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Original article

A novel integrated methodology for screening, assessment and ranking of promising oilfields for polymer floods

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Abstract:
Due to the deterioration of the structure of oil reserves, the demand for enhanced oil recovery technologies is increasing every year. These technologies are usually classified into the following: Chemical, gas, thermal and combined enhance oil recovery methods. Among the chemical methods, polymer flooding stands out. It has been actively studied since the middle of the last century and currently numbers hundreds of completed projects around the world. Despite the relatively long study period and the number of publications dedicated to polymer flooding, there is still a range of aspects requiring research and development as well as field testing. One of the crucial issues at the preparation stage of a polymer flooding project is necessity to select oilfield or pilot area to achieve the best possible technological and economic efficiency results. This article provides analysis of the key factors influencing effectiveness of polymer flooding implementation. The paper reflects historical evolution, i.e. expansion of the technology applicability limits. Their current values have been verified, based on the analysis of the experience of implementing the technology in extreme conditions. Applicability criteria has been established as well for the polymer flooding development. The paper includes development of a uniquely designed integrated methodology for screening, assessment and ranking of promising objects for the technology implementation. The methodology is designed on the basis of a background review of completed projects, as well as on the expertise of the specialists involved in the development and scientific support of chemical enhanced oil recovery projects implementation. The purpose of the methodology is to create a basic universal tool for an express assessment of the prospects for using polymer flooding in different fields, which a wide range of specialists in the oil and gas industry could apply.

1. Introduction

Due to the gradual depletion of global oil reserves, the development and implementation of methods and technologies aimed at sustaining oil production rates and increasing recovery efficiency, i.e., methods of enhanced oil recovery (EOR) are becoming more relevant. The current EOR methods can be generally categorized into five groups: Mobility-control, chemical EOR, miscible injection, thermal processes, and other EOR methods (Wu et al., 2023). In particular, research and development of chemical enhanced oil recovery (cEOR) methods keep being an important trend for modern science. Chemical EOR includes polymer, surfactant-polymer, alkali-surfactant-polymer flooding, and injection of low-volume slugs of polymer solutions to isolate highly permeable intervals (Manrique et al., 2010).

It is important to note that the abovementioned chemical agents can also be used in other field operations which are not related directly to EOR. Polymers, for example, can be used for preparing drilling fluids (Islamov et al., 2019; Leusheva, 2022), reducing sand production (Tananykhin et al., 2022, 2023), decreasing pipe friction, and for various other operations (Ghosh et al., 2022). Similarly, surfactants find app-

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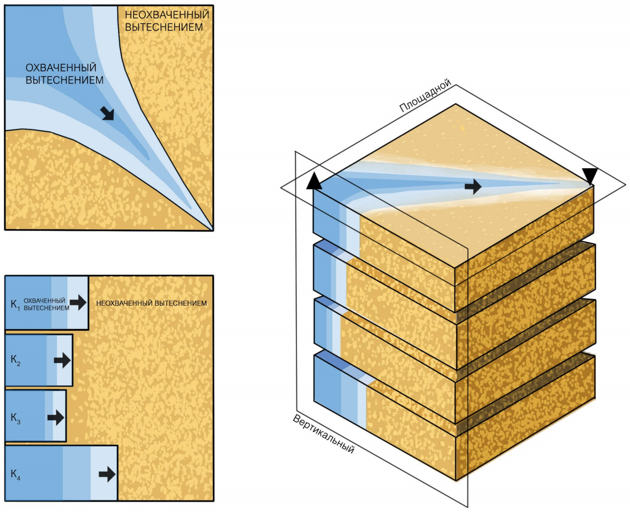

Fig. 1. Displacement agent injectivity profile when moving from the injection to the production well under unfavorable mobility ratio (waterflooding).

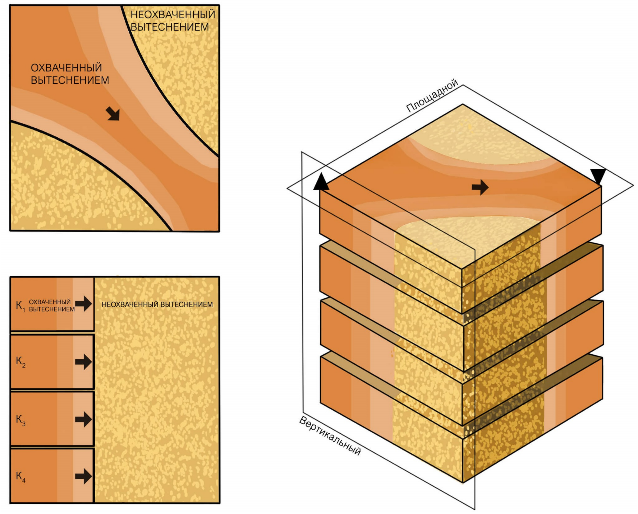

Fig. 2. Displacement agent injectivity profile when moving from the injection to the production well under favorable mobility ratio (polymer flooding).

lications in well-killing operations (Islamov et al., 2020; Mardashov, 2021; Mardashov and Limanov, 2022) or in technologies aimed at preventing or removing asphaltene deposits (Rogachev and Aleksandrov, 2021; Korobov et al., 2023).

Proceeding to EOR technologies discussion, it is necessary to emphasize that currently the most common methods are those based on injection of large-volume slugs of chemicals. A large-volume injection involves introduction of chemicals in reservoir in the amount of at least 3% of the pore volume either of the entire field (in case of a full-field project) or of a selected pattern (in case of a pilot project).

Injection of surfactants during these operations requires comprehensive research due to the diversity of surfactant formulations (Dean, 2011; Podoprigora, 2022; Petrakov et al., 2023). In turn, the injection of the polymer solutions at concentrations of 500-2,500 ppm, i.e. polymer flooding is one of the most common cEOR techniques is. The action of polymer flooding involves several key aspects (Thomas, 2018):

- Improving sweep efficiency;
- Improving the mobility ratio between displacing and displaced fluids;
- Reducing the impact of reservoir heterogeneity.

Sweep Efficiency Improvement. The sweep efficiency shows the degree of proximity to the ideal (piston-like) displacement, occurring when a well-defined interface is formed between oil and a displacing fluid, in front of which only oil moves, and behind only water (Hemmati-Sarapardeh et al., 2021). Fig. 1 shows the vertical and areal waterflooding profile; Fig. 2 illustrates the polymer flooding profile.

Mobility ratio improvement. Long-term water injection to maintain reservoir pressure eventually leads to incomplete reserve recovery and to the breakthrough of injected water to production wells. According to Craig (1971), this phenomenon is related to the difference in mobilities between displacing (injected water or gas) and displaced (oil) fluids. As a result, the oil bank gets diluted by the displacing agent, forming a channel between the producer and the injector. Such breakthroughs increase the water-cut of the producing wells, significantly elevating the operating costs for hydrocarbon production. One of the effective methods for preventing water breakthroughs is polymer flooding, which, by definition, involves injection of high-viscosity water (polymer solution). The effect of adding polymer to water can be explained through the mobility ratio (M) analysis:

$$M = \frac{k_{rw}(S_{or}) \cdot \mu_o}{k_{ro}(S_{wc}) \cdot \mu_w} \tag{1}$$

where $k_{rw}(S_{or})$ is relative permeability to water at residual oil saturation; $k_{ro}(S_{wc})$ is relative permeability to oil at residual water saturation, μ_o, μ_w are relative oil and water viscosity respectively, cP. For an effective oil displacement, the mobility ratio should not exceed 1, this value is considered favorable in cEOR (Chiappa et al., 2003).

Reduction of the reservoir heterogeneity impact. Alongside equalizing mobility ratio and improving sweep efficiency, polymer flooding contributes to increasing oil recovery by reducing the influence of reservoir heterogeneity. Unlike water, which mainly flows into highly permeable zones due to its physical properties, the viscous nature of polymer solution allows it to involve the unswept reservoir zones into production.

These effects were clearly demonstrated in the research of Seright et al. (2010), where the displacement fronts formed by water and polymer solution were compared for a layered heterogeneous model. The research results confirmed the effectiveness of polymer flooding over waterflooding for a multilayer reservoir model with different permeability in layers.

However, it is important to note that with extremely high permeability contrast, the effectiveness of polymer flooding could be insufficient (Seright et al., 2011). In this case, the technologies aimed at plugging the highly permeable zones should be implemented (Ketova et al., 2020; Raupov et al., 2023).

An important aspect of the successful polymer flooding

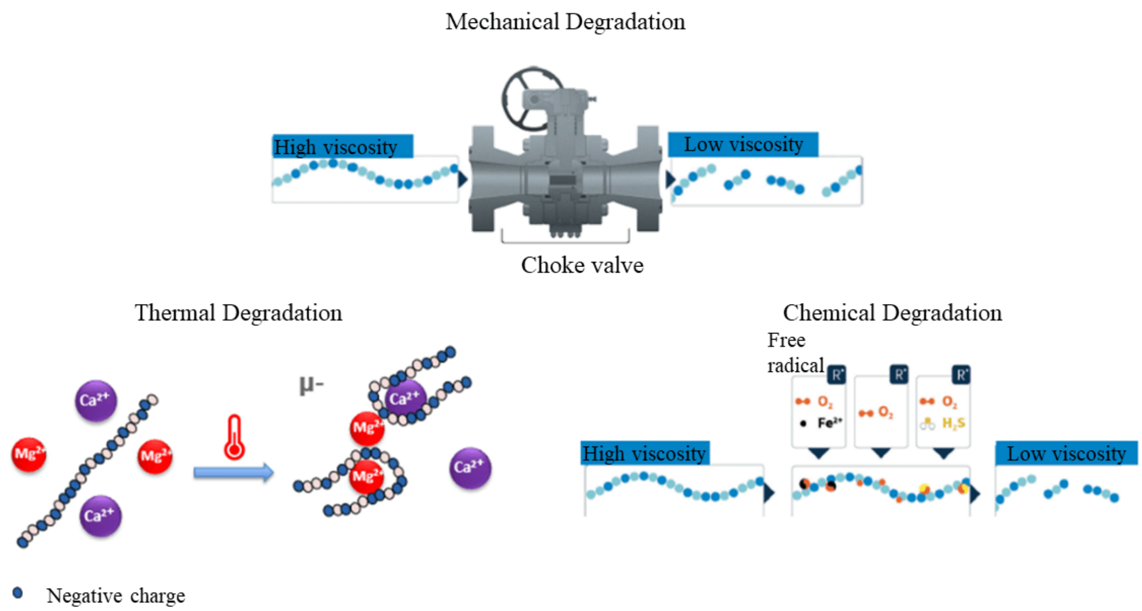

Fig. 3. Main types of polymer degradation.

implementation is maintaining the viscosity characteristics of polymer solution both at the surface and under reservoir conditions (Seright et al., 2010). Several factors can lead to an early loss or decrease in polymer viscosity. The most important of them is polymer degradation, i.e. a breakdown of the macromolecular chain structure. Polyacrylamide macromolecules are sensitive to several types of degradation: chemical, mechanical, and thermal (Fig. 3) (Gaillard et al., 2017).

Chemical degradation is related to the formation of free radicals that can react with the main polymer chain, leading to a reduction in molecular weight and viscosity. The formation of radicals is facilitated by the presence of various chemical impurities in water, such as combination of oxygen and divalent ions (Caulfield et al., 2003).

Mechanical degradation occurs when the main polymer chain is exposed to significant shear stress at high flow velocity and substantial pressure drops. To prevent polymer mechanical degradation during preparation and injection, special attention should be paid to the equipment design (Beloglazov et al., 2021), in particular to the selection of pumps, throttles, valves, fittings, mixers, etc. (Guo et al., 2022). In addition, when developing project design and selecting chemical formulations, it is important to keep in mind that an increase in flow rate in the reservoir proportionally raises the shear rate, reducing viscosity due to the non-Newtonian behavior of polymer solution (Jouenne et al., 2018).

Thermal degradation is often related to an increase of polymer hydrolysis degree with respect to temperature and time (Zhang et al., 2021). Furthermore, the presence of divalent cations (Ca^{2+} and Mg^{2+}) can cause precipitation of polymer particles, negatively affecting viscosity (Thomas et al., 2012). At the same time, specific polymers are stable at elevated temperatures (Hryc et al., 2022).

In addition to the reasons listed above, the following can also lead to a viscosity loss:

1) Dissolution in reservoir fluids. In the research (Himchenko, 2018) special attention was paid to the ability of the polymers to dissolve in reservoir water due to extensive contact between the flood front and the underlying aquifer. This interaction could result in reducing concentration and viscosity of the polymer solution.
2) Polymer retention in reservoir conditions. There are three fundamental retention mechanisms: (1) adsorption on rock; (2) mechanical entrapment due to the molecule size; and (3) hydrodynamic entrapment in unswept zones (Al-Hajri et al., 2018). Polymer retention can be minimized by selecting an agent that will be the most suitable for the reservoir conditions (Ilyasov et al., 2021).
3) Presence of clays. In the paper (Taber et al., 1997) polymer adsorption on rock with various mineral compositions and content is examined.. When the clay content exceeds 10%, adsorption becomes quite significant.

As of today, over 100 different polymer grades can be used as potential chemical agents. The broad spectrum of available chemicals is a result of the diverse geological and physical reservoir conditions. For example, incorporating monomers of acrylamido tertiary-butyl sulfonic acid or n-vinylpyrrolidone broaden the temperature and water salinity limits, within which polymer can be used without compromising its physical and chemical properties (Thomas et al., 2012).

The selection of polymer solution properties, such as molecular weight, number of sulfonated groups, charge type, etc., is primarily determined by the geological conditions of the reservoir. Also, the selection should be conducted individually for each project, with the declared properties being verified for stability under laboratory conditions that closely simulate those of the reservoir (Wang et al., 2020).

Given the technology's longstanding history and proven effectiveness, the number of polymer flooding projects in diff-

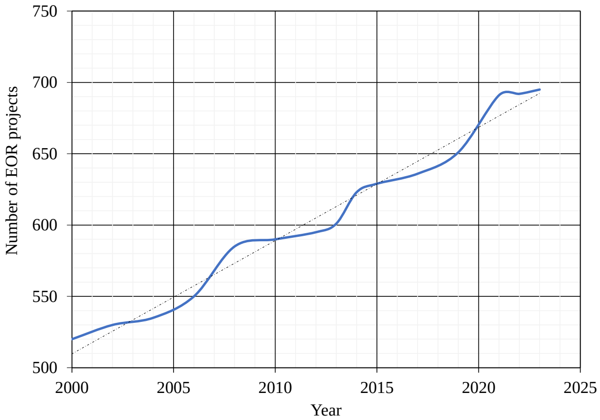

Fig. 4. Trends in the number of implemented polymer flooding projects worldwide.

erent reservoir conditions has been gradually increasing over the years. Currently, there are about 700 successfully implemented pilot and full-field projects (Sheng, 2015). Fig. 4 illustrates the growth in the number of implemented polymer flooding projects worldwide over the past two decades.

Taking into account the continuously increasing demand for the polymer flooding application, studying the technological aspects that influence the success and effectiveness of project implementation is essential. One of the key points in the technology design is the preparatory stage, which typically includes screening, analyzing, and selecting the most promising objects for the technology implementation (Mahdavi and Zebarjad, 2018).

At the same time, some reservoir properties, which are crucial for understanding the technology applicability, can be rapidly assessed to promptly estimate the feasibility of polymer flooding implementation under existing conditions (Taber et al., 1997; Suleimanov et al., 2016). Initially, parameters such as reservoir type, oil viscosity, water salinity, permeability, temperature, reservoir heterogeneity, clay content, as well as the presence of gas cap and active aquifer, are to be analyzed to determine the technology applicability. The method and procedure for analyzing these properties of a development object (reservoir) will be discussed in the following sections of the article.

In this regard, having a universal toolkit for an initial assessment of the technology applicability at a specific reservoir will foster heightened interest in applying polymer flooding from oil and gas companies' specialists and accelerate the transition to the specialized scientific developments for specific candidate fields.

The objective of this research is to develop a comprehensive methodology for screening, assessment, and ranking objects to predict the potential success of the polymer flooding technology implementation.

2. Materials and methods

The flowchart in Fig. 5 shows the principles and procedures for data processing utilized in the developing a methodology for screening, assessing and ranking potential objects for the polymer flooding technology implementation (hereinafter referred to as *the methodology*).

The developed methodology involves a three-stage procedure for assessing the candidates for polymer flooding implementation:

1) Screening of objects that meet the *current applicability limits*.
The polymer flooding technology applicability limits are determined as the minimum and maximum permissible values of certain reservoir characteristics. Meeting these limits indicates the technological feasibility of polymer flooding and directly depends on the current level of advancements in chemical industry, particularly in maintaining polymer properties under harsh conditions. If the values of one or more object parameters go beyond the applicability limits, this object cannot be considered as a candidate for polymer flooding implementation at the current level of technology development.
To update the applicability limits, an extensive literature review was conducted to identify potential applicability limits-i.e., restrictions on technology implementation derived from relevant review articles. After that, the potential applicability limits were verified through the analysis of the real field cases, leading to the establishment of *current applicability limits*.
2) Assessment of objects, based on their compliance with the applicability criteria, which is mathematically expressed in the calculation of an integrated applicability index for an object.
The polymer flooding technology applicability criteria represent a group of object characteristics values that show the prospects of this object for polymer flooding implementation. As a quantitative expression of the applicability criteria, the applicability index is used, which is a function reflecting the values of the object's parameters within the total dataset.
3) Ranking of objects based on the degree to which they meet the applicability criteria, i.e., in accordance with the obtained value of the applicability index.

The authors used two types of sources: (1) review articles, which formed the basis for defining potential applicability limits, and (2) specific case-study articles on polymer flooding technology implementation, used to verify these limits (determine the current applicability limits) and to establish the technology applicability criteria. A survey among cEOR experts was also conducted in order to assess the significance of each criterion, and, to formulate accordingly a methodology for assessing the applicability of polymer flooding technology.

Both the definition of the applicability limits and the derivation of applicability criteria are based on the analysis of the previously mentioned key geological and physical characteristics of the objects. These values directly affect the effectiveness of a polymer flooding project. The following list of characteristics has been determined on the basis of the analyzed review articles and the field experience of the authors of this study.

- Oil viscosity, μ_o, cP;
- Permeability, k, mD;

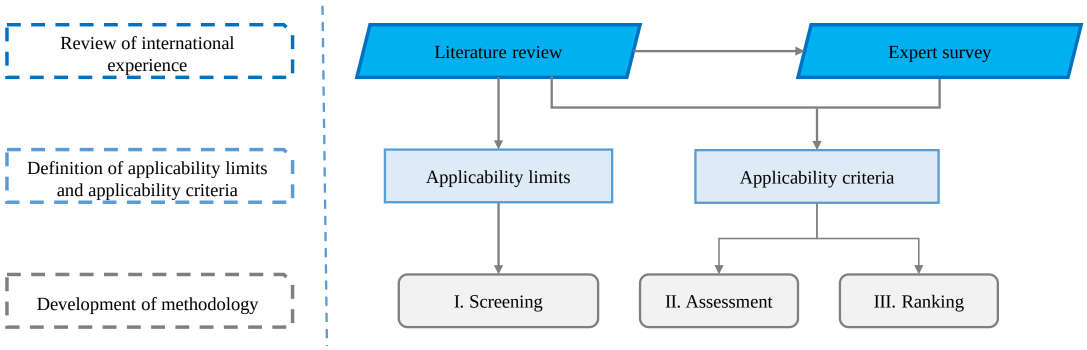

Fig. 5. Research methodology.

- Reservoir lithology;
- Injection water salinity, TDS, ppm;
- Reservoir temperature, T, °C;
- Clay content, CC;
- Reservoir heterogeneity (Dykstra-Parson coefficient), DP;
- Gas cap presence, GC;
- Aquifer presence, Aq.

2.1 Definition of applicability limits and criteria

Definition of current applicability limits. To define the current applicability limits of polymer flooding (minimum $x_{\min}$ and maximum $x_{\max}$), a comprehensive literature review was performed., whichThat included two successive stages: (1) analysis of the review articles focused on the historical perspectives of polymer flooding applicability limits; (2) analysis of the sources related to the pilots and full-field polymer flooding projects.

The conclusions regarding the applicability limits made in the review articles might have been based on various information sources, including purely scientific (laboratory) studies. Therefore, in the scope of this research, they were subjected to precise verification through a comparison with the successful polymer flooding field cases under the most extreme field conditions. As it was mentioned before, the applicability limits developed in the review articles are referred to as potential, because not all of them find confirmation in field experience; however, they show the most probable directions of the technology progress in the near future. The limits verified with a field experience, in turn, will be considered as the current limits, i.e., relevant and confirmed at the moment, but still subject to subsequent changes due to the implementation of successive polymer flooding projects that go beyond their limits.

Additionally, it is worth noting that the second stage analysis considered only field cases implemented after the year 2,000. This limitation was set to filter out information that might have become outdated due to the rapid evolution of technology and advancements in chemical manufacturing.

Definition of applicability criteria. At the next stage of the study, the materials related to the field cases were analyzed to define practical value ranges of the key field parameters. The extreme values of such parameters, in turn, had been established as the applicability limits at the previous stage.

The collected information about the values of key parameters in the field projects provides a statistically representative data sample of general population of polymer flooding projects due to the inclusion in the analysis of a large number of practical cases in various geographical, geological and physical conditions. The values obtained during the analysis were divided into intervals based on the median value and then processed to obtain the following statistical indicators.

- Mean, M;
- Median Me;
- Mode, Mo;
- Minimum and maximum ($x_{\min}$ and $x_{\max}$);
- Highest frequency interval.

Then, a frequency analysis was carried out on the data sample for each parameter in the following sequence.

1) Frequency analysis of the number of projects within the allocated intervals was carried out;
2) Empirical function of the relative cumulative frequencies was determined;
3) The resulting function was interpolated by the function $f_i(x_i^m)$;
4) Based on the frequency histograms obtained from the sample data, relative frequencies were determined, reflecting the probability of falling within the value range of each parameter. It should be noted that some parameters have discrete values, i.e., they are determined by some conditions, for instance, "clay content more than 10%" and "clay content less than 10%" (Carcoana, 1982). The functions of such parameters were systematized as follows:

$$f_i\left(x_i^m\right)=\begin{cases} p_i, x_i^m - \text{ favorable} \\ 1-p_i, x_i^m - \text{ unfavorable} \end{cases} \tag{2}$$

2.2 Expert assessment

The significance of a field parameter is expressed by the coefficient e_i, which shows the influence of this parameter on the expected effectiveness of polymer flooding technology implementation at any given object. The significance of the parameterParameters' significance iswas determined based on the results of a survey conducted in the cEOR the expert community survey.

Table 1. Questionnaire for the expert survey.

No.	Parameter	Rank
1	Oil viscosity	
2	Reservoir permeability	
3	Injection water salinity	
4	Reservoir temperature	
5	Clay content	
6	Reservoir heterogeneity (Dykstra-Parsons)	
7	Gas cap presence	
8	Aquifer presence	

In order to reduce the levelshare of subjectivity in the expert assessments, two solutions were proposedconsidered: engaging a high number of experts, which couldan ensure a broad coverage of the target audience, and leveraging the expertisecompetencies of the interviewed cEOR expertsspecialists. It should be noted that a mathematical model built on statistical data inherently involves a number of assumptions and will inevitably lead to errors. However, it is now evident, that the appliedthis approach yields the most consistent results with reality, thus serving as a valuable tool for petroleum engineers. The significance of the parameter is determined based on the results of the expert community survey.

Estimated parameters were divided into two groups according to the level of their significance: The first group (I) included the main parameters, which directly affect the potential effectiveness of polymer flooding, the second group (II) included complicating factors that should be taken into account when ranking objects (aquifer and a gas cap).

Complicating factors should be considered when evaluating a candidate object, but they should not play a decisive role in the overall evaluation of the field. For instance, an object with an active aquifer and a gas cap, but at the same time, with high permeability, favorable reservoir properties and containing high-viscosity oil, should not be excluded from the candidate list when assessing the polymer flooding applicability. In addition, these parameters depend on the technological features of field development, such as well construction, their operating mode, etc., and accordingly, they mainly determine the choice of a well pattern location for cEOR implementation, rather than the technology prospects at the field. Polymer flooding is quite adaptive and has already demonstrated its effectiveness, including at complex facilities, what is proven by its widespread implementation results.

To calculate the coefficient e_i, a survey of the expert community was conducted using the following methodology: Each expert was provided with a questionnaire withcontaining a table (see Table 1), which had to be filled out by, ranking the characteristics of fields according to the degree of their influence on the polymer flooding implementation potential effectiveness.

The survey results were subsequently processed to derive the following values: Significance score of the i-th parameter, assessed by the j-th expert:

$$S_{ij} = (n+1) - R_{ij} \tag{3}$$

where S_{ij} is the significance score of the i-th parameter; R_{ij} is the significance rank of the i-th parameter assessed by the j-th expert; n is the number of parameters.

Average significance score of the i-th parameter:

$$\overline{S_i} = \frac{\sum_{j=1}^{m} S_{ij}}{m} \tag{4}$$

where $\overline{S_i}$ is the average significance score of the i-th parameter; m is the number of experts;

Expert coefficient of the i-th parameter:

$$e_i = \frac{\overline{S_i}}{n(n+1)} \tag{5}$$

where e_i is the expert coefficient of the i-th parameter.

2.3 Methodology for assessing and ranking candidate oilfields

The quantitative assessment of the technology applicability for a given object in the scope of the developed methodology includes two stages: (a) calculation of primary applicability indexes for two groups of parameters; (b) calculation of the integral applicability index.

Primary applicability index for the m-th field for a group of l-parameters (l = I, II) can be calculated using the following equation:

$$\mathrm{Eff}_l^m = \textstyle\sum_i^n \mathrm{eff}_i(x_i^m) 100\% \tag{6}$$

Eff_l^m is the primary applicability index for the m-th field for a group of l-parameters; x_i^m is the i-th parameter of the m-th field (e.g., viscosity, temperature, water salinity, etc.); $\mathrm{eff}_i(x_i^m)$ is applicability coefficient for the m-th field with respect to the i-th parameter x_i^m, calculated usingby the formulaequation:

$$\mathrm{eff}_i(x_i^m) = f_i(x_i^m) e_i \tag{7}$$

As mentioned earlier, the coefficient e_i determines the significance of a field parameter, i.e., the degree of its influence on the result of polymer flooding implementation, from the experts' point of view. In turn, $f_i(x_i^m)$ is an empirical applicability coefficient, calculated as the probability of finding a field with the same parameter value among implemented projects worldwide, its value range is from 0 to 100%.

Note that the applicability index Eff_l^m has the same range of values. The closer it is to 100%, the more promising the field is for polymer flooding implementation.

The integral applicability index for the m-th field is determined by a formula that takes into account the applicability indexes for each group of parameters:

$$\mathrm{Eff}_m = \textstyle\sum_l \mathrm{Eff}_l^m = \mathrm{Eff}_I^m + \mathrm{Eff}_{II}^m \tag{8}$$

where Eff_I^m, Eff_{II}^m are the primary applicability index for the m-th field for a group of I, II parameters, respectively.

This function has a value range from 0 to 100%, its arguments Eff_I and Eff_{II}–from 0 to 50%.

Table 2. Polymer flooding applicability limits according to the estimates of various authors.

References	μ_o, cP	k, mD	Reservoir type	TDS, ppm	T, °C	CC	DP	GC	Aq
Brashear et al. (1978)	< 20	> 20	Preferably terrigenous	50,000	< 93	Low content	Preferably homogeneous	Preferably no	Preferably no
Chang (1978)	< 200	> 20	Preferably terrigenous	/	< 93	/	/	/	/
Carcoana (1982)	50-80	> 50	Terrigenous	Low	< 80	/	/	Weak	Weak
Goodlett et al. (1986)	100	> 20	Preferably terrigenous	100,000	< 93	/	/	/	/
Taber et al. (1997)	10-150	> 10	Preferably terrigenous	/	< 93	/	/	/	/
Al-Bahar et al. (2004)	< 150	> 50	Terrigenous	100,000	< 70	Low content	Homogeneous	No	No
Dickson et al. (2010)	10-1,000	> 100* $> 1,000$**	/	$< 1,000$* $< 3,000$**	< 76.7	/	/	/	/
Saleh et al. (2014)	$< 5,000$	> 10	Terrigenous or carbonate	6,500	< 98.9	/	/	/	/
Sheng et al. (2015)	/	> 50	Terrigenous	$< 50,000$	< 93	Low content	/	Weak	Weak
Thomas et al. (2018)	$< 10,000$	> 10	Preferably terrigenous	$< 250,000$	< 140	Low content	DP: 0.1-0.8	Preferably no	Preferably no
Hemmati-Sarapardeh et al. (2021)	$< 10,000$	> 10	Preferably terrigenous	$< 250,000$	< 121	/	/	/	/

Notes: * denotes if oil viscosity from 10 to 100 cP, ** denotes oil viscosity from 100 to 1,000 cP.

It is worth noting that Eq. (8) should satisfy certain requirements over the entire domain of Effi: since the parameters included in the first group are considered more significant than those in the second group (by definition of the introduced groups), selection of an object can be carried out under a necessary (but not sufficient) condition:

$$\forall m \in \mathbb{N}; \forall x_i^m \in \mathbb{R} : \mathrm{Eff}_I^m \geq \mathrm{Eff}_{II}^m \tag{9}$$

where $\mathbb{N}, \mathbb{R}$ are a set of natural and real numbers, respectively. Therefore, when determining the experimental applicability and significance coefficients, it will be necessary to check the Eq. (9).

3. Results and discussion

3.1 Definition of potential applicability limits

The applicability limits of polymer flooding technology are formed by a set of specific parameters, which evolved throughout lab tests and field implementation. This can primarily be attributed to the scientific and technological advancements in the production of chemicals used in these technologies and engineering enhancements in the manufacturing of injection components, allowing to maintain the rheological properties of polymer solutions during their injection. Table 2 summarizes the applicability limits of the technology, established by various authors. This table provides a list and values of the key field parameters affecting the effectiveness of polymer flooding implementation and shows the dynamics of changes in polymer flooding applicability limits.

The applicability limits demonstrated below were defined by their authors based on diverse methodological approaches, leading to significant variations in the quantitative values of the parameters considered. In particular, some experts examined the applicability limits of polymer flooding for geological and technological characteristics reproduced only in laboratory conditions. Others primarily relied on the real field cases. Notably, regardless of these varied approaches, a clear trend towards expanding the applicability limits of the technology over time is evident.

3.2 Analysis of implemented polymer flooding projects

As part of the study, data collection and statistical analysis (see Table 3) of the values of the key parameters of the fields where polymer flooding was implemented were conducted. That key parameters are: (1) oil viscosity, (2) permeability, (3) reservoir type, (4) injection water salinity and (5) reservoir temperature. The analysis of extreme values of these parameters allows us to establish the current applicability limits for polymer flooding. It should be noted that, when considering

Table 3. Descriptive statistics for continuous parameters defining applicability limits.

Statistical value	μ_o, cP	k, mD	TDS, ppm	T, °C
Mean, M	361.91	2,120	53,800.01	47.72
Median, Me	70.00	530	14,000.00	45.00
Mode, Mo	100.00	5,000	500.00	45.00
Minimum	0.65	2	250.00	16.00
Maximum	12,000.00	10,100	257,000.00	95.00
Sample volume	53	51	46	52
Highest frequency interval	0.65-61.78	675.2-2694.8	250-25,925	39.7-47.6
Established current applicability limits	0.65-12,000.00	2-10,100	250-257,000	16-95

Table 4. Current polymer flooding applicability limits.

Parameter	μ_o, cP	k, mD	Reservoir type	TDS, ppm	T, °C
Current applicability limits	0.65-12,000.00	2-10,100	Terrigenous	250-257,000	16-95

Table 5. Boundary values of the group of additional (discrete) parameters involved in the calculations at the second stage of the methodology–applicability criteria (not included in the first stage of the methodology).

Parameter	CC	DP	GC	Aq
Boundary values	Preferably $<$ 10%	Preferably homogeneous (0.1-0.8)	Preferably no	Preferably no

specific cases of the technology implementation, an analysis of all the specified parameters for each project is often not possible due to a lack of comprehensive data in public sources.

Despite the technical feasibility of polymer flooding for carbonate reservoirs, the majority of projects have been implemented in terrigenous reservoirs (less than 3% of all projects were implemented in carbonate reservoirs). This trend can be attributed to a broader range of suitable chemicals, a deeper understanding of their behavior in terrigenous conditions, and a less complicated injection design. As a result, the methodology will be assumed to be applicable only to terrigenous objects by default. In compliance, the significance coefficient e_i for the reservoir lithology parameter, in the context of the methodology development, will be excluded from further analysis. Evaluation ofConsidering the prospects of polymer flooding implementation in carbonate reservoirs requires a more detailed study of athe set of conditions of the object.

Table 4 presents the results of the field parameters analysis, corresponding to the current applicability limits (first stage of the methodology).

If the object under consideration fails to meet the applicability limits for any parameter, this indicates that there is currently no available way to implement polymer flooding and/or a more detailed study of the object is required and after some adaptive measures the object may be recognized as favorable for polymer flooding implementation.

3.3 Definition of the applicability criteria

Applicability criteria are established based on the distribution of the absolute and relative frequency values of reservoir parameters, resulting from an analysis of a sample comprising 70 projects implemented after the year 2000 and sufficiently covered in publications. Following parameters were analyzed to calculate the applicability criteria: (1) oil viscosity, (2) reservoir permeability, (3) injection water salinity, (4) reservoir temperature, (5) clay content, (6) reservoir heterogeneity-Dykstra-Parsons coefficient (DP), (7) presence of gas cap and (8) presence of aquifer, as determined from publications analysis (see Table 2).

For convenience and to derive quantitative values of applicability coefficients, these parameters were divided into two groups: Base parameters with continuous values (oil viscosity, reservoir permeability, injection water salinity, reservoir temperature-corresponding to characteristics determining the technology applicability limits) and additional parameters with discrete values (clay content, permeability, presence of a gas cap and an active aquifer). The boundary values of the group of base parameters are provided in Table 4. The boundary values of the group of additional parameters are given in Table 5.

These ranges correspond to the blue-colored areas in Fig. 6, i.e., show the highest frequency ranges of implemented projects.

If the analysis of an object shows that any of its parameter values fall outside these ranges, this doesn't necessarily indicate any lack of polymer flooding implementation prospects

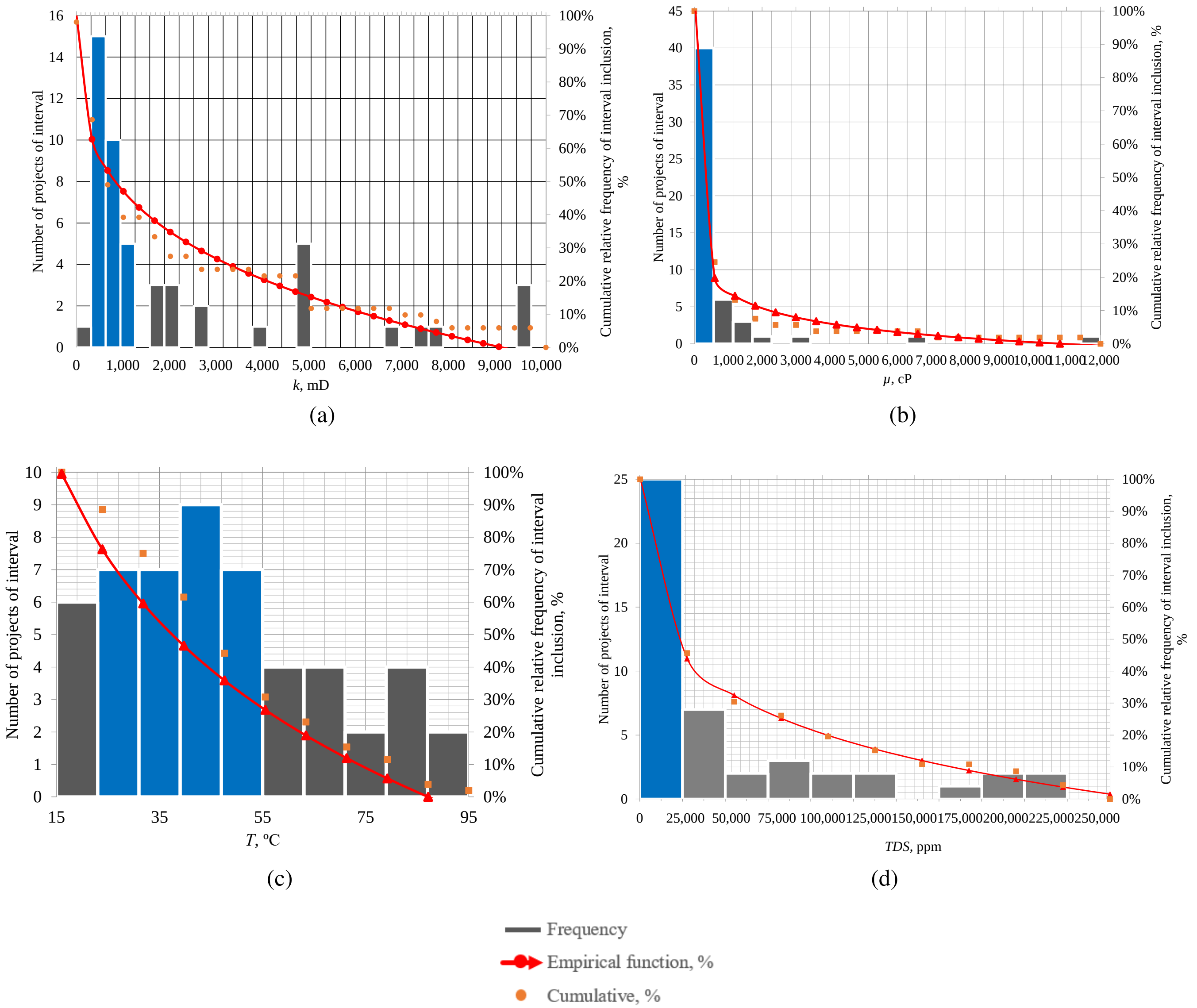

Fig. 6. Projects frequency distribution of base (continuous) parameters (a) permeability, (b) viscosity, (c) temperature and (d) TDS, and interpolation of relative frequencies. Ranges with the highest frequency are highlighted in blue.

Table 6. Interpolation of empirical functions of base (continuous) parameters.

Base parameter	Empirical function $f_i(x_i)$	R^2
μ_o, cP	$f(\mu_o) = 1.94\mu_o^{-0.07} - 0.995$	0.97
k, mD	$f(k) = -0.13k^{0.24} + 1.16$	0.99
TDS, ppm	$f(\text{TDS}) = -0.36(\text{TDS})^{0.13} + 1.72$	0.99
T, °C	$f(T) = -27.32T^{0.02} + 29.87$	0.99

in the given object. It simply suggests that for a more detailed assessment of the object within the methodology, it is necessary to quantify how far it is from the most favorable values of the parameters. This evaluation is performed by calculating the applicability indexes, which will be defined later.

The results of the analysis, showing the absolute frequency distributions of the projects across intervals of the base (continuous) parameters and the interpolation of their cumulative relative frequencies, are presented in Fig. 6 and Table 6. Equations presented in Table 6 were derived using a three-parameter approximation in a power-law form, processing world polymer flooding project data in MathCAD. The processing mechanism included: dividing numbers of projects on intervals, finding of values of cumulative frequency function, approximation of cumulative function. The approximated cumulative function will hereinafter be referred to as the empirical function. The analysis results for additional (discrete) parameters are shown in Table 7.

As a result of the calculations, empirical functions were defined for each considered parameters.

Table 7. Interpolation of empirical functions of additional (discrete) parameters.

Additional parameter	CC		DP		GC		Aq	
	Empirical function $f_i(x_i)$							
Favorable	CC $<$ 10%	0.9	DP$<$ 0.8	0.79	Absence: GC = 0	0.86	Absence: Aq = 0	0.76
Unfavorable	CC $<$ 10%	0.1	DP$\geq$ 0.8	0.21	Presence: GC = 1	0.14	Presence: Aq = 1	0.24

Table 8. Results of processing the expert survey.

Indicator	Parameters, *i*							
	1	2	3	4	5	6	7	8
	Oil viscosity	Permeability	Injection water salinity	Reservoir temperature	Clay content	Reservoir heterogeneity	Gas cap presence	Aquifer presence
Average significance score	6.27	6.82	4.73	4.27	3.73	5.55	2.00	2.64
Significance group	I	I	I	I	I	I	II	II
Significance coefficient	0.1742	0.1894	0.1313	0.1190	0.1035	0.1540	0.0556	0.0730

Table 9. Current polymer flooding applicability limits.

Parameter	μ_o, cP	k, mD	Reservoir type	TDS, ppm	T, °C
Applicability limits	$<$ 12,000	$>$ 2	Sandstone	$<$ 257,000	$<$ 95

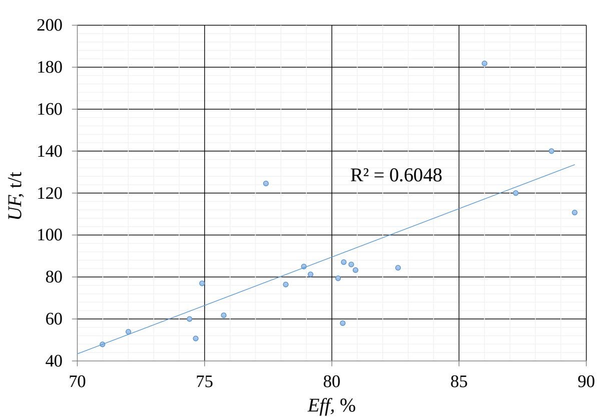

Fig. 7. Dependence of UF on Eff.

Expert assessment of the field parameters significance for polymer flooding implementation. To further develop the applicability criteria, leading experts in chemical EOR were surveyed to assess the significance of field parameters for a successful implementation of polymer flooding. The processed results of the expert survey are presented in Table 8.

Calculation of integral applicability index. To obtain the integral applicability index for two groups of parameters, the final function Eff should be as follows:

$$\mathrm{Eff}(\mathrm{Eff}_I, \mathrm{Eff}_{II}) = \mathrm{Eff}_I + \mathrm{Eff}_{II} \tag{10}$$

To reduce the degree of significance of the II group of parameters, as noted above, we need to ensure that Eq. (9) is met. This condition holds true for any parameter value if the following inequality is satisfied:

$$\min \mathrm{Eff}_I \geq \max \mathrm{Eff}_{II} \tag{11}$$

Using the empirical functions introduced in Tables 7 and 8, we confirm that inequality (Eq. (11)) is satisfied:

$$60.47 > 13.63 \tag{12}$$

3.4 Methodology for screening, assessment and ranking

As a result of the conducted analysis, there was developed a methodology consisting of 3 subsequent stages, including checking whether the considered objects meet the applicability limits, assessing their compliance with the applicability criteria, and ranking them by the integral applicability index values.

Stage I–primary selection of objects that meet the applicability limits. The field parameters must satisfy the conditions presented in Table 9.

Stage II–calculation of the integral applicability index in accordance with Eq. (15), obtained by calculating the applicability indexes for the I and the II groups of parameters (Eff_I and Eff_{II}) using Eqs. (13) and (14):

Table 10. Empirical functions and significance coefficients for the I group of parameters.

Parameter	$f_i\ (x_i^k\ )$	e_i
μ_o, cP	$f(\mu_o) = 1.94\mu_o^{-0.07} - 0.995$	$e_\mu = 0.1742$
k, mD	$f(k) = -0.13k^{0.24} + 1.16$	$e_k = 0.1894$
TDS, ppm	$f(\text{TDS}) = -0.36(\text{TDS})^{0.13} + 1.72$	$e_{\text{TDS}} = 0.1313$
T, °C	$f(T) = -27.32T^{0.02} + 29.87$ $e_T = 0.1190$	
CC, %	$f(\text{CC}) = \begin{cases} f(\text{CC} < 10\%) = 0.9 \\ f(\text{CC} \geq 10\%) = 0.1 \end{cases}$	$e_{\text{CC}} = 0.1035$
DP	$f(\text{DP}) = \begin{cases} f(\text{DP} < 0,8) = 0.21 \\ f(\text{DP} \geq 0,8) = 0.79 \end{cases}$	$e_{\text{DP}} = 0.1540$

Table 11. Empirical functions and significance coefficients for the II group of parameters.

Parameter	$f_i\ (x_i^k\ )$	e_i
Aquifer presence, Aq	$f(\text{Aq}) = \begin{cases} f(\text{Aq} = 0) = 0.76 \\ f(\text{Aq} = 1) = 0.24 \end{cases}$	$e_{\text{Aq}} = 0.0730$
Gas cap presence, GC	$f(\text{GC}) = \begin{cases} f(\text{GC} = 0) = 0.86 \\ f(\text{GC} = 1) = 0.14 \end{cases}$	$e_{\text{GC}} = 0.0556$

$$\text{Eff}_I = (f_k e_k + f_{\text{TDS}} e_{\text{TDS}} + f_\mu e_\mu + f_{\text{DP}} e_{\text{DP}} + f_T e_T + f_{\text{CC}} e_{\text{CC}})100\% \tag{13}$$

where f_k, f_{TDS}, f_μ, f_{DP}, f_T, f_{CC} are empirical functions corresponding to of permeability, total dissolved solids, oil viscosity, Dykstra-Parsonas coefficient, reservoir temperature, clay content, respectively; e_k, e_{TDS}, e_μ, e_{DP}, e_T, e_{CC} are expert coefficients of of permeability, total dissolved solids, oil viscosity, Dykstra-Parsonas coefficient, reservoir temperature, clay content, respectively.

$$\text{Eff}_{II} = (f_{\text{Aq}} e_{\text{Aq}} + f_{\text{GC}} e_{\text{GC}})100\% \tag{14}$$

where f_{Aq}, f_{GC} are empirical functions of aquifer presence and gas cap presence, respectively; e_{Aq}, e_{GC}–expert coefficient of aquifer presence and gas cap presence, respectively.

The integral applicability index is determined from Eq. (15):

$$\text{Eff}(\text{Eff}_I, \text{Eff}_{II}) = \text{Eff}_I + \text{Eff}_{II} \tag{15}$$

Stage III–Ranking the objects in accordance with the values of their integral applicability index.

4. Verification

To verify the functionality and reliability of the developed methodology, it was applied retrospectively to a selection of fields where polymer flooding had been previously implemented. The results of the analysis, presented in Table 11 and Fig. 7, indicate the actual efficiency of polymer flooding expressed as incremental oil production in tons per ton of dry polymer injected (t/t), a metric known as utility factor (UF), along with the integral applicability index of polymer flooding, calculated using the developed methodology.

Based on the comparison results, it can concluded that the potential success of implementing polymer flooding technology depends on how closely the characteristics of the selected field align with the applicability criteria. Therefore, based on the empirical evidence presented, the methodology can be considered verified.

5. Conclusions

1) Due to the ease of implementation and a wide range of applicability, polymer flooding can be identified as one of the leaders in potential for use among all EOR methods. In this regard, the development of a universal tool–a comprehensive methodology that allows for a rapid assessment of the prospects for technology implementation in field, as well as assessing the expected technological potential, is of particular relevance.
2) Based on the analysis of the implemented projects, as well as the experts' assessments, the applicability limits of polymer flooding have been updated and applicability criteria have been established. These criteria identify the conditions under which the implementation of polymer flooding has the highest technological effectiveness.
3) To assess the feasibility of polymer flooding implementation at a given object, a mathematical model has been developed based on the statistical research data of already

Table 12. Comparison of the Eff and UF data of implemented projects.

No.	Oilfield	Country	Eff	UF
1	Pelican Lake	Canada	86.00	181.81
2	JZ9-3	China	88.63	140.00
3	Captain	UK	77.41	124.60
4	Shengli, Gudao	China	87.23	120.00
5	Sirikit	Thailand	89.55	110.74
6	La-Sa-Xing	China	80.47	87.12
7	Grimbeek	Argentina	80.77	86.00
8	QD1, Xinjiang	China	78.90	85.00
9	Nimr	Oman	82.60	84.40
10	Yarigui-Cantagallo	Colombia	80.93	83.30
11	SZ36-1	China	79.16	81.24
12	Canto do Amaro	Brazil	80.24	79.38
13	Kalamkas	Kazakhstan	74.90	77.00
14	Palogrande-Cebu	Colombia	78.19	76.44
15	Dalia	Angola	75.75	61.74
16	Daqing	China	74.41	60.00
17	East Messoyakhskoe	Russia	69.16	59.00
18	Shengtuo	China	80.43	58.00
19	Matzen	Austria	72.00	53.90
20	Zaburunye	Kazakhstan	74.65	50.70
21	LD10-1	China	70.99	47.90
22	East Bodo	Canada	70.64	36.08

implemented projects. The model allows for calculation of the integral applicability index of relative effectiveness, characterizing the degree of potential success of polymer flooding implementation in a given field. The methodology for screening, assessment and ranking candidate objects, built on the basis of the developed mathematical model, consists of three stages: (1) primary selection of objects that meet the applicability limits, (2) calculation of the integral applicability indexes, i.e., assessment of their compliance with the applicability criteria, (3) ranking of candidate objects.

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Conflict of interest

The authors declare no competing interest.

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