers.

Definition 2.1. [2] *Assume a Banach space $\mathcal{X}$ and a self-mapping $\mathcal{G}$ defined on it. Then, the self-mapping $\mathcal{G}$ is a weak contraction if*

$$\|\mathcal{G}s - \mathcal{G}t\| \le \zeta \|s-t\| + P\|s - \mathcal{G}t\| \tag{2}$$

holds for all $s, t \in \mathcal{X}$, $\zeta \in (0,1)$ and some constant $P \ge 0$.

Berinde established the following result concerning the existence and uniqueness of a fixed point of a weak contraction.

Theorem 2.1. [2] *Assume a Banach space $\mathcal{X}$ and a self-mapping $\mathcal{G}$ defined on it, which admits Definition 2.1. Further, assume $\mathcal{G}$ satisfies*

$$\|\mathcal{G}s - \mathcal{G}t\| \le \zeta \|s-t\| + P\|s - \mathcal{G}s\|, \tag{3}$$

for all $s, t \in \mathcal{X}$, $\zeta \in (0,1)$ and some constant $P \ge 0$. Then the mapping $\mathcal{G}$ has a unique fixed point in $\mathcal{X}$.

The theoretical means by which the convergence speed of two iterations can be compared, has initially been proposed by Berinde [3, Definition 2.7]. Some authors [9, 11] have expressed their doubts against this method, which has been responded by Berinde in [4]. In their concerns, Phuengrattana and Suantai [9] proposed the following method.

Definition 2.2. [9] *Assume two different iterations such that they generate sequences (t_n) and (s_n). Further, let both of these sequences converge to the same fixed point c. Then (t_n) converges to c faster than (s_n) if*

$$\lim_{n\to\infty} \frac{\|t_n - c\|}{\|s_n - c\|} = 0.$$

However, this method relies on getting the estimate $\|s_n - c\| \ge z_n$, which is not possible for every fixed point iteration. Thus, in the article, the theoretical comparisons between convergence speed of different iterations have been drawn using Berinde's method.

3. Main Results

Theorem 3.1. *Consider a non-empty, closed and convex subset $\mathcal{V}$ of a Banach space $\mathcal{X}$. Further assume $\mathcal{G} : \mathcal{V} \to \mathcal{V}$ is a weak contraction satisfying (3) and (t_n) is a sequence defined by O_r-iteration (1). Then (t_n) exhibits strong convergence to a unique fixed point c of $\mathcal{G}$.*

Proof. From (3), we have

$$\begin{aligned} \|\mathcal{G}t_n - c\| &= \|\mathcal{G}t_n - \mathcal{G}c\| \\ &\leq \zeta \|t_n - c\| + P \|c - \mathcal{G}c\| \\ &= \zeta \|t_n - c\| . \end{aligned} \tag{4}$$

By using (4), we have from iteration (1)

$$\begin{aligned} \left\|s_n^1 - c\right\| &= \left\|\mathcal{G}^n((1-\sigma_n^1)\mathcal{G}^n t_n + \sigma_n^1 \mathcal{G}^{n+1} t_n) - \mathcal{G}c\right\| \\ &\leq \zeta^n \left\|(1-\sigma_n^1)\mathcal{G}^n t_n + \sigma_n^1 \mathcal{G}^{n+1} t_n - \mathcal{G}c\right\| \\ &\leq \zeta^n \left((1-\sigma_n^1)\|\mathcal{G}^n t_n - c\| + \sigma_n^1 \left\|\mathcal{G}^{n+1} t_n - c\right\|\right) \\ &\leq \zeta^n \left((1-\sigma_n^1)\zeta^n \|t_n - c\| + \sigma_n^1 \zeta^{n+1} \|t_n - c\|\right) \\ &= \zeta^{2n}(1-(1-\zeta)\sigma_n^1) \|t_n - c\| . \end{aligned}$$

Due to the pattern of iteration (1), we proceed by employing the same process for the r^{th} step of iteration to have

$$\begin{aligned} \|t_{n+1} - c\| = \|s_n^r - c\| &= \left\|\mathcal{G}^{n+r-1}((1-\sigma_n^r)\mathcal{G}^{n+r-1}s_n^{r-1} + \sigma_n^r \mathcal{G}^{n+r} s_n^{r-1}) - c\right\| \\ &\leq \zeta^{n+r-1} \left\|(1-\sigma_n^r)\mathcal{G}^{n+r-1}s_n^{r-1} + \sigma_n^r \mathcal{G}^{n+r} s_n^{r-1} - c\right\| \\ &\leq \zeta^{n+r-1} \left((1-\sigma_n^r)\left\|\mathcal{G}^{n+r-1}s_n^{r-1} - c\right\| + \sigma_n^r \left\|\mathcal{G}^{n+r} s_n^{r-1} - c\right\|\right) \\ &\leq \zeta^{2(n+r-1)}(1-(1-\zeta)\sigma_n^r) \left\|s_n^{r-1} - c\right\| \\ &\leq \prod_{i=0}^{r-1} \zeta^{2(n+i)} \prod_{j=1}^{r} (1-(1-\zeta)\sigma_n^j) \|t_n - c\| \\ &= \zeta^{r(2n+r-1)} \prod_{j=1}^{r} (1-(1-\zeta)\sigma_n^j) \|t_n - c\| . \end{aligned} \tag{5}$$

Deducing from (5), we have

$$\begin{aligned} \|t_n - c\| &\leq \zeta^{r(2n+r-3)} \prod_{j=1}^{r} (1-(1-\zeta)\sigma_{n-1}^j) \|t_{n-1} - c\| \\ \Rightarrow \|t_{n-1} - c\| &\leq \zeta^{r(2n+r-5)} \prod_{j=1}^{r} (1-(1-\zeta)\sigma_{n-2}^j) \|t_{n-2} - c\| \\ &\vdots \\ \|t_1 - c\| &\leq \zeta^{r(r-1)} \prod_{j=1}^{r} (1-(1-\zeta)\sigma_0^j) \|t_0 - c\| . \end{aligned}$$

Therefore, we inductively have

$$\|t_{n+1} - c\| \leq \zeta^{r(2n+r-1)}\zeta^{r(2n+r-3)} \dots \zeta^{r(r-1)} \prod_{i=0}^{n}\prod_{j=1}^{r}(1-(1-\zeta)\sigma_i^j)\,\|t_0 - c\|$$

$$= \zeta^{(n+1)r(n+r-1)} \prod_{i=0}^{n}\prod_{j=1}^{r}(1-(1-\zeta)\sigma_i^j)\,\|t_0 - c\|\,. \quad (6)$$

Since $\sigma_i^j \in (0,1)$, then $(1-(1-\zeta)\sigma_i^j) < 1$, from (6), we have

$$\|t_{n+1} - c\| \leq \zeta^{(n+1)r(n+r-1)}\,\|t_0 - c\|\,.$$

As $\zeta^{(n+1)r(n+r-1)} < \zeta < 1$, then (t_n) strongly converges to c. □

4. Comparative Analysis

In this section, we first present a result that compares all the iterations in the proposed O_r family as follows.

Theorem 4.1. *Consider a non-empty, closed and convex subset $\mathcal{V}$ of a Banach space $\mathcal{X}$. Further suppose $\mathcal{G} : \mathcal{V} \to \mathcal{V}$ to be a weak contraction satisfying* (3) *and* (k_n) *and* (t_n)*, respectively be the sequences generated by the* $(r+1)$*-stepped* O_{r+1} *and* r*-stepped* O_r *iterations. Also, let the control sequences* (σ_n^j) *satisfy* $0 < \sigma_n^j < 1$*, for all* $1 \leq j \leq r+1$*,* $j \in \mathbb{N}$*. Then the* O_{r+1}*-iteration is faster than the* O_r*-iteration.*

Proof. From (6), the estimate for O_r-iteration is

$$\|t_{n+1} - c\| \leq \zeta^{(n+1)r(n+r-1)} \prod_{i=0}^{n}\prod_{j=1}^{r}(1-(1-\zeta)\sigma_i^j)\,\|t_0 - c\| = x_n. \quad (7)$$

From a process analogous to Theorem 3.1, the estimate for O_{r+1}-iteration is

$$\|k_{n+1} - c\| \leq \zeta^{(n+1)(r+1)(n+r)} \prod_{i=0}^{n}\prod_{j=1}^{r+1}(1-(1-\zeta)\sigma_i^j)\,\|k_0 - c\| = y_n. \quad (8)$$

We assume $t_0 = k_0$ for the sake of comparing the speed of O_r and O_{r+1}. Now, clearly (8) $\leq$ (7). Also, as $\sigma_n^j \in (0,1)$, then $(1-(1-\zeta)\sigma_n^j) < 1$. Thus, we have

$$\begin{aligned} 0 \leq \frac{x_n}{y_n} &= \frac{\zeta^{(n+1)(r+1)(n+r)}}{\zeta^{(n+1)r(n+r-1)}} \prod_{i=0}^{n}(1-(1-\zeta)\sigma_i^{r+1}) \\ &= \zeta^{(n+1)(n+2r)} \prod_{i=0}^{n}(1-(1-\zeta)\sigma_i^{r+1}) \\ &\leq \zeta^{(n+1)(n+2r)}. \end{aligned}$$

Define

$$\chi_n = \zeta^{(n+1)(n+2r)}.$$

Then, we have

$$\frac{\chi_{n+1}}{\chi_n} = \zeta^{2(n+r+1)}.$$

Since $\zeta^{2(n+r+1)} < \zeta < 1$, then by ratio test, we have $\sum_{n=0}^{\infty} \chi_n < \infty$. This implies that $\lim_{n\to\infty} \chi_n = 0$. This further implies that $\lim_{n\to\infty} \frac{\|k_n - c\|}{\|t_n - c\|} = 0$. Therefore O_{r+1}-iteration is faster than O_r-iteration. □

Corollary 4.1. *Any m-stepped O_m-iteration is slower than any r-stepped O_r-iteration if $m < r$.*

For $r = 4$, the following result serves to theoretically compare the speed of O_r-iteration with other notable and recent iterations in literature.

Theorem 4.2. *Consider $\mathcal{V}$ to be a non-empty, closed and convex subset of a Banach space $\mathcal{X}$. Further suppose $\mathcal{G} : \mathcal{V} \to \mathcal{V}$ to be a weak contraction satisfying* (3). *Let (t_n), (f_n), (z_n), (s_n), (p_n), and (w_n), respectively be the sequences defined by O_4, JF, $\mathcal{Z}$, S^*, Picard-SP, and M-Fast iterations. Further assume that the control sequences (σ_n^j) satisfy $0 < \sigma_n^j < 1$, for all $1 \leq j \leq 4$, $j \in \mathbb{N}$. Then O_4-iteration is faster than all the aforementioned iterations.*

Proof. By substituting $r = 4$, the estimate for O_4-iteration can be obtained from (6) as

$$\|t_{n+1} - c\| \leq \zeta^{(n+1)4(n+3)} \prod_{i=0}^{n} \prod_{j=1}^{4} (1 - (1-\zeta)\sigma_i^j) \|t_0 - c\| = x_n. \tag{9}$$

The estimate for JF iteration is obtained by following the same process as

$$\|f_{n+1} - c\| \leq \zeta^{3(n+1)} \prod_{i=0}^{n} (1 - (1-\zeta)\sigma_i^1)(1 - (1-\zeta)\sigma_i^2) \|f_0 - c\| = a_n. \tag{10}$$

The estimates for iterations $\mathcal{Z}$, S^*, Picard-SP, and M-Fast, respectively can be obtained by utilizing the same procedure as

$$\|z_{n+1} - c\| \leq \zeta^{2(n+1)} \prod_{i=0}^{n} (1 - (1-\zeta)\sigma_i^1)(1 - (1-\zeta)\sigma_i^2) \|z_0 - c\| = b_n, \tag{11}$$

$$\|s_{n+1} - c\| \leq \zeta^{4(n+1)} \prod_{i=0}^{n} \prod_{j=1}^{4} (1 - (1-\zeta)\sigma_i^j) \|s_0 - c\| = c_n, \tag{12}$$

$$\|p_{n+1} - c\| \leq \zeta^{(n+1)} \prod_{i=0}^{n} \prod_{j=1}^{3} (1 - (1-\zeta)\sigma_i^j) \|p_0 - c\| = d_n, \tag{13}$$

and

$$\|w_{n+1} - c\| \leq \zeta^{4(n+1)} \prod_{i=0}^{n} \prod_{j=1}^{3} (1 - (1-\zeta)\sigma_i^j) \|w_0 - c\| = e_n. \tag{14}$$

Now, the strong convergence of the sequences generated by the iterations to the fixed point c of $\mathcal{G}$ directly follows from the above given estimates by following the process given in Theorem 3.1.

On the other hand, using the assumption $t_0 = f_0 = z_0 = s_0 = p_0 = w_0$, it can be observed that (9) $\leq$ (10), (9) $\leq$ (11), (9) $\leq$ (12), (9) $\leq$ (13), and (9) $\leq$ (14). Also, as $\sigma_n^j, \zeta \in (0,1)$, then $(1 - (1-\zeta)\sigma_n^j) < 1$. Therefore, we obtain

$$0 \leq \frac{x_n}{a_n} = \frac{\zeta^{(n+1)4(n+3)}}{\zeta^{3(n+1)}} = \zeta^{(n+1)(4n+9)}$$

$$0 \le \frac{x_n}{b_n} = \frac{\zeta^{(n+1)4(n+3)}}{\zeta^{2(n+1)}} = \zeta^{(2n+5)2(n+1)}$$

$$0 \le \frac{x_n}{c_n} = \frac{\zeta^{(n+1)4(n+3)}}{\zeta^{4(n+1)}} = \zeta^{(n+2)4(n+1)}$$

$$0 \le \frac{x_n}{d_n} = \frac{\zeta^{(n+1)4(n+3)}}{\zeta^{(n+1)}} = \zeta^{(4n+11)(n+1)}$$

and

$$0 \le \frac{x_n}{e_n} = \frac{\zeta^{(n+1)4(n+3)}}{\zeta^{4(n+1)}} = \zeta^{(n+2)4(n+1)}.$$

Now, we define

$$\theta_n^1 = \zeta^{(n+1)(4n+9)},\ \theta_n^2 = \zeta^{(2n+5)2(n+1)},\ \theta_n^3 = \zeta^{(n+2)4(n+1)},$$
$$\theta_n^4 = \zeta^{(4n+11)(n+1)},\ \theta_n^5 = \zeta^{(n+2)4(n+1)}.$$

We thus have

$$\frac{\theta_{n+1}^1}{\theta_n^1} = \zeta^{(8n+17)},\ \frac{\theta_{n+1}^2}{\theta_n^2} = \zeta^{2(4n+9)},\ \frac{\theta_{n+1}^3}{\theta_n^3} = \zeta^{8(n+2)},\ \frac{\theta_{n+1}^4}{\theta_n^4} = \zeta^{(8n+19)},\ \frac{\theta_{n+1}^5}{\theta_n^5} = \zeta^{8(n+2)}.$$

Since $\zeta^{(8n+17)} < \zeta < 1$, $\zeta^{2(4n+9)} < \zeta < 1$, $\zeta^{8(n+2)} < \zeta < 1$, and $\zeta^{(8n+19)} < \zeta < 1$, by ratio test, we have $\sum_{n=0}^{\infty} \theta_n^i < \infty$, where $i = 1, \ldots, 5$. This implies that $\lim_{n\to\infty} \theta_n^i = 0$, where $i = 1, \ldots, 5$. This further implies that $\lim_{n\to\infty} \frac{\|t_n - c\|}{\|f_n - c\|} = 0$, $\lim_{n\to\infty} \frac{\|t_n - c\|}{\|z_n - c\|} = 0$, $\lim_{n\to\infty} \frac{\|t_n - c\|}{\|s_n - c\|} = 0$, $\lim_{n\to\infty} \frac{\|t_n - c\|}{\|p_n - c\|} = 0$, and $\lim_{n\to\infty} \frac{\|t_n - c\|}{\|w_n - c\|} = 0$. Therefore, O_4 iteration is faster than JF, $\mathcal{Z}$, S^*, Picard-SP, and M-Fast iterations. This completes the proof. □

5. Computational Validation

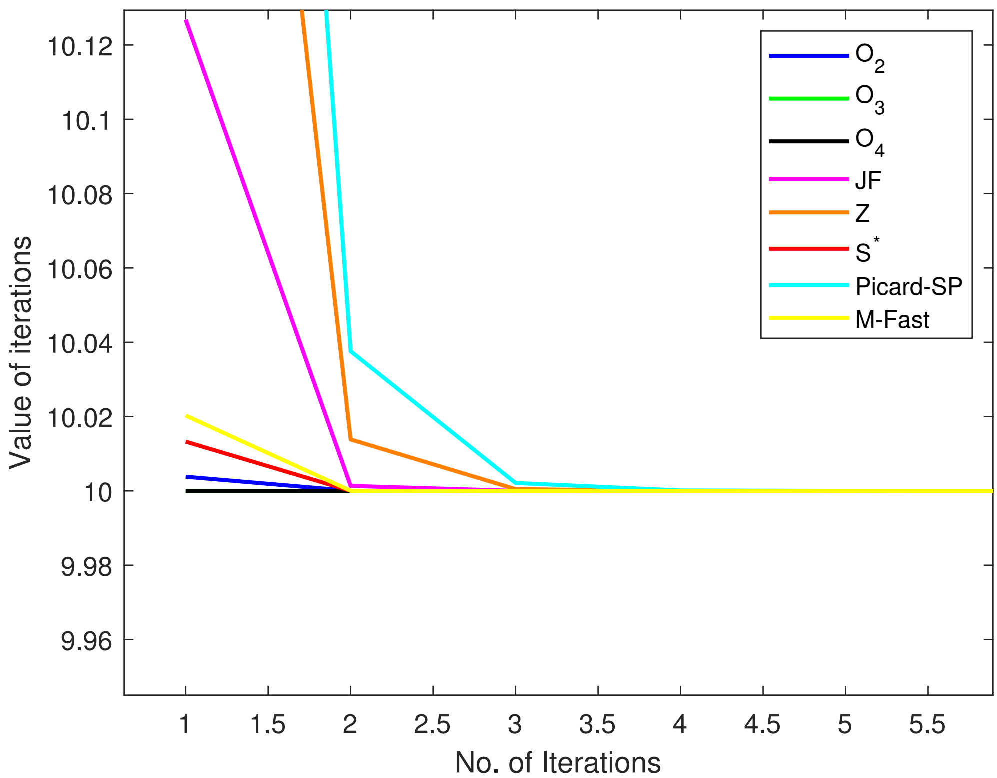
This section serves to computationally validate the results established previously. This validation is drawn as a comparison between the convergence speeds of various iterative schemes mentioned in our previous discussions.

Example 5.1. *Suppose $\mathcal{X} = \mathbb{R}$ be endowed with the usual norm. Assume further, a subset $\mathcal{V} = [0, 10^4]$ of $\mathbb{R}$. Now, define a self-mapping $\mathcal{G} : \mathcal{V} \to \mathcal{V}$ as $\mathcal{G}(t) = \sqrt[3]{5t^2 - 7t + 500}$. Due to mean value theorem, $\mathcal{G}$ can easily be verified to be a weak contraction satisfying* (3) *with $\zeta \in [0.034, 1)$. Let the control sequences be $(\sigma_n^1) = (0.1)$, $(\sigma_n^2) = (0.9)$, $(\sigma_n^3) = (0.7)$, $(\sigma_n^4) = (0.5)$, and $(\sigma_n^5) = (0.4)$. Table 1 demonstrates the convergence of various iterations derived from O_r family to unique fixed point $t = 10$ of mapping $\mathcal{G}$. It also showcases the effect of change of initial guesses on the speed of convergence. The computations have been carried out by using MATLAB R2021a software. Furthermore, Figure 1 illustrates Table 1 for $t_0 = 20$. Additionally, the graphical and tabular representations serve to verify Theorems 4.1 and 4.2.*

Table 1. Comparison of speed of convergence of O_r family with different iterations using Example 5.1

Iterations	Choice of t_0	t_1	t_2	t_3	No. of iterations
O_2	20	10.003807151627939	10.000000011011851	10.000000000000000	3
	10^4	10.529977325522056	10.000001558801250	10.000000000000041	4
O_3	20	10.000001747089186	10.000000000000000	10.000000000000000	2
	10^4	10.000247304367694	10.000000000000032	10.000000000000000	3
O_4	20	10.000000000097600	10.000000000000000	10.000000000000000	2
	10^4	10.000000013815614	10.000000000000000	10.000000000000000	2
JF	20	10.126797381444415	10.001338036031305	10.000014065645665	9
	10^4	24.988653557847094	10.198109458276249	10.002095072541088	10
$\mathcal{Z}$	20	10.403496294849102	10.013840811046387	10.000469515201033	11
	10^4	58.540839143864474	12.077336507483633	10.074344421439697	13
S^*	20	10.013259302495676	10.000014637315902	10.000000016152105	6
	10^4	11.998831323067998	10.002327805594248	10.000002568884941	7
Picard-SP	20	10.654693644687349	10.037586675600913	10.002127473230312	13
	10^4	126.312521175415554	17.180564295923052	10.457566813493964	15
M-Fast	20	10.020279876669138	10.000034186752000	10.000000057594962	6
	10^4	12.951789685497957	10.005366501255073	10.000009042488784	7

Figure 1. Illustration of Table 1 for $t_0 = 20$



6. Conclusion

In this study, we have introduced a family of iterative schemes. We have established the strong convergence of this family in the context of weak contractions. Thereafter, we have theoretically compared the speed of convergence of different iterations within the aforementioned family. We have also compared the speed of convergence of O_4 iteration, derived from the family, with some notable and efficient iterations in the literature. We have finally verified these theoretical findings by a proper exemplification, which is further illustrated in a table and a graph.

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